Received: 2 September 2022 | Revised: 1 December 2022 | Accepted: 2 January 2023

DOI: 10.1111/sms.14311

ORIGINAL ARTICLE

WILEY

Sex moderates the associations between physical activity intensity and attentional control in older adolescents

Dominika M. Pindus[1,2,3] | **Tatsuya T. Shigeta**[4] | **Angus A. Leahy**[5] | **Myrto F. Mavilidi**[5,6] | **Apurva Nayak**[7] | **Dante Marcozzi**[7,8] | **Bryan Montero-Herrera**[1] | **Zainab Abbas**[1] | **Charles H. Hillman**[4,9] | **David R. Lubans**[5]

[1]Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

[2]Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

[3]Neuroscience Program, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

[4]Department of Psychology, Northeastern University, Boston, Massachusetts, USA

[5]Centre for Active Living and Learning, College of Human and Social Futures, University of New Castle, Callaghan, New South Wales, Australia

[6]School of Education/Early Start, University of Wollongong, Keiraville, New South Wales, Australia

[7]The School of Molecular and Cellular Biology, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

[8]Department of Computer Science, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

[9]Department of Physical Therapy, Movement, & Rehabilitation Sciences, Northeastern University, Boston, Massachusetts, USA

Correspondence
Dominika M. Pindus, Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, 305 Louis Freer Hal, 906 S Goodwin Avenue, Urbana, Illinois 61801, USA.
Email: pindus@illinois.edu

Funding information
National Health and Medical Research Council, Grant/Award Number: (APP1120518); the New South Wales Department of Education School Sport Unit

Introduction: The relationship between physical activity (PA) intensity and executive functions in older adolescents remains poorly understood. This study aimed to examine the associations between PA intensity, volume, attentional control, and working memory and the moderating effects of sex in older adolescents.
Method: We analyzed baseline data from 418 participants (211 females, $M_{age} = 16.5 \pm 0.40$ years) from the Burn 2 Learn trial. Adolescents wore GT9X Link accelerometers on a non-dominant wrist for 7 days, 24-h·d^{-1}. PA intensity was expressed as intensity gradient (IG) and moderate-to-vigorous PA (MVPA, Hildebrand cut-points); PA volume was expressed as average acceleration (AvACC). Attentional control was measured with a standard deviation (SDRT) and a coefficient of variation (CVRT) of the reaction time on the incongruent trials of a flanker task. Working memory was expressed as a d prime (a signal discrimination index) on the 2-back task. The moderating effects of sex on the PA-executive functions associations, adjusting for age, BMI z-score, and cardiorespiratory fitness, were tested using multilevel random intercept models.
Results: After controlling for AvACC, sex moderated the relationships between IG and incongruent SDRT ($B = 0.53$, 95% CI: 0.12, 0.94) and CVRT ($B = 0.63$, 95% CI: 0.22, 1.05; $ps \leq 0.002$). Only girls with higher IG showed smaller incongruent SDRT and CVRT ($Bs \leq -0.26$, $ps \leq 0.01$). IG was not related to working memory. AvACC and MVPA were not associated with attentional control or working memory.

Conclusion: Our findings reveal a novel association between higher-intensity PA and superior attentional control among adolescent girls.

KEYWORDS
accelerometry, adolescents, executive functions, intensity gradient, moderate-to-vigorous physical activity

1 | INTRODUCTION

Globally, more than 80% of adolescents aged 11–17 years do not meet current recommendations for daily aerobic physical activity (PA).[1] Growing evidence suggests that low levels of PA can adversely impact cognitive and brain health in youth.[2,3] Randomized controlled trials indicate that engagement in moderate-to-vigorous PA (MVPA) and high-intensity PA can enhance executive functions in youth.[2–4] However, previous research has focused on preadolescents and young adolescents, with scarce evidence on the PA-executive functions relationship in older adolescents (15–18 years). Executive functions refer to a set of higher-order top-down cognitive operations that select, schedule, and coordinate perception, memory, and behavior in service of a goal. Two aspects of executive functions particularly important in the context of PA in youth are inhibitory control of attention (i.e., interference control at the perceptual level termed attentional control) and working memory (i.e., the ability to hold and actively manipulate information in mind) because they are related to better academic achievement,[5] and are amenable to PA interventions.[2,3]

PA-related cognitive gains seem to accrue faster with higher intensity PA (e.g., over 6–12 weeks)[2] compared to MVPA interventions (the majority lasting ≥12 weeks).[4] Thus, it is plausible that higher PA intensity may lead to greater cognitive gains in adolescents, but its associations with executive functions remain poorly understood. Observational studies using objective PA monitoring can complement randomized controlled trials. Such studies benefit from ecological validity by measuring PA levels in free living. Only few previous studies assessed the relationship between accelerometer-measured PA and executive functions in adolescents yielding equivocal findings.[6–8] For example, Booth et al.[8] found positive associations between accelerometer-measured MVPA and selective attention (an aspect of attentional control) in 11-year-old boys but not girls. In contrast, Ruotsalainen et al.[6] found no associations between MVPA and attentional control in 14 years old adolescents. Furthermore, Wickel et al.[7] found negative associations between accelerometer-measured MVPA and working memory in 15-year-old boys and null associations in girls. The differences in cognitive measures, the age of the samples, and the small sample size in the study by Ruotsalainen et al.[6] may have contributed to these discrepant findings. Thus, more studies are warranted to better understand the PA-executive functions relationships in adolescents.

Cut-point-based PA intensity estimates have limited sensitivity to measure PA-executive functions relationships because intensity thresholds provide estimates of absolute PA intensity, which are not accurate on an individual level. Furthermore, MVPA estimates from accelerometers are confounded by total PA volume, as evidenced by high correlations between MVPA and PA volume (e.g., *r*s > 0.92).[9,10] Accordingly, the cut-point measured MVPA does not uniquely capture moderate and vigorous PA. This is a limitation because PA interventions that improve executive functions in children and adolescents employ moderate and vigorous[3,4] or high-intensity PA.[2] Intensity gradient (IG), a cut-point independent PA metric, can help capture higher PA intensities (moderate and vigorous) and disentangle the relationship between higher PA intensity, PA volume, and health outcomes.[9,10] IG represents an individual's daily intensity profile, expressed as a slope of the regression line predicting time from the intensity.[9] A shallower slope indicates more time spent at higher PA intensities.[9] Previous research has shown that preadolescents who have a shallower IG (based on tertile) engage in higher levels of moderate and vigorous-intensity PA.[10] For example, English preadolescents in the third IG tertile accumulated 13 more minutes in vigorous PA and 18 more minutes in moderate-intensity PA compared to preadolescents in the first IG tertile, but there was no difference in light PA between IG tertiles.[10] Accordingly, IG may be better suited to capture the PA-executive functions relationship in adolescents because it is specific to an individual, captures inter-individual differences in moderate and high-intensity PA accumulated in free-living, and has shown positive associations with physical health outcomes (e.g., cardiorespiratory fitness [CRF], BMI) over and above that of PA volume.[9,10] To the best of our knowledge, no published report has considered the relationship between IG and executive functions in older (15–18 years old) adolescents.

Meta-analytical findings based on 80 chronic PA interventions suggest that sex can moderate the effect of PA interventions on executive functions.[11] Boys and men can benefit more from PA interventions, which progressively increase PA intensity towards a predetermined (rather than individually set) threshold.[11] Since girls engage in less vigorous PA than boys,[12] intervention protocols using fixed PA intensity may have led to overtraining in girls, negatively affecting the efficacy of PA to improve executive functions. In contrast to PA interventions, which aim to increase MVPA to the level of PA guidance compliance, accelerometer-measured daily PA intensity and volume represent ecologically valid levels of PA. Understanding how sex may moderate the relationship between daily accelerometer-measured PA and executive functions in older adolescents may help guide the design of better-tailored interventions that account for sex differences in daily PA. Furthermore, it can shed light on the discrepant findings from observational studies.[6–8] Two studies found a moderating effect of sex. They reported statistically significant associations between MVPA and vigorous PA and indices of executive functions primarily in boys (albeit in the opposite direction: positive[8] and negative[7]). In contrast, a study by Ruotsalainen et al.,[6] which did not consider sex as a moderator, found no associations between MVPA and executive functions.[6] To the best of our knowledge, no previous study assessed the moderating effects of sex on PA-executive functions relationship in older adolescents using cut-point independent metrics of PA intensity that allow dissociating the contribution of higher PA intensities (moderate and vigorous) from PA volume to these relationships.

Beyond traditional measures of accuracy and reaction time (RT), performance variability can provide complementary information about the relationship between PA and executive functions in youth. Intra-individual variability of trial-to-trial RT has been associated with better performance on tasks that require attentional control (e.g., reasoning and working memory) in young and older adults.[13] Furthermore, RT variability increases with the up-regulation of attentional control; prolonged decision time, which engages attentional control, largely accounts for this increase.[14] The sensitivity of the RT variability to attentional control is further supported by a neurofunctional study in young adults.[15] In this study, smaller RT variability on a modified flanker task (that requires overcoming perceptual interference from flanking stimuli) was associated with stronger anticorrelations in functional connectivity between the frontoparietal network (that supports task engagement) and the default mode network (which supports task-passive states) in young adults.[15] Furthermore, this association was stronger for incongruent flanker trials, which require greater up-regulation of attentional control. Next, performance stability increases until late adolescence, which is linked to the maturation of white matter tracts connecting frontoparietal brain regions.[16] Thus, stability in cognitive performance may be more malleable to PA due to the prolonged plasticity of white matter tracts that support it. We know of only one study, which assessed the relationship between objectively-measured PA and RT variability during a task of attentional control. This study showed that a larger volume of the anterior cingulate cortex mediated the relationship between higher MVPA and smaller RT variability (i.e., the coefficient of variation of the RT; CVRT) on the incongruent condition of the Stroop task that also required the up-regulation of attentional control.[17] The anterior cingulate cortex supports conflict resolution and stability of cognitive performance, and, therefore, more efficient attentional control. To the best of our knowledge, the relationship between daily PA and performance variability during executive function tasks has not been evaluated in older adolescents who continue to undergo white matter maturation, leading to increased stability of cognitive performance.[16] Accordingly, RT variability may provide a more complete understanding of the relationships between inter-individual variation in daily PA volume and intensity and attentional control in older adolescents.

