Aerobic Capacity and Cognitive Control in Elementary School-Age Children

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[1]Department of Kinesiology and Community Health, University of Illinois at Urbana–Champaign, Urbana, IL; [2]Department of Internal Medicine, Cardiovascular Research Institute, University of Kansas Medical Center, Kansas City, KS; and [3]Department of Health, Physical Education, and Recreation, Augustana College, Sioux Falls, SD

ABSTRACT

SCUDDER, M. R., K. LAMBOURNE, E. S. DROLLETTE, S. D. HERRMANN, R. A. WASHBURN, J. E. DONNELLY, and C. H. HILLMAN. Aerobic Capacity and Cognitive Control in Elementary School-Age Children. *Med. Sci. Sports Exerc.*, Vol. 46, No. 5, pp. 1025–1035, 2014. **Purpose**: The current study examined the relationship between children's performance on the Progressive Aerobic Cardiovascular Endurance Run subtest of the FitnessGram® and aspects of cognitive control that are believed to support academic success. **Methods**: Hierarchical linear regression analyses were conducted on a sample of second- and third-grade children (n = 397) who completed modified versions of a flanker task and spatial n-back task to assess inhibitory control and working memory, respectively. **Results**: Greater aerobic fitness was significantly related to shorter reaction time and superior accuracy during the flanker task, suggesting better inhibitory control and the facilitation of attention in higher-fit children. A similar result was observed for the n-back task such that higher-fit children exhibited more accurate target detection and discrimination performance when working memory demands were increased. **Conclusions**: These findings support the positive association between aerobic fitness and multiple aspects of cognitive control in a large sample of children, using a widely implemented and reliable field estimate of aerobic capacity. Importantly, the current results suggest that this relationship is consistent across methods used to assess fitness, which may have important implications for extending this research to more representative samples of children in a variety of experimental contexts. **Key Words:** PACER, AEROBIC FITNESS, WORKING MEMORY, INHIBITORY CONTROL, ACADEMIC ACHIEVEMENT

Promoting academic success in children remains an integral focus of parents, teachers, and administrators alike. One of the most widely adopted methods for accomplishing this task has been to allocate time toward classroom education at the expense of physical activity opportunities (i.e., physical education, recess, and after-school programming), which many researchers believe is a contributing factor to the growing obesity rates and health complications reported in children (30). Given the current educational climate, it is not surprising that children's academic performance has become a pivotal outcome measure for any program or study intent on providing increased opportunities for physical activity in school (e.g., TAKE 10!® [22] and Physical Activity Across the Curriculum [11]). Despite concerns regarding the potentially detrimental effect on academic achievement, research suggests that such an approach would, in a worst-case scenario, leave academic performance unaffected (34). In fact, this growing body of research has revealed that increased physical activity levels and/or improved fitness may actually provide benefits to cognition, including better academic achievement and cognitive control (4).

Cognitive control refers to the regulation of goal-directed behaviors (33) and has been related to school readiness and academic achievement (10,20). Several studies examining aerobic fitness have identified positive associations with aspects of cognitive control such as working memory, inhibitory control, and cognitive flexibility (e.g., 6,7,9,17,18,32,39). Studies incorporating children as young as 4.5 yr residing in low- or moderate-income households have reported that higher scores on cognitive control tasks during preschool are correlated with better mathematics and reading ability in kindergarten (1) and predict similar academic success ~ 3 yr later during primary school (2). Thus, although further research is necessary to construct a complete understanding of children's aerobic fitness and academic performance (20), continuing to explore factors that may mediate this interaction, such as cognitive control, is warranted (15). Investigations of cognitive control in children using laboratory-based measures of aerobic fitness (i.e., $\dot{V}O_{2max}$; 7,32,39) have indicated that compared with lower-fit children, those who are higher fit demonstrate shorter response times (RT) and greater accuracy on a modified version of the Eriksen flanker task (14). The flanker task is a popular and widely cited cognitive control task that measures an individual's ability to inhibit unnecessary or distracting

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information in the stimulus environment and direct attention toward relevant characteristics of the task at hand. By adhering to these methods, previous studies have not only established greater reliability of the findings but have also revealed a pattern of results such that lower-fit children exhibit disproportionately longer RT (7) and poorer accuracy (32,39) during the more difficult portions of the task that require the up-regulation of inhibitory control. Recently, it was further reported that increases in $\dot{V}O_{2max}$ after a randomized control trial (i.e., FITKids) were associated with improved working memory performance, an effect that became more evident as working memory demands increased (21). As such, the data suggest that higher aerobic fitness is associated with selectively greater performance as task difficulty increases and necessitates additional recruitment of cognitive control.

However, one limitation of this previous research has been the relatively smaller sample sizes of children, perhaps because of complex laboratory-based measures of aerobic fitness and expensive neuroimaging methods that were incorporated. Therefore, this area of research would gain considerable momentum if researchers were able to adopt more feasible methods for assessing fitness while maintaining sufficient validity. The FitnessGram® is a popular and reliable criterion-based fitness battery that tests aerobic capacity, muscle flexibility, muscle strength, and body mass (31). Its broad application across educational environments has led to numerous reports of a beneficial relationship between aerobic fitness and academic achievement as determined by the Progressive Aerobic Cardiovascular Endurance Run (PACER [5,36,40]) subtest. That is, children with higher levels of aerobic fitness commonly exhibit greater academic performance than their less-fit peers on topics such as reading and arithmetic. There is substantial evidence relative to the validity (25,26,37) and test–retest reliability (24,26) of the PACER as an accurate measure of aerobic capacity across a wide age range of children and adolescents (3,28). Despite the apparent influence of fitness on different aspects of cognitive control, surprisingly few studies have attempted to establish whether these relationships persist when using ecologically valid field measures of aerobic fitness. Hillman et al. (18) examined 24 children who were recruited and categorized according to the top (higher fit) or bottom (lower fit) 10% of PACER scores from a larger sample of 600 children. Compared with lower-fit participants, higher-fit children demonstrated shorter RT and marginally better accuracy while performing a simple stimulus discrimination task. In a subsequent study, Hillman et al. (17) investigated a sample of 38 children (similarly divided according to fitness) who completed a modified flanker task and revealed that higher-fit children performed more accurately relative to their lower-fit peers, including greater accuracy after errors of commission.

