Muscular and Aerobic Fitness, Working Memory, and Academic Achievement in Children

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[1]Department of Kinesiology and Community Health, University of Illinois at Urbana–Champaign, IL; [2]Department of Psychology, Northeastern University, Boston, MA; [3]Department of Kinesiology, Michigan State University, East Lansing, MI; and [4]Department of Health Sciences, Northeastern University, Boston, MA

ABSTRACT

KAO, S.-C., D. R. WESTFALL, A. C. PARKS, M. B. PONTIFEX, and C. H. HILLMAN. Muscular and Aerobic Fitness, Working Memory, and Academic Achievement in Children. *Med. Sci. Sports Exerc.*, Vol. 49, No. 3, pp. 500–508, 2017. **Purpose**: This study investigated the relationship between aerobic and muscular fitness with working memory and academic achievement in preadolescent children. **Methods**: Seventy-nine 9- to 11-yr-old children completed an aerobic fitness assessment using a graded exercise test; a muscular fitness assessment consisting of upper body, lower body, and core exercises; a serial n-back task to assess working memory; and an academic achievement test of mathematics and reading. **Results**: Hierarchical regression analyses indicated that after controlling for demographic variables (age, sex, grade, IQ, socioeconomic status), aerobic fitness was associated with greater response accuracy and d' in the 2-back condition and increased mathematic performance in algebraic functions. Muscular fitness was associated with increased response accuracy and d', and longer reaction time in the 2-back condition. Further, the associations of muscular fitness with response accuracy and d' in the 2-back condition were independent of aerobic fitness. **Conclusion**: The current findings suggest the differential relationships between the aerobic and the muscular aspects of physical fitness with working memory and academic achievement. With the majority of research focusing on childhood health benefits of aerobic fitness, this study suggests the importance of muscular fitness to cognitive health during preadolescence. **Key Words:** CARDIORESPIRATORY FITNESS, STRENGTH FITNESS, COGNITION, SCHOLASTIC PERFORMANCE, PREADOLESCENCE

Growing evidence has suggested an increasing prevalence of being physically inactive and unfit during childhood over the past few decades (9). Such a health trend is especially concerning given that academic achievement has been associated with physical fitness in school-age children (23), suggesting that lower levels of fitness may not only lead to poorer health outcomes, but may also lead to poorer cognitive health. Among the different components of physical fitness, childhood aerobic fitness and its relation with cognition and academic achievement have been most widely investigated (22). Research findings have suggested that aerobic fitness has a positive association with academic achievement (10,17,23). Such findings have led to efforts to investigate whether aerobic fitness may further benefit cognitive functions that support academic achievement (22).

To date, aerobic fitness is the most commonly studied aspect of physical fitness that has been associated with cognition. In particular, cognitive control has garnered considerable interest as a cognitive outcome of aerobic fitness during childhood (27). Cognitive control refers to a subset of top-down mental processes, which implement goal-directed behavior involving inhibition, working memory, and cognitive flexibility (15). Among these core domains of cognitive control, working memory involves the temporal storage and manipulation of information as part of the performance of complex cognitive tasks (3) and is important for academic

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achievement (1). Previous research has suggested that increased aerobic fitness in preadolescent children after a randomized controlled physical activity intervention was associated with enhanced performance during a working memory task (25). Other cross-sectional studies have indicated a similar association between aerobic fitness and working memory after controlling for confounding demographic and health variables. That is, this association was selective to task conditions that placed greater requirements on working memory (16,38). Collectively, these findings suggest that aerobic fitness may play an important role to working memory during preadolescence.

Although the majority of studies have focused on the cognitive benefits of aerobic fitness, accumulating evidence has suggested that muscular fitness may be another aspect of physical fitness that is beneficial for working memory and academic achievement. Specifically, the extant literature suggests that muscular fitness has health benefits for children, including improved bone heath, decreased central adiposity, and lower metabolic risk factors (39), which have been associated with enhanced cognitive control (24,37). Childhood muscular fitness is also associated with lower insulin resistance (7), which has been found to relate to cognitive functions such as working memory (20). Thus, it is plausible that muscular fitness, like aerobic fitness, may have a similar beneficial association with working memory. However, to the best of our knowledge, no direct evidence exists to determine this association in children. In addition, although muscular fitness has been associated with superior academic achievement (18,32,44), this association remains less conclusive as other investigations have failed to observe such associations between muscular fitness and academic achievement (10,17,42). Thus, further examination is necessary to understand the potential association between muscular fitness, working memory, and academic achievement in preadolescent children.