The primary aim of this study was to examine the associations between accelerometer-measured PA intensity (IG and MVPA), PA volume (AvACC), attentional control, and working memory in 15–18 years-old Australian high school students. The secondary aim was to assess the moderating effects of sex on these relationships. We hypothesized a positive relationship between PA intensity, attentional control, and working memory, independent of PA volume and CRF and specific to IG, due to the collinearity between MVPA and PA volume.[9,10] Our analyses of PA volume-executive functions associations were exploratory because few studies directly measured these relationships in adolescents.[8] Based on the positive associations between CRF and attentional control in adolescents,[18,19] we hypothesized that shallower IG, higher MVPA, and PA volume would be associated with better performance on the modified flanker task both on traditional measures (accuracy and RT) and response variability (smaller standard deviation of the RT [SDRT], and CVRT), particularly on the incongruent trials, which require the higher engagement of attentional control compared to congruent trials. We expected stronger associations for measures of RT variability based on the indirect associations between MVPA and SDRT on the incongruent trials of the Stroop task in young adults.[17] Furthermore, performance stability on the flanker task matures later (around 19 years)[16] compared to accuracy and response speed (around the age of 12 years).[20] Accordingly, we reasoned that this aspect of cognitive performance may be more malleable to PA and, therefore, more sensitive to inter-individual variability in daily PA in older adolescents. Conversely, we relied on measures of signal detection (a composite measure of accuracy and error rates) to assess working memory because this measure has differentiated high and low working memory performance in children, adolescents, and adults.[21] Regarding the secondary aim, we hypothesized a positive association between IG and executive functions in boys (better cognitive performance associated with a shallower IG)[11] but withheld the hypotheses specific to girls due to equivocal observational evidence.[7,8]

2 | MATERIALS AND METHODS

2.1 | Study design

Baseline data from the Burn 2 Learn (B2L) cluster randomized controlled trial (RCT; ACTRN12618000293268) were used for this cross-sectional study. The trial methods have been previously described.[22] Twenty government schools with senior high school students (grades 11 and 12) largely representative of the urban and regional secondary schools from New South Wales (NSW) were recruited. Within each school, two grade 11 teachers willing to deliver the PA intervention were identified (23 classes in total). All students in the recruited classes were eligible to participate in the trial (79% of eligible students returned informed consent). Baseline data were collected between February and April 2018 (cohort 1) and 2019 (cohort 2). The Human Research Ethics Committee of the University of Newcastle (H-2016-0424) and the NSW Department of Education (SERAP: 2017116) approved the study.

2.2 | Participants

Out of 670 students who consented to participate in the B2L trial and underwent baseline assessments, 554 participated in the accelerometry measurements. The inclusion criteria for this cross-sectional study were: (i) the availability of valid accelerometry data defined as ≥2 days of ≥10 h/day of accelerometer wear between 6 a.m. and midnight,[23] (ii) accelerometer signal passing quality assessments described (see Section 2.3.2), and (iii) availability of valid cognitive data with above-chance accuracy (> 50%) on each cognitive task. Figure 1 illustrates the numbers excluded with reasons. Four hundred eighteen (75%) provided valid accelerometer and cognitive data and were included in the study.

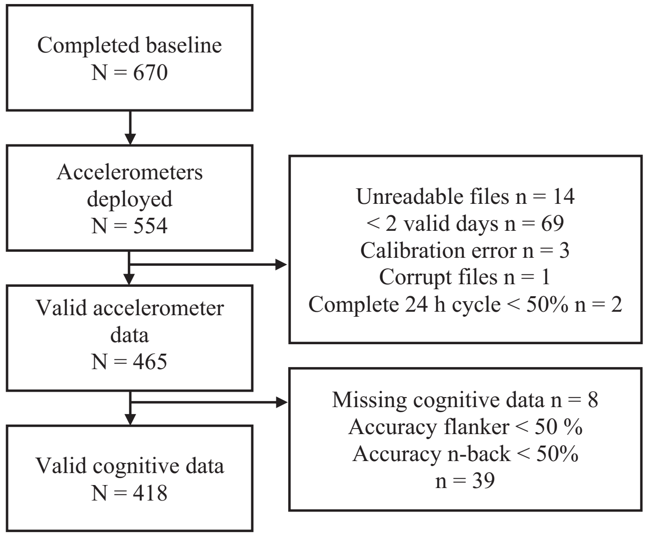

FIGURE 1 The number of included and excluded participants with reasons.

2.3 | Measures

2.3.1 | Accelerometry

Participants wore ActiGraph GT9X Link accelerometers (ActiGraph, Pensacola, FL) on a non-dominant wrist 24 h/day for 7 consecutive days, including water-based activities (e.g., swimming). Devices were distributed at schools and returned by participants at the end of the seven days. GT9X Link is a triaxial accelerometer with a dynamic range of ±8 g (where 1 g is the force of gravity: 9.806 $m*s^{-2}$). All accelerometers were initialized using ActiLife software (v. 6.13.4) to start recording at 7 a.m. The sampling frequency was set to 30 Hz with a normal filter setting enabled and "idle sleep mode" disabled. Raw data were downloaded to ActiLife, saved as .gt3x files, and converted to .csv format for further data processing in R (v. 3.6.2).

2.3.2 | Accelerometer data processing

Accelerometer files were reduced in R (v. 3.6.2) using the GGIR package (v. 2.1.0).[24] Detailed description of accelerometer data processing and valid file definition is provided in Supplementary Material 1, including calibration and non-wear detection. In addition, the GGIR script is provided in Supplementary Material 2. The non-wear periods were imputed using the average of similar time points on other measurement days as per the default GGIR settings. The accelerometer signal from three axes was converted to the Euclidean Norm Minus One (ENMO) over 5 s epochs.[25] To exclude the putative sleep time, only data between 6 a.m. and 11:59 p.m. were analyzed.[26] Hildebrand's cut-points were used to define time spent in light (≥50 mg), moderate (≥200, <707 mg), vigorous PA (≥707 mg), and MVPA (≥200 mg).[27] Cut-point independent PA intensity was expressed as IG, which captures a curvilinear relationship between intensity and time (see Supplementary Material 1 for further details).[9] IG is expressed as the slope of the linear regression line predicting time from the intensity with both values transformed using a natural log. IG is always negative, reflecting decreasing time spent at higher intensities. A steeper (more negative) IG reflects a smaller proportion of higher-intensity PA and a less advantageous intensity profile.[9] Total PA volume was expressed as AvACC (mg/day).[9] These metrics have been chosen because: (i) IG captures an individual's PA intensity in a single metric, (ii) IG and AvACC are only moderately correlated,[9,10] allowing the assessment of independent relationships between PA intensity, volume, and cognitive outcomes; and (iii) IG and AvACC metrics are standardized, and thus comparable across populations.

2.4 | Executive functions

Attentional control was measured with a modified Eriksen flanker task.[18,28] Participants completed cognitive tasks on 14-inch laptops (Dell Latitude 5490, Dell, Round Rock, TX) in a standard classroom at the study schools. PsychoPy software was used for stimulus presentation. Participants sat approximately 45 cm away from the laptop. They were presented with a sequence of five 3-cm long white arrows shown on a black background at the center of the laptop screen. Participants were instructed to respond to the directionality of the central arrow (the target) by pressing 'Q' on the keyboard with the left index finger if the central arrow was facing to the left and by pressing 'P' with the right index finger if the central arrow was facing to the right. On congruent trials, the flanking arrows were facing in the same direction as the target; on incongruent trials, the flankers were facing in the opposite direction to the target. The flankers create a perceptual pull to respond to the directionality of the flankers instead of the target. To respond correctly, a participant must override the prepotent response to the directionality of the incongruent flankers and respond to the directionality of the target. Both trial types up-regulate attentional control due to the need to process flanking stimuli and the uncertainty of the upcoming trial type. However, incongruent trials require greater up-regulation of attentional control due to perceptual conflict, resulting in longer and less accurate responses. Congruent and incongruent trials were equiprobable. Participants were instructed to respond as fast and as accurately as possible. Stimuli were presented for 100 ms, separated by a jittered inter-stimulus interval (ISI; 900 ms, 1050 ms, and 1200 ms), during which a blank black screen was presented. Responses were recorded from the onset of the stimulus to the end of the ISI. Following 25 practice trials (completed to the criterion of >70% accuracy), participants completed one block of 150 experimental trials. No feedback on performance was provided. Attentional control was expressed as incongruent mean RT, SDRT, CVRT (i.e., SDRT/RT), and accuracy. CVRT is a more conservative measure of variability because it standardizes SDRT relative to the mean RT. Congruent mean RT, SDRT, CVRT, and accuracy were used as measures of information processing efficiency.