Although there is consistency among findings in the literature, the amount of evidence directly comparing performance on field tests of aerobic fitness and cognitive control is less than comprehensive, primarily because of smaller and less representative samples of children. Such a limitation is unexpected considering that a primary benefit of field estimates is often the ability to collect large samples of data that laboratory-based experimental procedures might otherwise limit. There is also a lack of data with respect to working memory and aerobic fitness in children (38), regardless of the type of fitness measurement. Accordingly, the purpose of the current study was to investigate aerobic fitness in a large sample of second- and third-grade students using the PACER and measure their performance using the flanker as well as a spatial *n*-back task, which have been successfully administered and modified for use in children. Performance on the flanker task was expected to mirror earlier findings, such that greater aerobic fitness would be related to better inhibitory control (i.e., higher accuracy and shorter RT), with the strongest associations occurring during the more difficult task conditions when the up-regulation of cognitive control is necessary to ensure correct action. Similarly, aerobic fitness was predicted to relate positively with working memory performance, an effect that was expected to strengthen progressively as task conditions placed larger demands on working memory. Collectively, such a relationship would provide support for the influence of aerobic fitness on select aspects of cognition and suggest that field tests of aerobic fitness are ecologically valid tools for assessing this relationship in a large community-based sample of children.

METHODS

Participants

Baseline data were collected as part of a larger study in children from 17 schools participating in a cluster randomized trial (12). The University of Kansas Medical Center and the University of Illinois at Urbana–Champaign Human Subjects Committee approved the study, which compares academic and cognitive outcomes after the addition of physically active academic lessons delivered by classroom teachers to regular, sedentary lessons (control). The guardians of second- and third-grade students received a flyer describing the study and the assessment procedures. Parents of students interested in participation provided their contact information to the school. Because of a large response, a random sample of second- and third-grade students (stratified by grade and sex) in each school was selected from those who provided written parental consent/child assent to complete the outcome assessments used for this study, including cognitive function and cardiovascular fitness. Parents completed a demographic questionnaire that assessed the grade, age, sex, and race of their child as well as household income. Table 1 provides a summary of participant demographics.

Procedure

All assessments were completed at the respective schools by research staff that were trained and supervised by a

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TABLE 1. Participant demographic variables.

Measure	*N* / (*M*)	Pct. / (SD)	Range
N	397 (225 females)	56.7% female	—
Age (yr)	7.6	0.6	6–9
Grade			
Grade 2	183	46.1%	2nd–3rd
Grade 3	214	53.9%	2nd–3rd
Height (cm)	130.0	6.7	110.1–150.2
Weight (kg)	29.8	7.5	16.5–66.0
Household Income	7.1	3.3	1–11
Race			
White/Caucasian	325	81.8%	—
Black/African American	12	3.0%	—
Native Hawaiian/ Pacific Islander	1	0.3%	—
Asian	7	1.8%	—
American Indian/ Alaska Native	5	1.3%	—
Two or more races	44	11.1%	—
Refused/missing	3	0.8%	—
BMI (kg·m^{-2})	17.5	3.1	12.1–30.1
BMI percentile	61.6	29.0	0–100
PACER (no. laps)	17.1	8.9	1–52

qualified coinvestigator. Testing was completed on 2 d with fitness and cognitive assessments occurring during separate testing sessions, and each visit lasting approximately 1 hour. During cognitive testing, students were removed from the classroom and tested on an individual basis in a private area such as a counselor's office, a conference room, or an unused classroom, which were kept quiet and free of distractions. Cognitive testing was administered using a laptop and a handheld response pad (model TR-1×4-CR; Current Designs Inc., Philadelphia, PA), with all participants completing the flanker and spatial *n*-back tasks in a consecutive and identical order. Because of the volume of students who needed to be tested and the limited time constraints, it was not possible to complete testing at the same time of day for all children. Thus, children were tested in both morning and afternoon hours.

Fitness Testing

Aerobic fitness was assessed using the PACER (31), which has established reliability and validity as a measure of aerobic capacity in children (3,24–26,37). The PACER has been implemented in hundreds of thousands of children, as young as 6 yr old, in more than 35 countries around the world (28). Correlations (*r*) between the PACER and $\dot{V}O_2$ are moderate to strong in nature, ranging from 0.65 to 0.83 (25,26,37), with slight deviations based on the age and the number of participants included in each study. During the PACER, children are instructed to run back and forth between two lines, 20 m apart, paced by a tone on a CD player signaling when they should reach the opposite line. The pace began slowly and progressively increased until the test ended when the student failed to traverse the 20-m distance in the time allotted on two occasions. The fitness measure used for statistical analysis was the total number of laps completed on the PACER, with a greater number of laps indicating a higher level of aerobic capacity.

Cognitive Tasks

Flanker. To assess inhibitory control, performance was measured during the response compatible and incompatible conditions of a modified Eriksen flanker task, which has been used in several studies examining cognitive control and fitness in chidren (7,17,32,39). Stimuli were 2-cm-tall child-friendly yellow goldfish, which were presented focally for 200 ms on a blue background with a fixed interstimulus interval of 1700 ms. Participants first completed the compatible condition in which they were instructed to attend to the centrally presented goldfish while disregarding the lateral flanking goldfish and to respond as quickly and accurately as possible according to the direction the central goldfish was facing. Trials were divided evenly among congruent (i.e., all stimuli facing the same direction) and incongruent (i.e., the central and flanking stimuli faced opposite directions) trials. Participants were required to press a button with their left thumb using the response pad when the central fish faced left and a button press with their right thumb when the central fish faced right. Then task difficulty was further manipulated by introducing participants to a stimulus-response incompatible condition, which was designed to increase conflict by modifying response selection such that participants had to respond in the opposite direction of the centrally presented stimuli. For both conditions, participants received 40 practice trials followed by a block of 100 trials with equiprobable congruency and directionality.