Accordingly, the purpose of this study was to investigate whether muscular fitness was associated with working memory and academic achievement in school-age children. In addition, this study sought to examine whether muscular fitness exhibits similar or differential relationships with working memory and academic achievement relative to aerobic fitness. On the basis of previous studies (16,38), it was hypothesized that aerobic fitness would be positively associated with working memory after controlling confounding variables. This association was further hypothesized to be selective for task conditions placing greater demand on working memory (16,38). It was further hypothesized that muscular fitness would have a similar beneficial association with working memory, such that increased muscular fitness would be associated with enhanced working memory. Lastly, based on the literature (10,17,18,32,42), aerobic and muscular fitness were hypothesized to have differential associations with academic achievement, such that increased aerobic fitness would be associated with greater academic achievement, whereas muscular fitness would only exhibit a weak or insignificant association with academic achievement. Given that the majority of public health concern has centered around promoting aerobic fitness (11), less attention has been dedicated toward understanding the relation between muscular fitness and cognitive health. Results consistent with our predictions will fill this knowledge gap and highlight the importance of developing muscular fitness to improve cognitive health and effective functioning in school-age children.

METHOD

Participants. One hundred and thirty-five preadolescent children between the ages of 9 and 11 yr old from the East-Central Illinois region were contacted during the period from November 2013 to September 2014. One hundred and three participants were interested in the research and subjected to further screening. A total of 96 children were recruited as they were 1) free of neurological disease or attention deficit hyperactivity disorder, 2) capable of performing exercise based on a preexercise screening, and 3) not enrolled in an individualized education program. All participants provided written informed assent, and the legal guardians provided written informed consent approved by the Institutional Review Board of the University of Illinois at Urbana–Champaign. Socioeconomic status (SES) was calculated using a trichotomous index based on the following: 1) highest level of education obtained by the mother and father, 2) number of parents who worked full time, and 3) participation in a free or reduced-price lunch program at school (8). All participants were administered the Kaufman Brief Intelligence Test, Second Edition (K-BIT-2 [26]) by a trained experimenter to gain an estimate of intelligence quotient (IQ), followed by the measurement of height, weight, body mass index, and aerobic and muscular fitness. Three participants withdrew from the study following their first day of participation.

Aerobic fitness assessment. Maximal oxygen consumption ($\dot{V}O_{2max}$) was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400; Sandy, UT) with averages for oxygen uptake ($\dot{V}O_2$) and RER ($\dot{V}CO_2/\dot{V}O_2$) assessed every 20 s. A modified Balke protocol (2) used a motor-driven treadmill at a constant speed with a 2.5% grade increase every 2 min until volitional exhaustion. A Polar heart rate monitor (Polar WearLink +31; Polar Electro, Finland) measured heart rate throughout the test, and RPE values were assessed every 2 min with the children's OMNI scale (43). Relative peak oxygen consumption was expressed in milliliters per kilogram per minute and was based on maximal effort as evidenced by four confidence criteria: 1) a plateau in oxygen consumption corresponding to an increase of less than 2 $mL \cdot kg^{-1} \cdot min^{-1}$ despite an increase in workload, 2) a peak heart rate ≥ 185 bpm, 3) RER ≥ 1.0, and/or 4) ratings on the children's OMNI scale of perceived exertion ≥ 8.

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Muscular fitness assessment. Individual muscular fitness was determined in accordance with recommendations by the American College of Sports Medicine (2014) for pediatric resistance training using a full-body battery of assessments consisting of upper body, lower body, and core exercises, including 1) front squat, 2) push-up, 3) lunge, 4) bent-over row, 5) shoulder press, 6) calf raise, and 7) curl-up (19). For safety reasons, all exercises used either body weight or a rubberized medicine ball (Ecowise dual grip medicine balls). All participants selected a medicine ball with self-determined weight (2.7–8.1 kg) for each individual component of the muscular fitness assessment. Participants were then instructed in the proper form and allowed the opportunity to perform each exercise. If the participant struggled to perform the exercise with proper form, a lower-weight was selected; conversely, if the participant felt that they could perform the exercise with a heavier weight, they were allowed the opportunity to attempt the exercise with that weight while maintaining proper form. For each exercise in the muscular fitness assessment, once the appropriate weight was selected, participants were encouraged to complete as many repetitions as possible within 30 s while maintaining proper form. Thus, this pediatric assessment of muscular fitness was conceptually analogous to submaximal tests of muscular fitness used in adult populations and elite athletes (e.g., the NFL-225 bench press test [29,30]), while reflecting emphasis on muscular fitness across the entire body (2). To account for potential differences in muscular fitness resulting from differences in body size, the strength index for each exercise was reflected by ($weight_{medicine\ ball}$/$weight_{body}$) × repetition and was subsequently normalized across all participants. Body weight was used to calculate the strength index of push-up and curl-up ($weight_{body}$ × repetition). Overall strength was calculated by summation of the standardized strength indices of all exercises (see Table 1).