Working memory was measured with an n-back task.[18] Participants completed 1- and 2-back conditions in a counter-balanced order. During the n-back, participants viewed a series of standard 3-cm wide shapes (i.e., a red crescent, a green circle, a yellow triangle, an orange square, a blue cross, or a purple star) appearing one at a time at the center of the laptop screen. In the 1-back condition, they pressed the letter 'P' on the keyboard if the current shape was the same (i.e., a target trial) as the shape immediately preceding it and 'Q' otherwise (i.e., nontarget trial). In the 2-back condition, a target was the same shape as two trials prior to it. Stimuli were presented for 250 ms, followed by a 2500 ms ISI during which a blank black screen was presented. For each condition, participants first completed 20 practice trials (to the criterion of >70% accuracy), followed by two blocks of 72 trials comprising 24 target and 48 nontarget trials. Participants received no feedback on task accuracy during experimental trials. Working memory was expressed as d prime (d′) on a 2-back condition. D' measures signal discrimination factoring in accuracy and false alarms (i.e., d′ = z-score of false alarms - z-score of target accuracy). We adjusted for 100% target accuracy ($2-(1/n)$; n is the number of trials) and 0% false alarms ($1-(2-(1/n))$). A higher d' indicates superior signal discrimination ability with a maximum score of 4.9. Secondary working memory measures included mean RT, SDRT, CVRT, and accuracy on the 2-back target trials. One-back task performance (i.e., target and nontarget: accuracy, mean RT, SDRT, CVRT, a d') and 2-back nontarget mean RT, SDRT, CVRT, and accuracy were used to measure information processing efficiency.

2.4.1 | Covariates

Demographics. Participants self-reported their age and sex. Socioeconomic status was measured at the school level using Socioeconomic Indexes for Areas Index of Relative Socioeconomic Disadvantage (IRSD), based on the area postcode.[29] The IRSD index was expressed in percentiles representing the ranking of the areas on the continuum from the most (low percentiles) to the least disadvantaged (high percentiles).

Body mass index (BMI). Height was measured to the nearest 0.1 cm and weight to the nearest 0.01 kg using a portable stadiometer (Seca 213 Portable Height Measuring Rod Stadiometer) and a portable digital scale (A&D Medical UC-352-BLE Digital Scales), respectively. BMI was calculated as (weight [kg]/height [m^2]). Weight status was determined using International Obesity Task Force cut-offs.[30]

CRF was measured using a 20-m Progressive Aerobic Cardiovascular Endurance Run (PACER) test according to the FitnessGram testing procedures (The Cooper Institute).[31] CRF was expressed as the number of successfully completed laps. Participants were classified as low fit if their number of laps was below the 40th percentile based on international age and sex-specific norms.[31]

2.5 | Statistical analyses

Age and BMI z-score were used as covariates in all models based on bivariate Spearman rho correlations (Supplementary Material 3); CRF was included in all models to control for sex differences in CRF and CRF-EFs associations. Missing BMI data for two subjects and CRF data for 44 subjects (11%; 16 girls) were mean replaced with sex-and school-specific mean values. Sex differences in the number of valid days, weight status, CRF, PA variables, and cognitive performance were tested using a chi-square test and independent sample t-tests, as appropriate. To place our results based on the IG in the context of commonly used cut-point-based PA intensities, we performed within-subject one-way ANOVAs to test the differences in cut-point-dependent PA intensities by IG tertiles.

The associations between PA, attentional control, and working memory were assessed using multilevel mixed-effects models with random intercepts and students (level-one units) nested within schools (level-two units, $n = 20$). First, we modeled an interaction between level-one explanatory variables (IG, MVPA, or AvACC) and sex, adjusting for covariates. We statistically compared each interaction model against a null (intercept only) and a covariate plus PA model (IG, MVPA, or AvACC). Model fit was tested using the Bayesian Information Criterion (BIC). We used Nagakawa's marginal coefficient of variation (R^2_m) as a measure of variance explained due to the fixed effect of IG, MVPA, or AvACC. If sex was a significant moderator, we tested the associations between PA exposure and a given cognitive outcome separately in boys and girls. To understand whether PA intensity (IG) or volume (AvACC) was a stronger predictor of cognitive performance, we mutually adjusted for AvACC and IG, respectively. We present mutually adjusted and unadjusted models with IG and AvACC as predictors. To assess the relative selectivity of physical activity associations with flanker performance on incongruent trials, we performed secondary analyses when the association between PA variables and performance on incongruent trials was significant. All models were assessed for normality of level-one and level-two residuals, heteroscedasticity, and linearity. Due to the non-normality of level-one residuals, all cognitive variables were transformed using the Tukey ladder of powers and scaled to values between 0.0 and 1.0. Across tasks, accuracy scores were first reversed due to negatively skewed distributions. Thus, *positive beta* coefficients for models estimating accuracy denote a *negative* relationship, and *negative betas* denote a *positive* relationship. All models without interaction terms had variance inflation factors ≤1.54. Statistical Package for Social Sciences (v. 27.0.0.0; IBM corp.) was used to conduct all tests but multilevel models. Multilevel models were tested using packages lme4 and lmerTest in R (v. 3.6.2). Statistical significance was set at $p < 0.05$. All statistically significant findings in the primary analyses are adjusted for false discovery rate ($q = 0.05$) using Benjamin-Hochberg corrected *p*-values. Secondary analyses are unadjusted for false discovery rate.

3 | RESULTS

Table 1 presents sample characteristics. Girls were less physically active than boys, irrespective of an intensity metric. Girls responded slower, and their performance was more variable across congruent and incongruent flanker trials (Table 2). They were also less accurate, less consistent on nontarget trials, and had poorer signal detection on the 2-back task.

3.1 | Task manipulation

3.2 | Flanker task

Participants were more accurate, faster, and more consistent in their responses on the congruent compared to the incongruent trials ($ps < 0.0001$; Supplementary Material 4), confirming successful task manipulation resulting in the congruency effect.

3.3 | *N*-back task

Participants were more accurate, faster, and more consistent in their responses on target and nontarget trials

TABLE 1 Characteristics of the sample

	All $N = 418$	Girls $N = 211$	Boys $N = 207$
	M (SD)	M (SD)	M (SD)
Age	16.5 (0.40)	16.5 (0.40)	16.5 (0.41)
BMI	23.2 (4.32)	23.4 (3.77)	23.1 (4.83)
BMI z-score	0.76 (1.02)	0.78 (0.93)	0.74 (1.11)
Overweight (N, [%])[a]	92 [22]	50 [24]	42 [20]
Obese (N, [%])[a]	37 [9]	17 [8]	20 [10]
School SES SEIFA percentile (1–100)	52.5 (24.3)	52.1 (25.00)	53.0 (23.7)
Cardiorespiratory Fitness # Laps	49.5 (25.1)	47.5 (25.4)	51.7 (24.8)
Low Fit ≤40th percentile (n, [%])[b]	149 [36]	57 [27]*	92 [44]
Complete 24 h Cycle (accelerometer data: 0–1)	0.94 (0.13)	0.94 (0.12)	0.93 (0.13)
Valid days (n)	5.6 (1.65)	5.6 (1.70)	5.6 (1.61)
Valid days ≥4 (n, [%])	352 [84]	174 [82.5]	178 [86]
AvACC (mg)	40.9 (11.9)	37.9 (10.8)*	43.9 (12.2)
IG (logn mg / logn min)	−2.20 (0.19)	−2.26 (0.18)*	−2.14 (0.18)
MVPA (min/day)	33.6 (17.8)	28.8 (15.6)*	38.5 (18.5)

Note: Statistically significant sex difference: *$ps < 0.001$; all other comparisons: $ps \geq 0.09$.

[a]Defined based on the International Obesity Task Force cut-offs.[31] SES: Socio-economic status measured at the school level using Socio-Economic Indexes for Areas Index of Relative Socioeconomic Disadvantage (IRSD), based on the area postcode,[30] and expressed in percentiles low percentiles represent the most disadvantaged areas. Cardiorespiratory fitness was measured using the 20-m PACER test, and expressed as the number of successfully completed laps.[32]

[b]Defined based on international norms[32]; AvACC: Average daily acceleration between 6 a.m. and midnight; IG: average daily intensity gradient between 6 a.m. and midnight.

on the 1-back compared to the 2-back task condition ($ps < 0.0001$; Supplementary Material 5), confirming increased task difficulty with an increased working memory load.

3.4 | The associations between physical activity and attentional control

3.4.1 | Cut-point independent physical activity intensity (IG)

Model fit statistics are presented as Supplementary Material 6 (models with interactions) and 8 (models specific to girls). IG was not related to measures of attentional control (i.e., incongruent RT, SDRT, CVRT, or accuracy), in the full sample ($ps \geq 0.08$), except for the incongruent SDRT and CVRT ($ps = 0.04$; Table 3). However, these relationships were explained by selective associations between IG, incongruent SDRT, and CVRT in girls (Table 3), and IG was not related to incongruent SDRT or CVRT in boys ($ps \geq 0.13$; Table 3). Sex moderated the relationship between IG, congruent accuracy ($B = 0.56$, 95% CI: 0.14–0.97, $p = 0.049$), and RT variability: incongruent SDRT ($B = 0.54$, 95% CI: 0.13–0.95, $p = 0.04$), and CVRT ($B = 0.64$, 95% CI: 0.23–1.06, $p = 0.02$). Girls with shallower IG were more consistent on incongruent trials, as indicated by smaller SDRT and CVRT with shallower IG ($ps \leq 0.02$; Table 3; Figure 2). However, they were not more accurate on congruent trials ($p = 0.06$; Supplementary Material 8 and 14). The moderating effects of sex on the relationships between IG and incongruent SDRT and CVRT remained statistically significant after adjusting for A vACC ($ps \leq 0.049$). Girls with shallower IG had smaller SDRT and CVRT on incongruent trials ($ps < 0.01$). For every *SD* increase in IG (indicating a shallower IG), there was a 0.26 *SD* decrease in incongruent SDRT and a 0.27 *SD* decrease in incongruent CVRT after adjusting for AvACC. Intraclass correlation coefficients (ICCs ≤ 0.08; Supplementary Material 7 and 9) suggested that all these associations were largely consistent across schools. The school (a second-level covariate) explained ≤8% of the variance across models. In the post hoc analyses testing selectivity of the IG-SDRT and IG-CVRT associations to incongruent