Spatial *n*-back. Participants also performed a modified child-friendly spatial *n*-back task, previously used by Drollette et al. (13), which was designed to assess variable working memory demands during the online monitoring and manipulation of remembered information (29). The task included six white-framed boxes, each measuring 4 × 4 cm, arranged in a circular orientation 9.5 cm from a centrally presented fixation cross. Participants viewed an illustrated black-and-white cow (named "Tab") that appeared pseudorandomly inside one of the six boxes. Three conditions were completed by each participant beginning with the 0-back task, which asked participants to respond as quickly and accurately as possible with a right thumb press when Tab appeared in the upper right box (i.e., target) and with a left thumb button press when Tab appeared in any of the remaining five boxes (i.e., correct reject for a nontarget trial). For the 1-back and 2-back conditions, participants were instructed to respond as quickly and accurately as possible with a right button press if Tab appeared in the same box as the previous trial during the 1-back condition, and two trials prior for the 2-back condition. In both of these conditions, the left button was pressed if Tab appeared in any of the other five locations (i.e., correct reject). Errors of commission were deemed as a "false alarm" when participants incorrectly identified a nontarget trial with a right button press and a "miss" when target trials engendered a left

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button response. All trials were presented for 250 ms with a fixed interstimulus interval of 2500 ms on a green background. Targets were presented with 33.3% probability in all conditions with the 0-back condition containing 45 trials (15 targets) and the 1- and 2-back conditions containing 72 trials (24 targets). The outcome variable d' was calculated as z(adjusted target accuracy) $-$ z(adjusted false alarm rate) in accordance with the formula provided by Sorkin (35). Adjustments were implemented for perfect scores. If the probability of target response accuracy was 1.0, then the adjustment of $2^{-(1/n)}$ (n = number of trials) would replace the maximum probability, and if the probability of the false alarm rate was 0.0, then the adjustment of $1 - (2^{-(1/n)})$ would replace the minimum probability. Higher values of d' indicate increased ability to discriminate between targets and nontargets with the highest possible score after adjustment equal to 3.7 for the 0-back condition and 4.1 for the 1- and 2-back conditions.

Statistical Analysis

Pearson product-moment correlations were conducted between the number of laps run on the PACER test (representing aerobic fitness), body mass index (BMI), age, grade, sex (coded as 0 = female, 1 = male), and household income (coded as 1: <\$10,000 per year through 11: >\$100,000 per year, with \$10,000 increments) using the Statistical Package for the Social Sciences (version 21; IBM Corp., Armonk, NY). Separate linear hierarchical regression analyses were conducted using the four dependent flanker variables (congruent RT/accuracy and incongruent RT/accuracy) from each response compatibility manipulation (compatible/incompatible), as well as the six dependent variables from the n-back task (target RT/accuracy, nontarget RT/accuracy, false alarm rate, and d') across the 0-, 1-, and 2-back conditions. To assess the unique contribution of aerobic fitness, PACER was entered into step 2 in the hierarchical regression analysis after the inclusion of significant demographic variables (step 1). Flanker accuracy and RT were also characterized using a condition (compatible, incompatible) $\times$ trial (congruent, incongruent) multivariate analysis of variance (MANOVA). n-back accuracy and RT were compared similarly with condition (representing the 0-, 1-, and 2-back conditions) and trial (indicating target or nontarget). n-back false alarm rate and d' were also compared across the three conditions. Analyses with three or more within-subject levels report P values after the Greenhouse–Geisser correction for violations of sphericity. Significance levels were set at $P = 0.05$, and *post hoc* comparisons were conducted using the Bonferroni correction. Cohen's d is reported to indicate effect size. Assumptions of linearity, equality of variance, independence, and normality were plotted, inspected, and verified using studentized residuals. Participants were included in the analyses if their overall mean flanker accuracy was higher than 50% across compatible and incompatible conditions, and their mean d' score was higher than 0 across the 1- and 2-back conditions of the spatial n-back task (indicative of performance at or above chance; 35).[1]

RESULTS

Initial Pearson product-moment correlations revealed that fitness was significantly related to BMI (Pearson's r = -0.32), age (r = 0.17), grade (r = 0.19), sex (r = 0.23), and household income (r = 0.27), indicating the need to control for these demographic variables in step 1 of the regression analyses. Grade was included in the analyses rather than age because it was more strongly associated with fitness and the dependent cognitive variables.

Flanker

Task manipulation. The analysis of flanker RT uncovered the main effects of condition ($F_{1,\ 396} = 125.5$, $P < 0.001$, $\eta^2 = 0.24$) and trial ($F_{1,\ 396} = 141.3$, $P < 0.001$, $\eta^2 = 0.26$), which were superseded by an interaction of condition $\times$ trial ($F_{1,\ 396} = 10.5$, $P = 0.001$, $\eta^2 = 0.03$). *Post hoc* analysis confirmed that RT was prolonged in the incompatible compared with the compatible condition (Cohen's d's ≥ 0.3). Incongruent trials also resulted in longer RT than congruent trials across both conditions, d's ≥ 0.1 (see Fig. 1A).

For flanker accuracy, a main effect of trial was observed ($F_{1,\ 396} = 272.4$, $P < 0.001$, $\eta^2 = 0.41$), which was superseded by a condition $\times$ trial interaction ($F_{1,\ 396} = 132.5$, $P < 0.001$, $\eta^2 = 0.25$). Comparing congruent and incongruent trial types within each response compatibility condition revealed that in both the compatible and the incompatible conditions, accuracy was greater for congruent trials compared with incongruent trials, d's ≥ 0.1. Significant differences were also witnessed when comparing trial types across compatibility conditions, indicating that congruent trial accuracy was greater in the compatible compared with the incompatible condition, $d = 0.2$. Analysis further revealed that incongruent trial accuracy was significantly higher in the incompatible compared with the compatible condition, $d = 0.3$ (see Fig. 1B).