Cognitive task. A child-friendly serial n-back task was used using Neuroscan Stim2 software (Compumedics, Charlotte, NC) to assess working memory (16). The task contains a sequence of stimuli presented with a duration of 200 ms and a fixed interstimulus interval of 2500 ms. Each stimulus was presented focally and consisted of a 3-cm-tall shape selected from six different shapes. Participants were instructed to respond as quickly and accurately as possible with a right thumb press when the current stimulus matched the one from n steps earlier in the sequence (i.e., target) and with a left thumb press when the current stimulus did not match the one n steps earlier in the sequence (i.e., nontarget). In the present study, 1- and 2-back tasks were used in a counterbalanced order. Each task included three blocks of randomized target trials (n = 24) and nontarget (n = 48) trials. Outcome variables derived from each task condition included mean response accuracy, mean reaction time (RT), false alarm rate (the probability of incorrectly identifying a nontarget as a target), and d prime (d'). Calculation of d' used the formula provided by Sorkin (40), z(adjusted target accuracy) − z(adjusted false alarm rate). If the probability of target accuracy was 1.0, an adjustment of $2^{-(1/n)}$ (n = number of trials) was used to replace the maximum probability, and if the probability of false alarm rate was 0.0, an adjustment of $1 - (2^{-(1/n)})$ was used to replace the minimum probability. Higher values of d' indicate an increased ability to discriminate between targets and nontargets with the highest possible score after adjustment equal to 4.9.

TABLE 1. Mean values for demographic and fitness measures.

Measure	Mean (SD)	Range
N	79 (male = 44)	
Age (yr)	10.1 ± 0.6	9–11.6
Grade	4.2 ± 0.8	3rd–6th
SES	2.6 ± 0.7	1–3
IQ	114.5 ± 12.7	81–141
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	44.3 ± 6.7	32.0–62.2
Body mass index ($kg \cdot m^{-2}$)	18.7 ± 3.9	13.2–37.1
Weight (kg)	37.8 ± 9.8	24.8–70.0
Front squat (reps)	16.0 ± 3.6	7–26
Front squat weight (kg)	3.8 ± 2.2	2.7–8.1
Lunge (reps)	10.4 ± 2.6	6–23
Lunge weight (kg)	3.8 ± 1.0	2.7–6.8
Bent-over row (reps)	18.6 ± 6.5	6–37
Bent-over row weight (kg)	3.6 ± 1.0	2.7–8.1
Shoulder press (reps)	15.2 ± 4.2	7–23
Shoulder press weight (kg)	3.5 ± 1.0	2.7–6.8
Calf raise (reps)	13.5 ± 3.1	7–24
Calf raise weight (kg)	3.5 ± 1.0	2.7–8.1
Push-up (reps)	16.0 ± 4.0	8–28
Curl-up (reps)	12.1 ± 3.1	7–20

Academic achievement. The academic achievement test used in this study was adapted from the released test questions from the Grades 3–5 California Standards Test forms in 2003–2007. This study used a mathematics test containing three categories of questions: 1) number sense (NS)—place value, fractions, decimals, addition, subtraction, multiplication, and division (11–12 questions); 2) algebra and functions (AF; 7–8 questions); and 3) measure and geometry (MG; 3–4 questions). The reading test contained two categories of questions: 1) reading comprehension (RC; 8–10 questions) and 2) written conventions (WC; 8–10 questions). Participants were administered age-appropriate variants of these assessments. Participants who were third or fourth grade and younger than 9.5 yr took the third- to fourth-grade version of the mathematics and reading tests, and participants above fourth grade and older than 9.5 yr were administered the fourth- to fifth-grade version of the mathematics and reading tests. The percentage of correct items in each category was calculated for the comparison of academic achievement across participants (NS, 61.2% ± 22.9%; AF, 62.2% ± 27.6%; MG, 59.8% ± 33.9%; overall mathematics, 61.0% ± 21.2%; RC, 76.8% ± 18.4%; WC, 61.4% ± 26.3%; overall reading, 68.7% ± 19.4%). All participants were given 15 min to complete the mathematics and another 15 min to complete reading tests. The order of test administration was counterbalanced across participants. Three participants had just started their sixth-grade school year before the administration of academic achievement test. However, they did not exhibit significant differences in reading and mathematics performance in comparison with other fourth and fifth graders, who were administered the same fourth- to fifth-grade version of academic achievement, F's(3, 39) ≤ 2.34,

P's ≥ 0.088, $\eta^2_p \leq 0.15$. Thus, these sixth graders were included in the analysis for academic achievement.