TABLE 2 Cognitive performance on the modified flanker, 1- and 2-back tasks (mean (*SD*))

Task	Accuracy (% correct)	RT (ms)	SDRT (ms)	CVRT (ms)
Flanker				
Congruent				
Girls	93 (6.5)	430.9 (51.2)***	88.7 (33)***	0.20 (0.06)***
Boys	94.2 (7.1)	405.4 (49.9)	74.5 (38.1)	0.18 (0.07)
Incongruent				
Girls	80.2 (12.7)	491.9 (56.9)***	92.1 (34.1)***	0.19 (0.06)**
Boys	77.7 (13.3)	469.9 (57.6)	81 (35.3)	0.17 (0.06)
1-Back				
Target				
Girls	91.8 (8.2)	562.9 (102.8)	158.5 (54.6)	0.28 (0.07)
Boys	91.2 (8)	565.9 (120.5)	159.4 (65.1)	0.28 (0.07)
Nontarget				
Girls	95 (6)	668.1 (128.2)	205.3 (71.1)	0.30 (0.07)
Boys	94.6 (6.2)	661.1 (141.1)	202.5 (78.1)	0.30 (0.07)
d′				
Girls	3.4 (0.8)			
Boys	3.2 (0.8)			
2-Back				
Target				
Girls	78 (12.5)	726.3 (185.6)	283 (100.5)	0.39 (0.09)
Boys	78.6 (14.3)	715.9 (195.7)	273.2 (99.2)	0.38 (0.09)
Nontarget				
Girls	86.7 (9.9)**	856.2 (197.6)	286.1 (83.1)*	0.34 (0.06)
Boys	89.3 (8.2)	823.5 (198.3)	267.3 (85.7)	0.33 (0.08)
d′				
Girls	2.1 (0.8)*			
Boys	2.3 (0.8)			

Abbreviations: CVRT, coefficient of variation of the RT (*SD*/mean RT); d′, d prime; RT, reaction time; SDRT, standard deviation of the RT.Statistically significant sex difference: ***$p \leq 0.001$, **$p \leq 0.01$, *$p < 0.05$.

flanker trials, sex moderated the relationships between IG and incongruent CVRT after adjusting for congruent CVRT ($ps \leq 0.03$; Supplementary Materials 16 and 17). The moderating effects of sex on IG-incongruent SDRT relationships were reduced to a trend level after adjusting for congruent SDRT (ps = 0.07 and 0.08, unadjusted and adjusted for AvACC, respectively). The post-hoc analyses within each sex confirmed that girls with shallower IG had smaller CVRT and SDRT on incongruent trials after adjusting for congruent CVRT and SDRT, respectively ($ps < 0.01$; Supplementary Material 18). Taken together, our results suggest that a shallower IG was related to better attentional control (smaller incongruent SDRT and CVRT) selectively in girls. These relationships were independent of PA volume (AvACC).

3.4.2 | Cut-point-dependent physical activity intensity (MVPA)

MVPA was not related to performance on the flanker task (i.e., congruent and incongruent RT, SDRT, CVRT, and accuracy) in the total sample ($ps \geq 0.32$; Table 3; Supplementary Material 14). The relationships between MVPA and congruent CVRT (B = 0.06, 95% CI: 0.02–0.11) and MVPA and incongruent SDRT (B = 0.06, 95% CI: 0.01–0.11) and CVRT (B = 0.07, 95% CI: 0.02–0.12) were moderated by sex ($ps \leq 0.048$; Figure 2). However, when analyses were stratified by sex, only the association between higher MVPA and smaller congruent CVRT in girls was statistically significant (p = 0.02; Table 3). ICCs suggested consistency of the reported associations across schools (ICCs

TABLE 3 The relationship between physical activity volume, intensity, and moderate-to-vigorous physical activity, and flanker task performance.

	ACC				IG				MVPA	
	Mod 2		Mod 3		Mod 2		Mod 3		Mod 2	
	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)
Congruent RT										
Combined	0.07	−0.01 (−0.02, 0.01)	0.07	−0.00 (−0.02, 0.01)	0.07	−0.08 (−0.18, 0.03)	0.07	−0.07 (−0.19, 0.05)	0.07	−0.00 (−0.02, 0.01)
Girls	0.01	−0.01 (−0.03, 0.01)	0.02	−0.00 (−0.03, 0.02)	0.02	−0.10 (−0.23, 0.04)	0.02	−0.09 (−0.25, 0.08)	0.01	−0.01 (−0.03, 0.01)
Boys	0.01	−0.01 (−0.03, 0.01)	0.02	−0.005 (−0.03, 0.02)	0.01	−0.07 (−0.21, 0.07)	0.02	−0.06 (−0.22, 0.10)	0.01	−0.003 (−0.02, 0.02)
Congruent SDRT										
Combined	0.07	−0.00 (−0.01, 0.01)	0.08	0.00 (−0.01, 0.01)	0.08	−0.09 (−0.19, 0.01)	0.08	−0.09 (−0.21, 0.03)	0.07	−0.00 (−0.01, 0.01)
Girls	0.04	−0.02 (−0.03, 0.00)	0.05	−0.01 (−0.03, 0.01)	0.05	−0.18 (−0.31, −0.04)	0.052	−0.13 (−0.29, 0.03)	0.04	−0.02 (−0.03, 0.00)
Boys	0.04	0.01 (−0.01, 0.02)	0.04	0.01 (−0.01, 0.03)	0.037	0.01 (−0.14, 0.15)	0.041	−0.03 (−0.19, 0.13)	0.04	0.01 (−0.01, 0.02)
Congruent CVRT										
Combined	0.07	−0.00 (−0.02, 0.01)	0.07	0.00 (−0.01, 0.01)	0.07	−0.09 (−0.19, 0.02)	0.07	−0.09 (−0.21, 0.03)	0.07	−0.01 (−0.02, 0.01)
Girls	**0.05**	**−0.02 (−0.03, 0.00)***	0.06	−0.01 (−0.03, 0.01)	**0.05**	**−0.19 (−0.32, −0.05)***	0.06	−0.13 (−0.29, 0.03)	**0.05**	**−0.02 (−0.03, −0.01)***
Boys	0.04	0.01 (−0.01, 0.03)	0.04	0.01 (−0.01, 0.03)	0.04	0.03 (−0.12, 0.17)	0.04	−0.02 (−0.18, 0.15)	0.04	0.01 (−0.01, 0.03)
Incongruent RT										
Combined	0.04	−0.01 (−0.02, 0.01)	0.04	−0.00 (−0.02, 0.02)	0.04	−0.09 (−0.20, 0.01)	0.044	−0.09 (−0.21, 0.03)	0.04	−0.01 (−0.02, 0.01)
Girls	0.00	−0.01 (−0.03, 0.01)	0.01	−0.00 (−0.02, 0.02)	0.01	−0.10 (−0.24, 0.04)	0.01	−0.09 (−0.26, 0.07)	0.01	−0.01 (−0.03, 0.01)
Boys	0.02	−0.01 (−0.03, 0.01)	0.03	−0.00 (−0.02, 0.02)	0.03	−0.11 (−0.25, 0.03)	0.03	−0.10 (−0.26, 0.06)	0.02	−0.01 (−0.02, 0.01)
Incongruent SDRT										
Combined	0.06	−0.00 (−0.01, 0.01)	0.07	0.01 (−0.01, 0.02)	**0.07**	**−0.12 (−0.23, −0.02)***	**0.07**	**−0.16 (−0.28, −0.04)***	0.06	−0.00 (−0.01, 0.01)
Girls	0.02	−0.02 (−0.03, 0.00)	0.07	−0.00 (−0.02, 0.02)	**0.07**	**−0.26 (−0.40, −0.13)***	**0.07**	**−0.26 (−0.42, −0.10)***	0.03	−0.02 (−0.03, 0.00)
Boys	0.09	0.009 (−0.01, 0.03)	0.09	0.01 (−0.01, 0.03)	0.09	0.01 (−0.13, 0.14)	0.09	−0.04 (−0.20, 0.12)	0.09	0.01 (−0.01, 0.03)

(Continues)

TABLE 3 (Continued)

	ACC				IG				MVPA	
	Mod 2		Mod 3		Mod 2		Mod 3		Mod 2	
	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)
Incongruent CVRT										
Combined	0.04	−0.00 (−0.01, 0.01)	0.06	0.01 (−0.01, 0.02)	**0.05**	**−0.12 (−0.22, −0.02)***	**0.06**	**−0.16 (−0.27, −0.04)***	0.04	0.00 (−0.01, 0.01)
Girls	0.02	−0.02 (−0.04, 0.00)	0.07	−0.01 (−0.17, 0.15)	**0.07**	**−0.27 (−0.41, −0.14)****	**0.07**	**−0.27 (−0.42, −0.11)****	0.02	−0.02 (−0.04, 0.00)
Boys	0.010	0.01 (0.00, 0.03)	0.10	0.10 (−0.05, 0.26)	0.09	0.04 (−0.10, 0.17)	0.10	−0.01 (−0.17, 0.14)	0.10	0.01 (0.00, 0.03)

Abbreviations: AvACC, Average acceleration (mg); CVRT, coefficient of variation of the reaction time; IG, intensity gradient; Mod, Model; SDRT, standard deviation of the reaction time.R^2_m: Nagakawa's marginal coefficient of variation; B: standardized betas (95% CI).