RT regression analyses. Table 2 provides a summary of each flanker regression analysis along with all corresponding statistical values for PACER effects. For the flanker compatible condition, fitness demonstrated a significant effect for both congruent and incongruent trials (see Fig. 2A), in addition to grade (β's ≥ -0.20, P's ≤ 0.001) and sex (β's ≥ -0.11, P's ≤ 0.03). These findings indicate that across both types of flanker trials, RT was shorter in higher-fit children as well as males and older participants. Comparable

[1] In addition to excluding participants who performed below chance for flanker (n = 97) and spatial n-back (n = 72) tasks, participants reporting a neurological disorder were withheld from all analyses, including those with ADHD (n = 55), dyslexia (n = 3), or a learning disability (n = 20). Participants who could not complete all aspects of cognitive testing (e.g., were absent from school, did not follow instructions, etc.) and anyone missing necessary demographic information were also excluded (n = 22).

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results were observed for the incompatible condition, with fitness exhibiting an effect for congruent and incongruent trials (see Fig. 2B). Grade (β's ≥ -0.28, P's ≤ 0.001) and sex (β's ≥ -0.11, P's ≤ 0.02) were again negatively correlated, mirroring the earlier analysis.

Accuracy regression analyses. Higher-fit children performed more accurately on congruent trials during the compatible condition. This effect explained a significant amount of the variance in addition to grade ($\beta = 0.11$, $P < 0.03$) and household income ($\beta = 0.10$, $P < 0.05$), indicating that older participants and children living in higher-income families were more accurate. Higher-fit children also had better incongruent trial accuracy (see Fig. 2C), yet no demographic variables exhibited a significant effect. In the incompatible condition, fitness (see Fig. 2D), grade ($\beta = 0.10$, $P < 0.05$), and household income ($\beta = 0.12$, $P < 0.02$) were positively

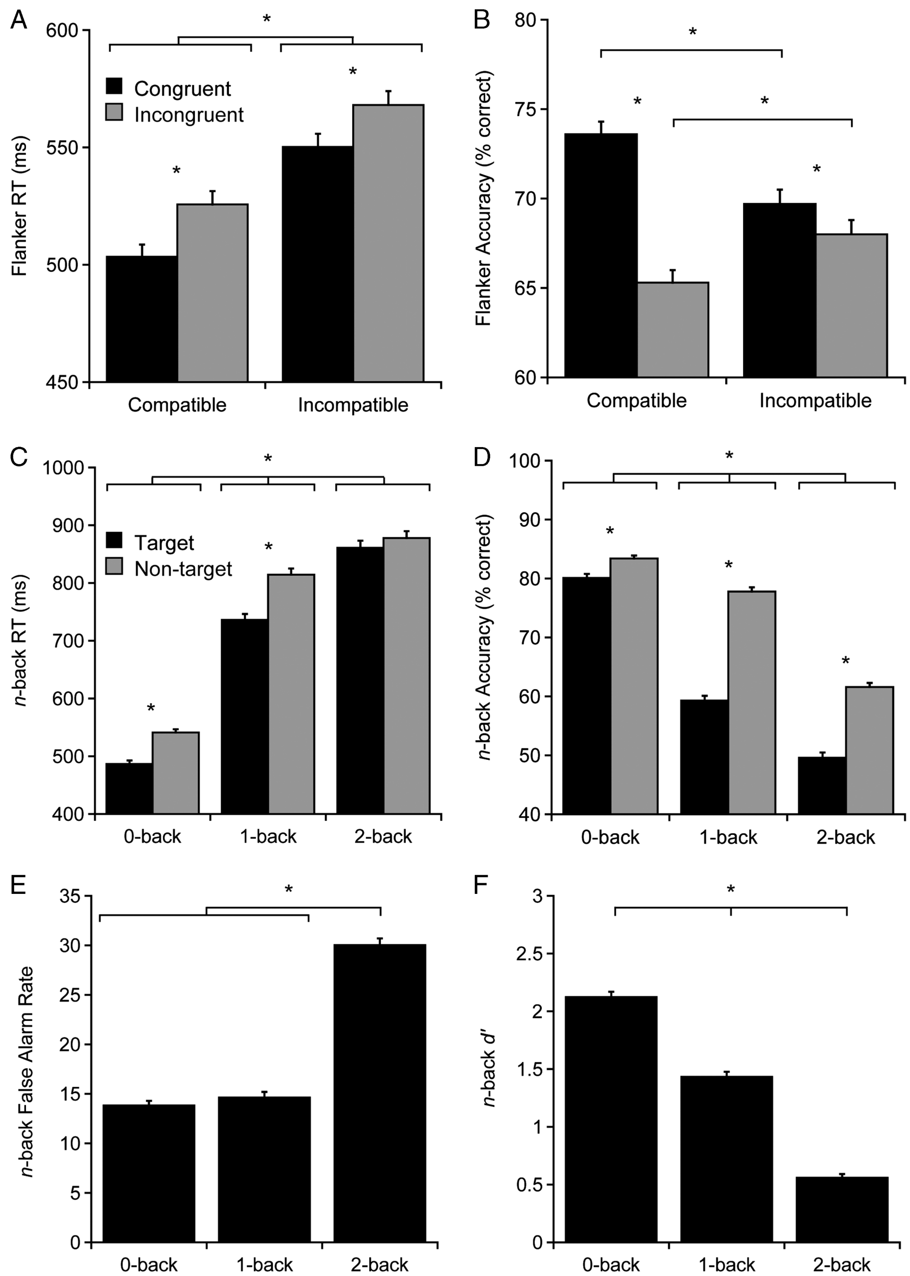

FIGURE 1—Children's behavioral performance is displayed for both cognitive control tasks. A. Incongruent trials resulted in longer RT across both conditions, yet overall flanker RT was delayed in the incompatible condition. B. Congruent trials resulted in higher accuracy across both conditions compared with incongruent trials; however, congruent trial accuracy decreased during the incompatible condition whereas incongruent accuracy significantly increased. C. Overall RT for the *n*-back task was delayed across each subsequent condition, and target trials resulted in shorter RT compared with nontarget trials in the 0- and 1-back conditions. D. Overall accuracy decreased across *n*-back conditions, with target trials having lower accuracy compared with nontarget trials in each condition. E. False alarm rate was significantly higher in the 2-back condition, yet no difference was observed between the 0- and the 1-back conditions. F. Mirroring the effect of *n*-back accuracy, d' scores progressively decreased across the subsequent conditions.