Procedure. On the first day to the laboratory, after written informed assent and consent were obtained, legal guardians completed the demographic questionnaire and participants completed K-BIT and academic achievement tests. All participants were provided 72 practice trials of the n-back task for each condition. A 30-min rest period was provided between the muscular fitness assessment and the aerobic fitness assessment. On the second day of testing, participants were seated in a sound attenuated chamber and performed a computerized n-back task after 20 practice trials for each condition of the n-back task. The average gap between the first and second days was (8.5 ± 10.2 d). Participants were provided monetary compensation for their participation.

Statistical analyses. Data were analyzed using the Statistical Package for the Social Sciences (version 22; SPSS Inc., Chicago, IL) with family-wise alpha threshold for all tests set at $P = 0.05$. Bivariate correlations were conducted using Pearson product–moment correlation coefficients between demographic variables, fitness indices, n-back tasks performance measures across 1- and 2-back conditions (mean response accuracy, mean RT, false alarm rate, and d'), and performance of the academic achievement tests (percentage of correct answer in reading, mathematics, and each question category). Separate linear hierarchical regression analyses were performed using working memory or academic achievement measures that were significantly correlated with either aerobic or muscular fitness measures. Aerobic or muscular fitness measures were entered into step 2 in separate hierarchical regression analyses after the inclusion of demographic variables that were significantly correlated with working memory or academic achievement measures into step 1. To assess the unique contribution of aerobic and muscular fitness, dependent variables that were predicted by $\dot{V}O_{2max}$ and strength separately were used for similar hierarchical regression analyses entering aerobic fitness into step 2 and muscular fitness into step 3. Analogous regression analyses were conducted entering muscular fitness into step 2 and aerobic fitness into step 3. Assumptions of linearity, normality, multicollinearity, autocorrelation, and homoscedasticity were plotted, inspected, and verified using studentized residuals. No multicollinearity was observed among any of the independent variables (VIF < 10). Working memory measures were analyzed separately using a 2 (order: 1-back followed by 2-back, 2-back followed by 1-back) × 2 (condition: 1-back, 2-back) repeated-measures ANOVA to examine task condition and task order effects.

Analyses were conducted on a final sample of 79 participants after excluding participants who 1) exhibited an IQ score lower than 80 ($n = 1$), 2) did not have data across all of the fitness assessments ($n = 1$), 3) did not achieve $\dot{V}O_{2max}$ plateau or at least two other confidence criteria during their aerobic fitness assessment ($n = 3$), 4) achieved less than 50% response accuracy in the n-back task ($n = 3$; [35]), 5) exhibited d' score ≤ 0 for any of the n-back conditions ($n = 3$ [16,38]), and 6) were diagnosed as influential outliers in regression analyses for d' scores using covariance ratio ($n = 3$ [5]). A sensitivity analysis was performed based on the current sample of 79 participants with alpha = 0.05 and power = 0.8, indicating that the present investigation was powered to detect a small to medium effect size exceeding $f^2 = 0.10$ (13) for the variance explained by aerobic or muscular fitness while accounting for five demographic variables (age, grade, sex, IQ, and SES) in the hierarchical regression analysis. Demographic data for the current sample are shown in Table 1.

RESULTS

Manipulation Check

ANOVA analyses did not reveal a significant order–condition interaction, F's(1, 77) ≤ 1.26, P's ≥ 0.265, $\eta^2_p \leq 0.16$, or Order effect, F's(1, 77) ≤ 0.55, P's ≥ 0.460, $\eta^2_p \leq 0.07$, for any of the working memory measures. A significant main effect of Condition was demonstrated for all working memory measures, with increased response accuracy and d' and decreased RT and false alarm rate for the 1-back

TABLE 2. Bivariate correlations between variables.