Model 2: Adjusted for age, sex (combined sample only), BMI z-score, and aerobic fitness.

Model 3: Adjusted for covariates in Model 1 and mutually adjusted for IG and AvACC.

Bolded values are statistically significant after Benjamin-Hochberg adjustments for false discovery rate at the following alpha levels: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

≤0.08). No other statistically significant associations between MVPA and flanker task performance were noted in the analyses stratified by sex ($ps \geq 0.06$). In summary, MVPA was selectively related to improved information processing in girls. MVPA was not associated with attentional control in either boys or girls or the total sample.

3.4.3 | Physical activity volume (AvACC)

The AvACC was not related to the accuracy or RT measures (i.e., RT, SDRT, and CVRT) on either congruent or incongruent trials in the full sample after adjusting for covariates, including sex ($ps \geq 0.08$; Table 3; Supplementary Material 14) and the IG ($ps \geq 0.17$). Sex moderated the relationship between AvACC, congruent ($B = 0.52$, 95% CI: 0.13–0.91), and incongruent CVRT ($B = 0.52$, 95% CI: 0.12–0.91), and incongruent SDRT ($B = 0.45$, 95% CI: 0.05–0.84; $ps \leq 0.048$; Supplementary Material 7). The moderation by sex of AvACC-CVRT relationships remained statistically significant after adjusting for IG ($ps \leq 0.048$), but sex did not moderate the AvACC-incongruent SDRT relationship after adjusting for IG ($p = 0.07$). Before adjusting for IG, greater AvACC was related to a decreased congruent CVRT in girls ($p = 0.02$) but not boys ($p = 0.28$; Table 3; Supplementary Material 8). However, this relationship was not statistically significant after adjusting for IG ($p = 0.17$). ICC values (ICCs ≤0.08) suggested that the associations were largely consistent across schools. No other statistically significant associations were noted between the AvACC and SDRT or CVRT ($ps \geq 0.11$). In summary, PA volume was not related to attentional control (expressed as incongruent RT, SDRT, CVRT, or accuracy) in either boys or girls. Girls with greater PA volume showed better information processing (i.e., smaller congruent CVRT), but this relationship was not independent of PA intensity.

3.5 | The associations between physical activity and working memory

3.5.1 | Cut-point independent physical activity intensity (IG)

IG was also not related to 1-back task performance in the entire sample ($ps \geq 0.07$; Table 4, Supplementary Material 15). Adjusting for AvACC did not modulate these findings ($ps \geq 0.12$). Sex did not moderate the relationship between the IG and any cognitive measure on the 1-back task ($ps \geq 0.15$).

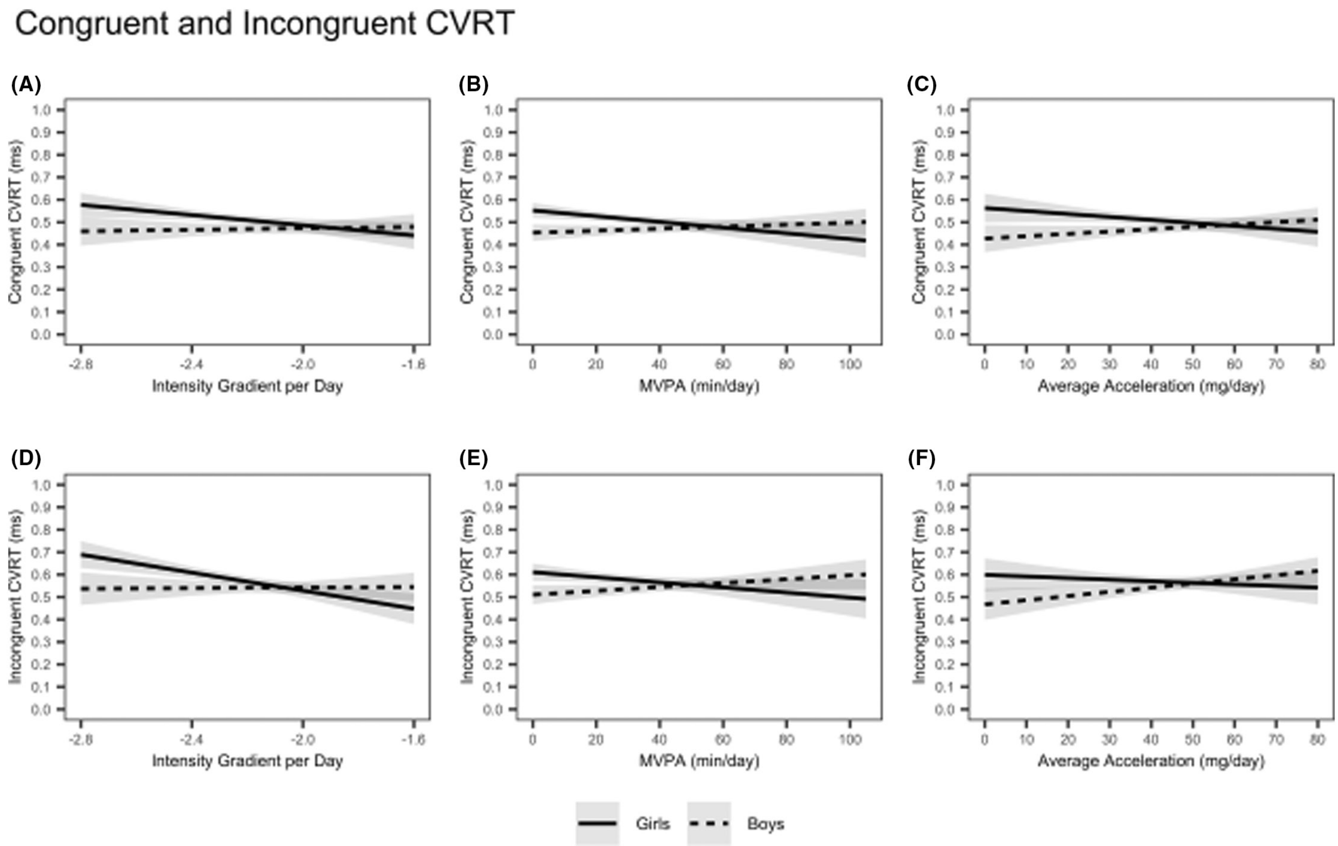

FIGURE 2 Moderating effects of sex on the relationship between physical activity intensity (IG), MVPA, physical activity volume (AvACC), and reaction time variability (CVRT) on congruent and incongruent trials of the flanker task. IG and AvACC are mutually adjusted. A–C models predict congruent CVRT from IG (A), MVPA (B), and AvACC (C); D–F models predict incongruent CVRT from IG (D), MVPA (E), and AvACC (F). AvACC: average acceleration (mg); IG: intensity gradient; MVPA: moderate-to-vigorous physical activity. Congruent CVRT was transformed using the Tukey ladder of powers and scaled to 0–1. Shaded areas around the prediction lines indicate 95% confidence intervals.

IG was not related to 2-back task performance in the total sample ($ps \geq 0.05$; Table 2; Supplementary Material 15). Sex moderated the relationship between IG and 2-back nontarget accuracy ($B = 0.08$, 95% CI: 0.02–0.15, $p = 0.04$). Model fit statistics are presented as Supplementary Materials 10 (models with interactions) and 12 (models specific to girls). After adjusting for AvACC, the moderating effect of sex remained statistically significant ($p = 0.04$). However, IG was not related to nontarget accuracy in either boys or girls ($ps \geq 0.08$); adjusting for AvACC did not modify these findings ($ps \geq 0.08$). These findings were largely consistent across schools (ICCs ≤ 0.08; Supplementary Material 11 and 13). No other statistically significant relationships between IG and 2-back task performance were noted ($ps \geq 0.05$). In summary, IG was not related to working memory or measures of information processing (1-back task and nontarget 2-back trials) in either boys or girls.

3.5.2 | Cut-point-dependent physical activity intensity (MVPA)

No associations were noted between MVPA and d′, accuracy, RT, SDRT, or CVRT on 1- or 2-back tasks in the full sample ($ps \geq 0.12$; Table 4, Supplementary Material 15). Sex did not moderate these relationships ($ps \geq 0.06$); ICCs (≤0.13) indicated that findings were largely consistent across schools. In summary, MVPA was not related to working memory in adolescents.

3.5.3 | Physical activity volume (AvACC)

AvACC was not related to cognitive measures on 1- or 2-back tasks in the entire sample ($ps \geq 0.19$). Sex did not moderate these relationships ($ps \geq 0.06$), and adjustment for IG did not modify these findings ($ps \geq 0.07$). ICCs (≤0.12) indicated that findings were largely consistent

TABLE 4 The relationship between physical activity volume, intensity, and moderate-to-vigorous physical activity, and *n*-back task performance.