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TABLE 2. Flanker task hierarchical regression values for PACER laps.

Measure	Step 1 R^2	Step 2 ΔR^2	B	SE B	β	t
Compatible congruent RT	0.053**	0.031**	−2.53	0.69	−0.20	−3.7
Compatible incongruent RT	0.042**	0.024**	−2.42	0.76	−0.18	−3.2
Compatible congruent accuracy	0.015*	0.010*	0.18	0.09	0.12	2.0
Compatible incongruent accuracy	0.001	0.010*	0.18	0.09	0.11	2.0
Incompatible congruent RT	0.093**	0.012*	−1.61	0.71	−0.12	−2.3
Incompatible incongruent RT	0.095**	0.009*	−1.52	0.76	−0.11	−2.0
Incompatible congruent accuracy	0.021*	0.013*	0.21	0.09	0.13	2.3
Incompatible incongruent accuracy	0.010	0.004	0.14	0.10	0.08	1.3

Step 1 included demographic variables (BMI, grade, sex, and household income), and step 2 included PACER (representing aerobic fitness).
*$P \leq 0.05$.
**$P \leq 0.01$.

associated with congruent trial accuracy. Accordingly, higher-fit and older children as well as those living in higher-income families elicited greater accuracy for congruent trials. Similar trends were observed for incongruent trials; however, none of these effects reached significance during the incompatible condition.

Spatial *n*-Back

Task manipulation. The MANOVA for *n*-back RT uncovered the main effects of condition ($F_{1.8,\ 720.7}$ = 886.3, P <0.001, η^2 = 0.69) and trial ($F_{1,\ 396}$ = 172.5, P < 0.001, η^2 = 0.30) and a condition–trial interaction ($F_{1.8,\ 699.6}$ = 30.0, P < 0.001, η^2 = 0.07). This interaction indicated that RT was delayed for both trial types, with greater delays observed across each subsequent condition, d's ≥ 0.3. However, when comparing the two trial types within each condition, target trials resulted in shorter RT in the 0-back and 1-back conditions, d's ≥ 0.4, yet no difference was observed for the 2-back condition, d = 0.1, after the Bonferroni correction (see Fig. 1C).

The MANOVA for *n*-back accuracy also revealed effects of condition ($F_{2.0,\ 783.7}$ = 923.0, P < 0.001, η^2 = 0.70) and trial ($F_{1,\ 396}$ = 275.0, P < 0.001, η^2 = 0.41) and a condition–trial interaction ($F_{1.9,\ 747.4}$ = 79.0, P < 0.001, η^2 = 0.16). The decomposition of the interaction indicated that target and

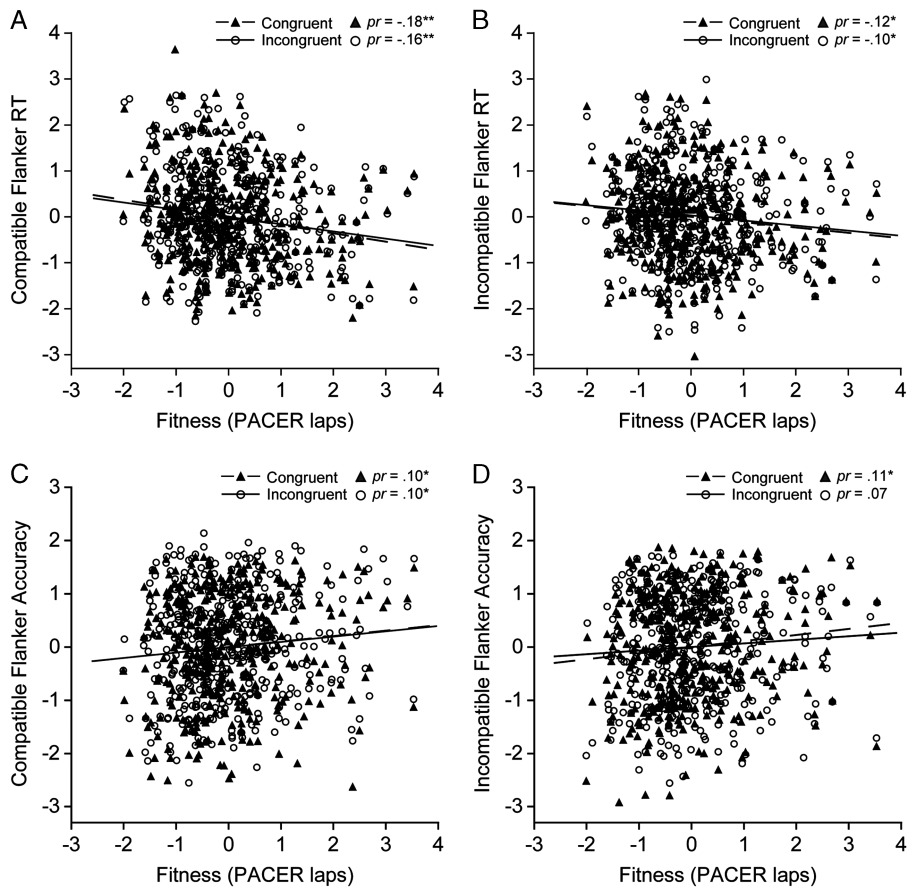

FIGURE 2—Partial regression plots depicting the relationship between fitness and flanker task performance for compatible RT (A), incompatible RT (B), compatible accuracy (C), and incompatible accuracy (D) after controlling for grade, sex, household income, and BMI. Partial correlations (*pr*) are provided. *$P \leq 0.05$, **$P \leq 0.01$.