	ACC				IG				MVPA	
	Mod 2		Mod 3		Mod 2		Mod 3		Mod 2	
	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)	R^2_m	B (95% CI)
1-Back										
Target Acc.										
Combined	0.01	−0.01 (−0.03, 0.01)	0.01	−0.01 (−0.03, 0.01)	0.01	−0.01 (−0.02, 0.01)	0.01	0.00 (−0.02, 0.02)	0.01	−0.01 (−0.03, 0.01)
Girls	0.00	0.002 (−0.02, 0.03)	0.00	0.00 (−0.03, 0.03)	0.00	0.00 (−0.02, 0.03)	0.002	−0.00 (−0.03, 0.03)	0.00	−0.00 (−0.03, 0.02)
Boys	0.02	−0.02 (−0.04, 0.01)	0.016	−0.02 (−0.05, 0.01)	0.01	−0.01 (−0.03, 0.02)	0.02	0.00 (−0.03, 0.03)	0.02	−0.02 (−0.04, 0.01)
Nontarget Acc.										
Combined	0.01	−0.00 (−0.02, 0.02)	0.01	0.01 (−0.01, 0.02)	0.01	−0.01 (−0.03, 0.01)	0.01	−0.01 (−0.03, 0.01)	0.01	−0.00 (−0.02, 0.01)
Girls	0.01	−0.01 (−0.03, 0.01)	0.02	0.00 (−0.02, 0.03)	0.02	−0.02 (−0.04, 0.00)	0.02	−0.02 (−0.05, 0.00)	0.02	−0.01 (−0.04, 0.01)
Boys	0.01	0.01 (−0.01, 0.03)	0.01	0.01 (−0.02, 0.03)	0.01	0.00 (−0.02, 0.02)	0.01	−0.00 (−0.03, 0.02)	0.01	0.01 (−0.01, 0.03)
d′										
Combined	0.01	0.01 (−0.01, 0.03)	0.02	0.00 (−0.02, 0.03)	0.02	0.01 (−0.01, 0.03)	0.02	0.01 (−0.01, 0.04)	0.01	0.01 (−0.01, 0.03)
Girls	0.00	0.00 (−0.02, 0.03)	0.01	−0.01 (−0.04, 0.03)	0.01	0.02 (−0.01, 0.04)	0.01	0.02 (−0.01, 0.05)	0.00	0.01 (−0.02, 0.04)
Boys	0.02	0.01 (−0.02, 0.04)	0.02	0.01 (−0.02, 0.04)	0.02	0.01 (−0.02, 0.03)	0.02	0.00 (−0.03, 0.03)	0.02	0.01 (−0.02, 0.04)
2-Back										
Target Acc.										
Combined	0.01	0.00 (−0.01, 0.02)	0.01	0.01 (−0.01, 0.02)	0.01	−0.01 (−0.02, 0.01)	0.01	−0.01 (−0.03, 0.01)	0.01	0.01 (−0.01, 0.02)
Girls	0.01	−0.01 (−0.03, 0.01)	0.05	0.01 (−0.02, 0.03)	**0.05**	**−0.03 (−0.05, −0.01)***	0.05	−0.03 (−0.05, −0.01)	0.01	−0.01 (−0.03, 0.01)
Boys	0.01	0.01 (−0.01, 0.03)	0.02	0.00 (−0.02, 0.03)	0.02	0.02 (−0.01, 0.04)	0.02	0.01 (−0.01, 0.04)	0.01	0.01 (−0.01, 0.03)
Nontarget Acc.										
Combined	0.02	0.00 (−0.01, 0.02)	0.03	0.01 (−0.01, 0.03)	0.03	−0.01 (−0.03, 0.00)	0.03	−0.02 (−0.03, 0.00)	0.02	−0.00 (−0.02, 0.01)
Girls	0.01	−0.01 (−0.03, 0.01)	0.05	0.01 (−0.01, 0.03)	0.05	−0.03 (−0.05, −0.01)	0.05	−0.04 (−0.06, −0.01)	0.01	−0.01 (−0.03, 0.01)
Boys	0.02	0.01 (−0.01, 0.03)	0.02	0.01 (−0.02, 0.03)	0.02	0.01 (−0.01, 0.03)	0.02	0.01 (−0.02, 0.03)	0.02	0.00 (−0.02, 0.02)
d′										
Combined	0.01	−0.00 (−0.02, 0.02)	0.02	−0.01 (−0.03, 0.01)	0.02	0.01 (0.00, 0.03)	0.02	0.02 (0.00, 0.04)	0.01	−0.00 (−0.02, 0.01)
Girls	0.01	0.01 (−0.01, 0.04)	0.06	−0.01 (−0.04, 0.02)	**0.06**	**0.04 (0.02, 0.06)****	**0.06**	**0.05 (0.02, 0.07)****	0.01	0.01 (−0.01, 0.03)
Boys	0.01	−0.01 (−0.04, 0.01)	0.01	−0.01 (−0.03, 0.02)	0.01	−0.02 (−0.04, 0.01)	0.01	−0.01 (−0.04, 0.02)	0.01	−0.01 (−0.04, 0.01)

Abbreviations: Acc., Accuracy; AvACC, Average acceleration (mg); CVRT, coefficient of variation of the reaction time; IG, intensity gradient; Mod, Model; SDRT, standard deviation of the reaction time.R^2_m: Nagakawa's marginal coefficient of variation; B: standardized betas (95% CI).

Model 2: Adjusted for age, sex (combined sample only), BMI z-score, and aerobic fitness.

Model 3: Adjusted for covariates in Model 1 and mutually adjusted for IG and AvACC.

Bolded values are statistically significant based on Benjamin-Hochberg adjustments for false discovery rate at the following alpha levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

across schools. In summary, AvACC was not associated with working memory or information processing.

4 | DISCUSSION

We assessed the direct and sex-moderated associations between cut-point independent (IG) and cut-point dependent (MVPA) PA intensity, PA volume (AvACC), attentional control, and working memory. We found no associations between PA intensity, PA volume, and attentional control or working memory in the entire sample. However, sex moderated the relationship between IG and attentional control such that higher PA intensity (shallower IG) was related to enhanced attentional control selectively in girls. As predicted, this relationship was independent of PA volume. The relationships between IG and attentional control were specific to measures of RT variability (i.e., incongruent SDRT and CVRT). In contrast, neither PA volume nor intensity (IG or MVPA) was related to working memory.

Novel to our investigation is the observation of better attentional control in girls who engaged in higher intensity PA (had shallower IG). These associations were independent of total PA volume, suggesting that attentional control increased with the increasing proportion of higher-intensity daily PA among girls with varying levels of total PA. Our secondary analyses confirmed the selectivity of these associations to incongruent trials, which up-regulated attentional control to a greater extent than congruent trials. For every *SD* increase in IG (equal to 0.18 units), we observed a 0.26 *SD* (9 ms) decrease in SDRT and a 0.27 *SD* (2%) decrease in CVRT. The magnitude of these associations is comparable to the small effect of chronic PA interventions on EFs in children and adolescents (Cohen's $d = 0.20$).[3] The magnitude of the decrease in SDRT with greater engagement in higher PA intensities is also comparable to the previously reported ~6–10 ms developmental decrease in SDRT between the ages of 16 to 24 years in Scottish adolescents.[32] Thus, our findings suggest that adolescent girls who accumulated more PA at higher intensities (by one *SD*) showed more developmentally mature levels of attentional control.

The selectivity of the association between higher PA intensity and attentional control in girls in our study may reflect sex differences in PA intensity. We tested this hypothesis in post hoc exploratory analyses. Sex differences in attentional control (incongruent SDRT and CVRT) were selective to adolescents with lower PA intensity, defined based on sex-specific 50th percentile split on the IG. Only girls who engaged in lower levels of high-intensity PA (MVPA $M = 20.8 \pm 11.1$ min/day, VPA $M = 1.10 \pm 0.95$ min/day) showed more variable performance on the attentional control task than boys with lower levels of high-intensity PA (MVPA $M = 31.3 \pm 16.3$ min/day, VPA $M = 2.75 \pm 1.89$ min/day). In contrast, sex differences in attentional control were no longer present in adolescents engaging in higher intensity PA (Girls: MVPA $M = 36.8 \pm 15.4$ min/day, VPA $M = 4.56 \pm 3.25$ min/day; boys: MVPA $M = 45.7 \pm 17.8$ min/day, VPA $M = 7.45 \pm 3.94$ min/day). Taken together with these post hoc analyses, our findings suggest that adolescent girls who engage in little to no high-intensity PA may benefit most cognitively from interventions increasing their levels of high-intensity PA.

Few observational studies examined the moderating effect of sex on the relationship between daily PA intensity and EFs in adolescents. Our findings partly align with the longitudinal study by Wickel and Howie,[33] who reported better problem solving (a higher-order cognitive function that relies on attentional control) with increased vigorous PA between the ages of 9–15 years in girls but not boys. However, these authors did not adjust for PA volume and, therefore, could not determine whether the associations between vigorous PA and problem solving were specific to PA intensity. Adjusting for the total PA volume, Booth et al.[8] found that MVPA was related to higher performance on a mental flexibility task in 11-years old boys and girls. Boys engaging in more MVPA also had better selective attention (an aspect of attentional control) after adjusting for PA volume. Due to the protracted development of executive functions and brain networks that support them,[34] these cognitive functions are more plastic during childhood and early adolescence and could be more amenable to modulations by PA in boys and girls. Alternatively, the generalized MVPA-mental flexibility association in boys and girls reported by Booth et al.[8] could be explained by the confounding effect of CRF (a well-established correlate of executive functions in children and adolescents), which was not measured in their study. Individual differences in CRF have been related to greater functional connectivity between brain regions supporting executive functions (i.e., fronto-parietal regions) that support performance on executive function tasks.[35] Positive associations between MVPA and mental flexibility among boys and girls in the study by Booth et al.[8] may, therefore, partly reflect the CRF-EFs associations. This interpretation aligns with our previous study in a similar sample of youth from the Burn 2 Learn trial, showing a positive association between higher CRF, attentional control, and working memory independent of sex.[18] Our study complements these findings by demonstrating that girls who engage in more high-intensity PA have better attentional control, irrespective of their CRF.

Thus, our findings suggest that PA interventions should target girls across CRF levels.