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TABLE 3. Spatial *n*-back task hierarchical regression values for pacer laps.

Measure	Step 1 R^2	Step 2 ΔR^2	*B*	SE *B*	β	*t*
0-back nontarget RT	0.058**	0.009	−1.50	0.78	−0.11	−1.9
0-back target RT	0.041**	0.016**	−2.11	0.83	−0.14	−2.6
0-back nontarget accuracy	0.021*	0.001	0.04	0.06	0.03	0.5
0-back target accuracy	0.020*	0.003	0.12	0.09	0.07	1.2
0-back false alarm rate	0.010	0.001	−0.03	0.06	−0.03	−1.1
0-back d'	0.025**	0.003	0.01	0.005	0.07	1.2
1-back nontarget RT	0.039**	0.004	−1.84	1.38	−0.08	−1.3
1-back target RT	0.031**	0.008	−2.50	1.34	−0.11	−1.9
1-back nontarget accuracy	0.016*	0.013*	0.21	0.09	0.13	2.3
1-back target accuracy	0.027**	0.019**	0.28	0.10	0.16	2.8
1-back false alarm rate	0.005	0.011*	−0.12	0.06	−0.12	−2.1
1-back d'	0.011	0.021**	0.02	0.005	0.17	3.0
2-back nontarget RT	0.038**	0.003	1.83	1.57	0.07	1.2
2-back target RT	0.008	0.000	0.03	1.70	0.00	0.0
2-back nontarget accuracy	0.015*	0.010*	0.18	0.09	0.12	2.0
2-back target accuracy	0.056**	0.016**	0.28	0.11	0.14	2.6
2-back false alarm rate	0.001	0.004	−0.11	0.08	−0.08	−1.3
2-back d'	0.044**	0.027**	0.01	0.003	0.19	3.4

Step 1 included demographic variables (BMI, grade, sex, and household income), and step 2 included PACER (representing aerobic fitness).
*$P \leq 0.05$.
**$P \leq 0.01$.

nontarget trial accuracy decreased as difficulty was elevated across each subsequent condition, d's ≥ 0.4. Further, children were more accurate for nontarget trials compared with target trials across all three *n*-back conditions, d's ≥ 0.2 (see Fig. 1D). An effect of condition ($F_{1.8,\ 710.7} = 468.5$, $P < 0.001$, $\eta^2 = 0.54$) for the false alarm rate revealed that the 2-back condition engendered a significantly greater number of false alarms than either the 0-back or 1-back conditions, d's ≥ 1.6. The rate of false alarms in the 0- and 1-back conditions was equivalent, $d = 0.1$ (see Fig. 1E). Lastly, the analysis of d' scores resulted in an effect of condition ($F_{2.0,\ 784.5} = 887.8$, $P < 0.001$, $\eta^2 = 0.69$), which revealed steadily declining values as task difficulty increased across conditions, d's ≥ 0.9 (see Fig. 1F).

Zero-back regression analyses. Table 3 provides a summary of all *n*-back regression analyses and contains the statistical values for each PACER effect. Comparable with the flanker results, fitness was significantly correlated with target trial RT (see Fig. 3A), signifying that higher-fit children exhibited shorter RT. Further, effects of grade ($\beta = -0.19$, $P < 0.001$) and sex ($\beta = -0.11$, $P < 0.04$) suggested that older children and males also demonstrated shorter RT for target trials. No significant fitness effects were witnessed for nontarget trial RT, accuracy, false alarm rate, or d'.

One-back regression analyses. An effect of fitness was observed for the false alarm rate (see Fig. 3B), indicating that children with greater fitness generated fewer false alarms, whereas no demographic variables were significantly related. Effects of fitness (see Fig. 3C) and household income (β's ≥ 0.11, P's ≤ 0.04) were significant for both target and nontarget trial accuracy, indicating that higher-fit children and children living in higher-income families outperformed their peers on both trial types. In addition, an effect of BMI ($\beta = -0.14$, $P < 0.01$) revealed that individuals with lower BMI achieved greater accuracy for target trials. Lastly, higher-fit individuals and children living in higher-income families ($\beta = 0.13$, $P < 0.02$) achieved superior d' scores, representing an increased ability to accurately discriminate between target and nontarget stimuli. No significant fitness effects were observed for RT.

Two-back regression analyses. The analysis of target trial accuracy indicated effects of fitness, sex ($\beta = 0.16$, $P = 0.001$), and household income ($\beta = 0.18$, $P < 0.001$), suggesting that higher-fit children, males, and those living in families reporting greater household income demonstrated greater accuracy. For nontarget trial accuracy, effects of fitness (see Fig. 3D) and grade ($\beta = 0.13$, $P < 0.02$) were observed signifying that higher-fit and older children performed more accurately for nontarget trials. Lastly, the regression analysis for d' revealed significant effects for fitness (see Fig. 3E), sex ($\beta = 0.15$, $P < 0.01$), and household income ($\beta = 0.14$, $P < 0.01$), confirming that higher-fit participants, males, and those living in families reporting greater household income exhibited an increased propensity to accurately distinguish targets from nontarget stimuli. No significant findings were discovered for the false alarm rate or for RT.

DISCUSSION

The current findings are consonant with previous investigations of fitness and inhibitory control using flanker tasks (7,17,32,39). Incongruent trials successfully placed a larger demand on cognitive control processes, which was reflected by longer RT and decreased accuracy compared with congruent trials. The introduction of the response incompatible condition resulted in a further overall delay in RT and decrease in accuracy, reflecting the need for greater inhibitory control and heightened attention. Although the hypothesis that higher-fit children would demonstrate better performance was upheld, it did not appear that this effect was selectively modulated for situations necessitating increased cognitive control (failing to support the selectivity hypothesis). This study is not the first to report such findings

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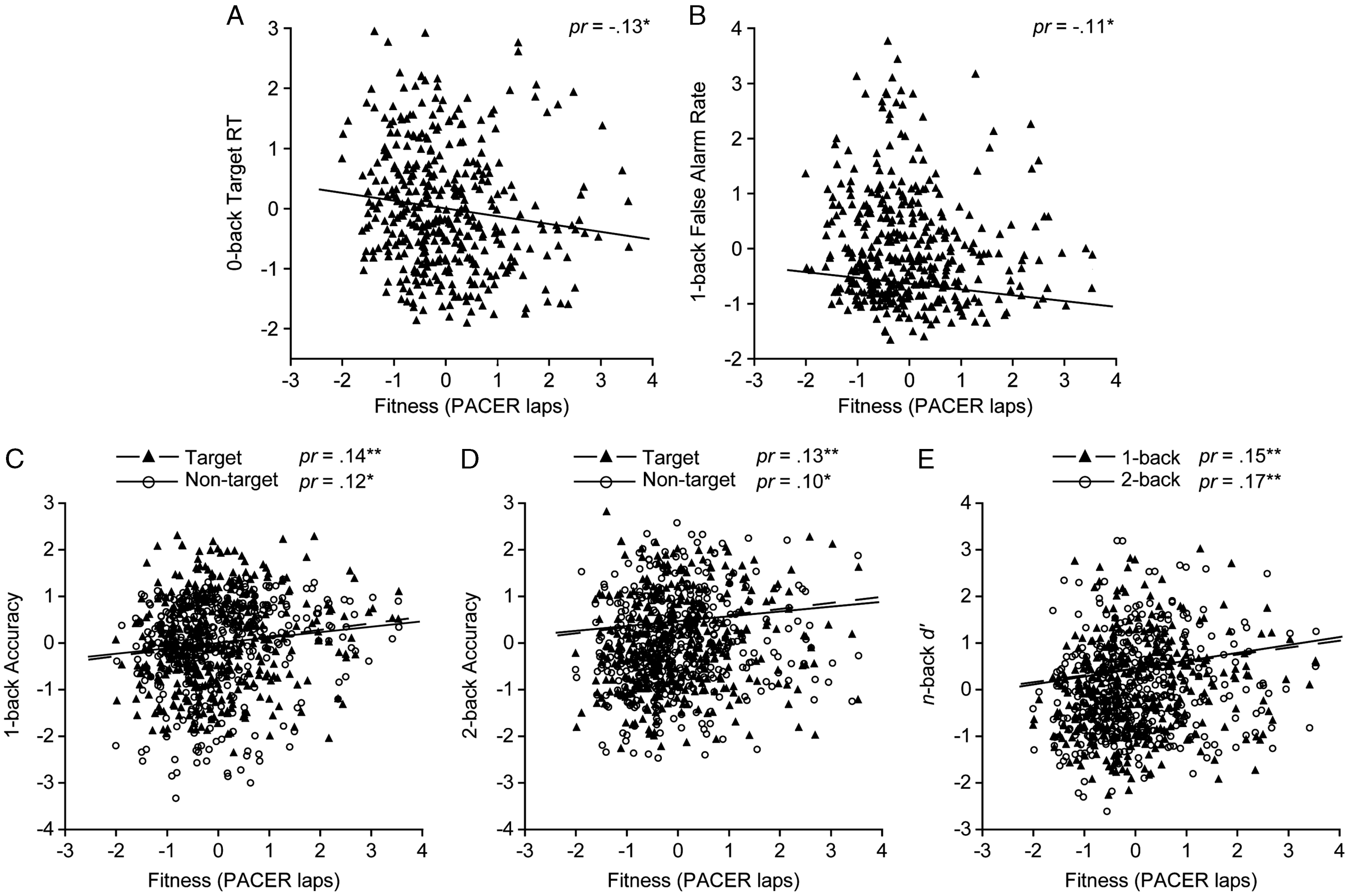

FIGURE 3—Partial regression plots depicting the relationship between fitness and spatial *n*-back task for 0-back target RT (A), 1-back false alarm rate (B), 1-back accuracy (C), 2-back accuracy (D), and *d′* scores in the 1- and 2-back conditions (E) after controlling for grade, sex, household income, and BMI. Partial correlations (*pr*) are provided. *$P \leq 0.05$, **$P \leq 0.01$.

using a flanker task, as Hillman et al. (17) observed general fitness differences on behavioral and neuroelectric measures in 9- to 10-yr-old children across congruent and incongruent trials. As such, it is reasonable to conclude that the lack of consensus in the literature between general and selective fitness effects may be due to the nuances in study design or the differences in the age or maturation of preadolescent participants across studies. For instance, previous cross-sectional studies reporting selective benefits in children (7,32,39) have incorporated individuals from opposite ends of the fitness spectrum, residing either below the 30th or above the 70th percentiles for fitness. With regard to maturation, the mean age of children in the current study was only 7.6 yr as compared with other studies in which the mean age was ~ 10 yr. It is conceivable that the overall increased difficulty of the flanker task at younger age ranges may alter the pattern of results with respect to aerobic fitness, yet a detailed and controlled account of this relationship across different age ranges does not currently exist. Given the conflicting results regarding general and selective findings in children, future research needs to explore this relationship to better understand the interaction between fitness, maturation, and inhibitory control.

Contrary to the flanker findings, children's behavior during the spatial *n*-back supported the *a priori* hypothesis that fitness would exhibit a stronger association with task performance when working memory demands were increased during the 1- and 2-back conditions. Importantly, the data suggest that difficulty was successfully modulated across conditions, which was evidenced by overall delays in RT, a larger number of false alarms in the 2-back condition, decreases in accuracy, and lower *d′* scores. Fitness was related to target trial RT during the 0-back condition, which served as a control condition as it does not require the storage or manipulation of remembered information. As such, these results closely align with those first reported by Hillman et al. (18), which indicated that high fit children (i.e., those in the top 10% of completed PACER laps) displayed shorter RT during the successful identification of a prespecified stimulus.