In contrast to attentional control, neither PA intensity nor volume was related to working memory in boys or girls. Our null findings in relation to working memory align with previous research in preadolescent children,[36,37] where accelerometer-measured MVPA[37] and vigorous PA[36] were not related to behavioral measures of working memory. In contrast, Wickel et al.[7] found a negative association between accelerometer-measured MVPA and vigorous PA, and working memory in 15-years old adolescents. The differences in sample characteristics and measured confounders may have contributed to the discrepancy between our findings and Wickel et al.'s.[7] It is also possible that the negative association between MVPA and vigorous PA observed by Wickel et al.[7] represented a suppression of the PA-working memory relationship by CRF, which was not measured in their study. Lambourne et al.[38] observed a negative relationship between accelerometer-measured PA and academic achievement in mathematics, a correlate of working memory, when CRF was not included in the model. In contrast, the mediated effect of PA on math achievement through CRF was positive. Given the positive effect of chronic PA interventions on working memory in adolescents,[4] and the role of working memory in academic achievement,[5] there is a need to better understand the unique contributions of daily PA and CRF to working memory in youth. Future studies should explore the mediating effects of CRF on PA-executive function relationships.

This appears to be the first study to compare the relationships between the cut-point independent measure of PA intensity (IG) and cognitive performance in older adolescents relative to the cut-point dependent measure of PA intensity (MVPA). Although IG is a relatively new metric of PA intensity, it showed positive correlations with a traditional cut-point-dependent accelerometer measure of MVPA in previous studies.[9,10] IG also showed expected in directionality associations with CRF,[10] and adiposity[9,10] in preadolescents, adolescent girls, and adults with type 2 diabetes. Adolescent girls in our study had comparable IG to English adolescent girls ($M = -2.25$, $SD = 0.18$).[9] Consistent with sex differences in PA, boys in our study had shallower IG compared to adolescent girls in our and a previous study.[9] To place our results in the context of cut-point-dependent PA intensity metrics, we plotted the proportions of inactive, light, moderate, and vigorous intensity PA split by IG tertiles and sex (Figure 3). The differences in IG tertiles were driven by an increase in vigorous PA in boys and girls. In girls, vigorous PA increased by 5-fold (i.e., from 1 to 5 min) between the 1st and the 3rd IG tertile. Thus, our study suggests that future interventions to improve attentional control in adolescent girls should focus on increasing vigorous PA.

Accordingly, the IG was superior in capturing higher PA intensities (moderate and vigorous) in adolescents

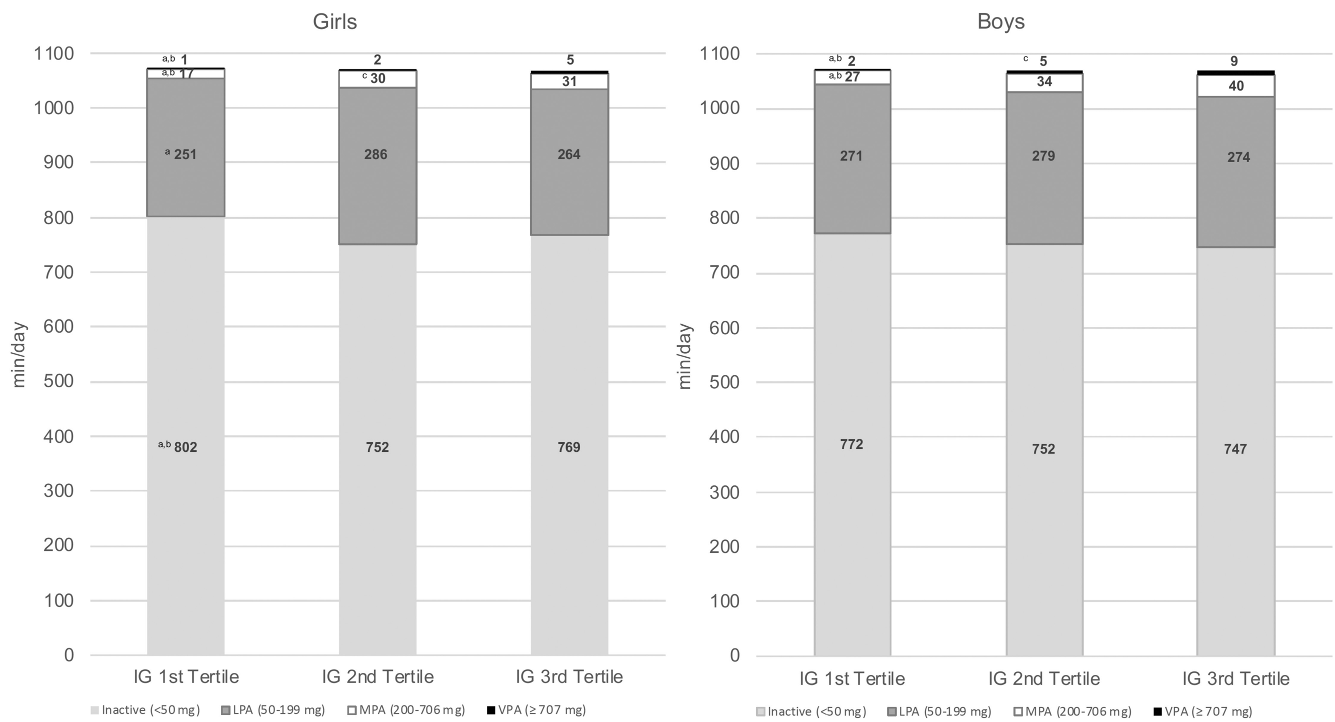

FIGURE 3 Differences in the time spent in physical activity intensities by the tertiles of intensity gradient in boys and girls. [a,b,c] denote statistically significant differences between the IG tertiles at $p < 0.05$; [a]1st vs. 2nd IG tertile; [b]1st vs. 3rd IG tertile; [c]2nd vs. 3rd IG tertile.

compared to MVPA, which was collinear with PA volume (Suppl. Material 19). Our study aligns with previous research suggesting that cut-point-defined MVPA does not uniquely capture higher PA intensities in youth.[9,10] Conversely, IG has been shown to capture inter-individual differences, specifically in moderate and vigorous PA intensities in preadolescents.[10] Unsurprisingly, the associations between MVPA and cognitive outcomes in our study were largely equivalent to the associations between PA volume, attentional control, and working memory. Accordingly, our study underscores the value of using IG to dissociate higher PA intensities from PA volume to capture the relationship between PA intensity and EFs.

In contrast to PA intensity, PA volume was not related to attentional control in our study. Although sex significantly moderated the relationship between PA volume and incongruent SDRT and CVRT on the flanker task, PA volume was not associated with these measures in the analyses stratified by sex. A single positive association between PA volume and information processing in girls (smaller congruent CVRT on the flanker task) was no longer significant after adjusting for IG. PA volume was also not associated with working memory, and sex did not moderate this relationship. Our null findings concerning PA volume align with the study by Booth et al.,[8] who found null associations between PA volume (expressed as accelerometer counts per minute), selective attention (an aspect of attentional control), and mental flexibility in 11-years old adolescent boys and girls. Taken together, our results suggest that in older adolescents, increasing PA volume (without a specific focus on PA intensity) may not be sufficient to enhance executive functions or information processing.

The strengths of our study include the focus on older (15–18 years old) adolescents, understudied in the PA and cognition literature. We included a large sample of adolescents ($N = 418$) and assessed PA using accelerometers. We applied a novel cut-point independent metric of PA intensity (IG) and compared IG-executive functions associations to executive functions associations with a commonly used cut-point dependent PA intensity metric, MVPA. IG allowed us to dissociate the contribution of PA intensity from PA volume to interindividual differences in attentional control. For the first time, we evaluated sex as a moderator of the relationship between PA intensity and executive functions in 15–18 years old adolescents. By employing sensitive computerized tasks of attentional control and working memory, we were able to assess the intra-individual variability of RT, which is more sensitive to individual differences in cognitive performance in older adolescents.[32] Furthermore, we controlled for covariates previously linked to attentional control and working memory in the pediatric literature, including age, school SES, BMI, and CRF. Finally, wrist-worn accelerometers resulted in high compliance (84% of the sample provided at least four valid days of ≥10 h/day). Several limitations of our study also need to be considered when interpreting the findings. The cross-sectional design precludes causal inferences. We did not adjust for IQ. However, we excluded youth with low cognitive scores (≤ 50% accuracy) on both cognitive tasks. Importantly, partialling out the proportion of variance in attentional control and working memory associated with the full-scale IQ (i.e., a composite score of crystallized and fluid intelligence) would only be appropriate if the relationship between the full-scale IQ, attentional control, and working memory was of no interest to the measured associations between PA and these cognitive functions in our study.[39] The theoretical premise of the PA and cognitive health research is that changing environmental influences by increasing PA can lead to generalized cognitive improvements. Thus, our results are representative of PA associations with higher-order cognitive functions that contribute to variance in IQ. Lastly, wrist-worn accelerometers do not differentiate between weight-bearing activities and cycling. However, we captured water-based activities such as swimming.

5 | PERSPECTIVE

This is the first study to assess the moderating effects of sex on the relationships between objectively measured PA intensity, attentional control, and working memory in older adolescents (15–18 years). We showed that adolescent girls engaging in higher-intensity PA (indexed by a cut-point independent metric of PA intensity; IG) had superior attentional control, irrespective of PA volume and CRF. In contrast, higher PA intensity was not related to attentional control in boys. Cut-point dependent measure of PA intensity, MVPA, was collinear with PA volume and showed null associations with attentional control and working memory, consistent with the null associations between PA volume and executive functions. Accordingly, our study confirmed the greater sensitivity of IG to measure higher intensity PA in youth and extended previous reports utilizing IG to cognitive health outcomes.[9,10] Our findings underscore the need to dissociate PA intensity from PA volume when studying their associations with cognitive health. The specificity of the relationships between higher PA intensity and attentional control in adolescent girls suggests that future PA interventions to improve executive functions in adolescents should employ gender-specific strategies to increase vigorous PA in girls. Our study paves the way for future interventions to better understand the mechanisms underlying the moderating effects of sex on PA-executive functions relationships in youth.