Working memory *d′* scores were elevated, and accuracy was significantly greater in higher-fit children for target and nontarget trials during both the 1- and 2-back conditions. Further, higher-fit individuals committed fewer false alarms in the 1-back condition, suggesting an increased propensity for correctly discriminating nontarget trials. Kamijo et al. (21) recently demonstrated that an increase in $\dot{V}O_{2max}$ after a

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randomized controlled physical activity intervention was associated with improved working memory accuracy and that such effects were absent in the control group. Importantly, the effect only existed for the more demanding conditions (i.e., those placing increased demands on working memory) of a modified Sternberg task. Fisher et al. (16) conducted an exploratory randomized controlled trial in younger children (5–6 yr old) and administered working memory measures of the Cambridge Neuropsychological Test Battery (CANTAB) before and after a 10-wk physical activity intervention. The authors indicated that children who received physical education class with added emphasis on time spent in moderate to vigorous aerobic physical activity demonstrated a reduction in the number of spatial working memory errors at posttesting. However, these findings were tempered by several limitations described by the authors, and aerobic fitness information was not provided. Although the nature of these relationships are inherently different across studies because of the differences in study design and methods for measuring fitness and working memory, the similarities in the pattern of results are intriguing and together suggest a beneficial association. The current results provide evidence of a selective relation between fitness and tasks requiring greater amounts of working memory; however, as a recent meta-analysis has indicated, there is still a need for additional research exploring aerobic fitness and working memory because of the limited number of studies (38).

It is worth noting that evidence from the opposite end of the age spectrum supports the conclusion that improved fitness or increased physical activity levels may exert selectively greater cognitive benefits for more difficult tasks. General improvements in flanker RT have been associated with greater physical activity levels in both young and older adult cohorts, yet increased physical activity was selectively related to better accuracy during incongruent trials in the older group (19). Meta-analytic reviews in older populations (8) provide further support for such a selectivity hypothesis. It is important to continue exploring these different aspects of cognitive control because the pattern of results informs researchers about the possible neural networks that may be amenable to physical activity interventions or changes in fitness. For instance, in addition to the selective behavioral effects that have been previously witnessed in higher- and lower-fit children, neuroimaging methods have revealed that these differences may be linked to underlying brain activation patterns involving the prefrontal cortex (39) and the integrity of specific brain structures such as the basal ganglia (7) and the hippocampus (6). These discoveries have lead researchers to suggest that the observable patterns in children's cognitive performance may reflect their ability to adopt certain cognitive control strategies, which may have considerable implications for learning and academic achievement (32,39).

Fortunately, the popular application of the flanker task permits further validation of the current results in accordance with demographic factors that significantly interacted with fitness and cognitive performance. Mezzacappa (27) successfully identified several important sociodemographic correlates in a large and diverse group of children, demonstrating that age and socioeconomic status (SES) were significantly related to better performance and shorter RT, which was corroborated in the present findings. It was also reported that race influenced RT; however, given the ethnic distribution of the current population, which was predominately Caucasian children living in higher-income families, it is doubtful that race had a significant influence on the outcome measures of this study but does potentially limit the generalizability to children of other races. It is important to highlight the similarities and differences that exist across variables such as fitness, SES, and age because it will help identify child populations who may derive the greatest benefit from physical activity programs and interventions, such as associated improvements in academic performance. For instance, working memory training has been developed for use in children and often results in adaptive performance, even for tasks that are not specifically included in the training regimen (23). Although relatively few physical activity interventions have explored cognitive outcomes in children, including academic achievement, the overall benefits may prove worthwhile.

However, certain limitations within the current study will require additional research to confirm the positive associations between children's PACER performance and cognitive control. Because of the cross-sectional nature of the findings, the causal inference of aerobic fitness on cognitive control cannot be determined. Longitudinal designs and interventions to improve children's fitness levels will be required to examine whether these changes are in fact related to better cognitive performance. Such approaches would further benefit from the inclusion of racially diverse samples of children. Relatedly, although the regression analyses controlled for factors such as SES and grade, it is impossible to completely control for the influence of these demographic variables, given that findings may change based on the manner in which they are measured (e.g., SES was only represented by household income). Lastly, because of the time constraints and the large number of children that were tested, children's cognitive performance was measured at different times throughout the day. As such, future studies will wish to try and control for potential "time of day" effects.

In summary, a strength of the current study was the inclusion of a large sample of children to establish a broad perspective of aerobic fitness and cognitive control. This was made possible by having children complete the PACER at their respective schools, as opposed to using a laboratory-based measure, such as $\dot{V}O_{2max}$, which has been the standard procedure throughout much of the literature. Fortunately, the use of the flanker task permitted comparisons with prior research and provided greater reliability for the current findings. Incorporating the spatial *n*-back task was also a considerable advantage as it allowed for an extension of the previous literature by measuring children's working memory, which has received little attention throughout this area of study.

Importantly, the data from both of these tasks suggests that higher-fit children outperformed their lower-fit peers.

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The relative ease of conducting the PACER (in addition to the low costs and minimal participant burden) makes this subtest a viable option for schools and researchers to effortlessly track the progression of children's fitness levels. It is conceivable that with the reliability and widespread use of fitness field tests, especially in educational domains, this area of research will continue to extend to larger representative samples of children as well as interested researchers without the capabilities for laboratory assessments. Collectively, the current findings support the development of comprehensive health recommendations for children from the perspective of influencing cognitive function and improving overall health and well-being.

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Mark R. Scudder drafted the initial manuscript and collaborated with Eric S. Drollette on the design of the cognitive tasks, data analysis/interpretation, and subsequent manuscript drafts. Kate Lambourne was involved in drafting and revising the manuscript and collaborated with Stephen Herrmann, who also revised the manuscript and contributed to data acquisition and interpretation. Richard Washburn, Joseph E. Donnelly, and Charles H. Hillman are investigators on the project and were involved in the concept and design of the study, in the interpretation of the data, and in overseeing manuscript preparation.

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