AUTHOR CONTRIBUTIONS

DMP: Conceptualization of the presented study, methodology, formal analyses, writing original draft; TS: methodology, software, formal analyses, writing review and editing; AAL: investigation, resources, data curation, writing- review and editing; MFM: investigation, data curation, writing- review and editing; AN: data pulling, writing review and editing; DM: data pulling, writing review and editing; ZA: data pulling, writing review and editing; CHH: methodology, software, resources, writing- review and editing, funding acquisition; DRL: conceptualization of the Burn 2 Learn trial, methodology, investigation, resources, writing- review and editing, supervision, funding acquisition.

FUNDING INFORMATION

Support for this project was provided by the National Health and Medical Research Council (NHMRC; APP1120518) and the New South Wales Department of Education School Sport Unit. DRL is funded by an NHMRC Senior Research Fellowship (APP1154507). The study sponsors did not play a role in designing the study, collecting, analyzing, and interpreting the data, writing the report, or deciding to submit the manuscript for publication.

CONFLICT OF INTEREST

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available upon reasonable request. Requests for access to data from the study should be addressed to the senior author (Prof. David Lubans) at david.lubans@newcastle.edu.au. The study protocol has been published. All proposals requesting data access will need to specify how it is planned to use the data, and all proposals will need the approval of the trial co-investigator team before the data release.

ORCID

Dominika M. Pindus https://orcid.org/0000-0001-7288-7921

REFERENCES

1. Guthold R, Stevens GA, Riley LM, Bull FC. Global trends in insufficient physical activity among adolescents: a pooled analysis of 298 population-based surveys with 1.6 million participants. *Lancet Child Adolesc Heal*. 2020;4(1):23-35.
2. Leahy AA, Mavilidi MF, Smith JJ, et al. Review of high-intensity interval training for cognitive and mental health in youth. *Med Sci Sports Exerc*. 2020;52(10):2224-2234.
3. Xue Y, Yang Y, Huang T. Effects of chronic exercise interventions on executive function among children and adolescents: a systematic review with meta-analysis. *Br J Sports Med*. 2019;39(30):4687-4703.
4. Haverkamp BF, Wiersma R, Vertessen K, van Ewijk H, Oosterlaan J, Hartman E. Effects of physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults: a meta-analysis. *J Sports Sci*. 2020;1(24):2637-2660.
5. St Clair-Thompson HL, Gathercole SE. Executive functions and achievements in school: shifting, updating, inhibition, and working memory. *Q J Exp Psychol*. 2006;59(4):745-759.
6. Ruotsalainen I, Gorbach T, Perkola J, et al. Physical activity, aerobic fitness, and brain white matter: their role for executive functions in adolescence. *Dev Cogn Neurosci*. 2020;42:100765.
7. Wickel EE. Sedentary time, physical activity, and executive function in a longitudinal study of youth. *J Phys act Heal*. 2017;14(3):222-228.
8. Booth JN, Tomporowski PD, Boyle JM, 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(3):212-219.
9. Rowlands AV, Edwardson CL, Davies MJ, Khunti K, Harrington DM, Yates T. Beyond cut points: accelerometer metrics that capture the physical activity profile. *Med Sci Sport Exerc*. 2018;50(6):1323-1332.
10. Fairclough SJ, Taylor S, Rowlands AV, Boddy LM, Noonan RJ. Average acceleration and intensity gradient of primary school children and associations with indicators of health and well-being. *J Sports Sci*. 2019;37(18):2159-2167.
11. Ludyga S, Gerber M, Pühse U, Looser VN, Kamijo K. Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in healthy individuals. *Nat Hum Behav*. 2020;4:603-612.
12. Corder K, Sharp SJ, Atkin AJ, et al. Age-related patterns of vigorous-intensity physical activity in youth: the international Children's Accelerometry database. *Prev Med Reports*. 2016;4:17-22.
13. Hultsch DF, MacDonald SWS, Dixon RA. Variability in reaction time performance of younger and older adults. *Journals Gerontol - Ser B Psychol Sci Soc Sci*. 2002;57(2):101-115.
14. Bunce D, MacDonald SWS, Hultsch DF. Inconsistency in serial choice decision and motor reaction times dissociate in younger and older adults. *Brain Cogn*. 2004;56(3):320-327.
15. Kelly AMC, Uddin LQ, Biswal BB, Castellanos FX, Milham MP. Competition between functional brain networks mediates behavioral variability. *Neuroimage*. 2008;39(1):527-537.
16. Tamnes CK, Fjell AM, Westlye LT, Østby Y, Walhovd KB. Becoming consistent: developmental reductions in intraindividual variability in reaction time are related to white matter integrity. *J Neurosci*. 2012;32(3):972-982.
17. Bento-Torres J, Bento-Torres NVO, Stillman CM, et al. Associations between cardiorespiratory fitness, physical activity, intraindividual variability in behavior, and cingulate cortex in younger adults. *J Sport Heal Sci*. 2019;8(4):315-324.
18. Shigeta TT, Leahy AA, Smith JJ, Eather N, Lubans DR, Hillman CH. Cardiorespiratory and muscular fitness associations with older adolescent cognitive control: fitness associations with adolescent cognitive control. *J Sport Heal Sci*. 2021;10(1):82-90.

19. Westfall DR, Gejl AK, Tarp J, et al. Associations between aerobic fitness and cognitive control in adolescents. *Front Psychol*. 2018;9:1298.
20. Huizinga M, Dolan CV, van der Molen MW. Age-related change in executive function: developmental trends and a latent variable analysis. *Neuropsychologia*. 2006;44(11):2017-2036.
21. Pelegrina S, Lechuga MT, García-Madruga JA, et al. Normative data on the n-back task for children and young adolescents. *Front Psychol*. 2015;6:1544.
22. Lubans DR, Smith JJ, Eather N, et al. Time-efficient intervention to improve older adolescents' cardiorespiratory fitness: findings from the burn 2 learn cluster randomised controlled trial. *Br J Sports Med*. 2021;55(13):751-758.
23. Wolff-Hughes DL, McClain JJ, Dodd KW, Berrigan D, Troiano RP. Number of accelerometer monitoring days needed for stable group-level estimates of activity. *Physiol Meas*. 2016;37(9):1447-1455.
24. Migueles J, Rowlands A, Huber F, Sabia S, van Hees V. GGIR: a research community–driven open source R package for generating physical activity and sleep outcomes from multi-day raw accelerometer data. *J Meas Phys Behav*. 2019;2:188-196.
25. van Hees VT, Gorzelniak L, Dean León EC, et al. Separating movement and gravity components in an acceleration signal and implications for the assessment of human daily physical activity. *PLoS One*. 2013;8(4):e61691.
26. Steene-Johannessen J, Hansen BH, Dalene KE, et al. Variations in accelerometry measured physical activity and sedentary time across Europe – harmonized analyses of 47,497 children and adolescents. *Int J Behav Nutr Phys act*. 2020;17(1):38.
27. Hildebrand M, van Hees VT, Hansen BH, Ekelund U. Age group comparability of raw accelerometer output from wrist- and hip-worn monitors. *Med Sci Sports Exerc*. 2014;46(9):1816-1824.
28. Eriksen BA, Eriksen CW. Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept Psychophys*. 1974 Jan;16(1):143-149.
29. Australian bureau of statistics. *Technical Paper. Socio-Economic Indexes for Areas [Internet]*. Census; 2018 Available from: https://www.abs.gov.au
30. Cole TJ, Lobstein T. Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. *Pediatr Obes*. 2012;7(4):284-294.
31. Tomkinson GR, Lang JJ, Tremblay MS, et al. International normative 20 m shuttle run values from 1 142 026 children and youth representing 50 countries. *Br J Sports Med*. 2017;51(21):1545-1554.
32. Deary IJ, Der G. Reaction time, age, and cognitive ability: longitudinal findings from age 16 to 63 years in representative population samples. *Aging, Neuropsychol Cogn*. 2005;12(2):187-215.
33. Wickel EE, Howie EK. Prospective bi-directional associations between sedentary time and physical activity with cognitive performance: a cohort study. *J Sports Sci*. 2019;37(6):630-637.
34. Crone EA, Steinbeis N. Neural perspectives on cognitive control development during childhood and adolescence. *Trends Cogn Sci*. 2017;21(3):205-215.
35. Talukdar T, Nikolaidis A, Zwilling CE, et al. Aerobic fitness explains individual differences in the functional brain connectome of healthy young adults. *Cereb Cortex*. 2018;28(10):3600-3609.
36. Mora-Gonzalez J, Esteban-Cornejo I, Cadenas-Sanchez C, et al. Fitness, physical activity, working memory, and neuroelectric activity in children with overweight/obesity. *Scand J Med Sci Sports*. 2019;29(9):1352-1363.
37. Pindus DM, Drollette ES, Scudder MR, et al. Moderate-to-vigorous physical activity, indices of cognitive control, and academic achievement in preadolescents. *J Pediatr*. 2016;173:136-142.
38. 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(3):165-171.
39. Dennis M, Francis DJ, Cirino PT, Schachar R, Barnes MA, Fletcher JM. Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. *J Int Neuropsychol Soc*. 2009;15(3):331-343.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pindus DM, Shigeta TT, Leahy AA, et al. Sex moderates the associations between physical activity intensity and attentional control in older adolescents. *Scand J Med Sci Sports*. 2023;00:1-17. doi:10.1111/sms.14311