	$\dot{V}O_{2max}$	Strength	Age	Sex	Grade	IQ	SES
1-back response accuracy (%)	0.16	0.15	0.17	−0.26*	0.03	0.28*	0.10
2-back response accuracy (%)	0.24*	0.27*	0.22*	−0.11	0.21	0.35**	0.17
1-back d'	0.19	0.17	0.11	−0.21	−0.03	0.27*	0.07
2-back d'	0.26*	0.28**	0.17	−0.08	0.16	0.30**	0.15
1-back false alarm rate (%)	−0.19	−0.10	0.00	0.07	0.15	−0.24*	0.05
2-back false alarm rate (%)	−0.24*	−0.10	−0.01	−0.16	−0.01	−0.26*	−0.09
1-back RT (ms)	0.17	0.29*	−0.16	0.10	−0.29**	−0.15	0.29**
2-back RT (ms)	0.16	0.28*	−0.12	−0.00	−0.26*	−0.03	0.26*
Number sense (%)	0.13	0.17	0.25*	−0.14	0.21	0.47**	0.19
Algebra and functions (%)	0.33**	0.12	0.27*	0.02	0.21	0.54**	0.14
Measure and geometry (%)	−0.00	0.04	0.04	−0.13	−0.00	0.11	−0.06
Mathematics (%)	0.22*	0.15	0.26*	−0.11	0.20	0.54**	0.15
Reading comprehension (%)	0.17	−0.07	0.34**	−0.06	0.24*	0.50**	0.20
Witten conventions (%)	0.04	−0.13	0.11	−0.24*	0.08	0.60**	−0.00
Reading (%)	0.11	−0.12	0.21	−0.20	0.15	0.64**	0.08

*$P \leq 0.05$.
** $P \leq 0.01$.

(response accuracy: 86.2% ± 6.9%; RT: 768.6 ± 155.0 ms; d': 2.5 ± 0.6; false alarm rate: 5.3% ± 3.7%) relative to the 2-back condition (response accuracy: 75.2% ± 8.0%; RT: 860.9 ± 188.4 ms; d': 1.5 ± 0.5; false alarm rate: 10.6% ± 6.3%), F's(1, 77) ≥ 59.42, P's < 0.001, $\eta^2_p \geq 0.44$.

Bivariate Correlations

Table 2 summarizes the results of the initial Pearson product–moment correlations. The results show that response accuracy, d', and false alarm rate across 1- and 2-back conditions were consistently correlated with IQ (|r's| ≥ 0.24). Response accuracy was also correlated with sex in the 1-back condition (r = −0.26) and age in 2-back condition (r = 0.22). RT was correlated with grade (r's ≤ −0.26) and SES (r's ≥ 0.26) across the 1- and 2-back conditions. Academic achievement was consistently correlated with age (r's ≥ 0.25) and IQ (r's ≥ 0.47), except MG, WC, and overall reading. Grade was also correlated with RC (r = 0.24). Sex was correlated with WC (r = −0.24). Sex was included in analyses because relative $\dot{V}O_{2max}$ values are not standardized across sex. Therefore, age, sex, grade, IQ, and SES were entered into step 1 of the regression analyses. The bivariate analysis revealed that aerobic and muscular fitness were correlated (r = 0.30). Aerobic fitness was associated with increased response accuracy, greater d', decreased false alarm rate in the 2-back condition, greater performance in algebraic function, and overall mathematics (|r's| ≥ 0.22). Muscular fitness was associated with longer RT in the 1- and 2-back conditions and increased response accuracy and d' in the 2-back condition (r's ≥ 0.27). These measures were used as dependent variables in the regression model.

Hierarchical Regression Analyses

The association between aerobic fitness, working memory, and academic achievement. No performance measure of the 1-back condition was used for hierarchical regression analysis because their lack of bivariate correlation with aerobic fitness. However, for the 2-back condition, hierarchical regression analysis indicated that children with higher aerobic fitness exhibited greater d', β = 0.26, pr = 0.26, t = 2.26, P = 0.027, Cohen's f^2 = 0.07 (see Table 3 and Fig. 1), after controlling for age, sex, grade, IQ, and SES. Higher aerobic fitness also exhibited greater response accuracy in the 2-back condition, β = 0.23, pr = 0.23, t = 2.04, P = 0.045, Cohen's f^2 = 0.06 (see Table 3 and Fig. 1). In addition, higher aerobic fitness was associated with greater performance of algebraic functions, β = 0.24, pr = 0.27, t = 2.36, P = 0.021, Cohen's f^2 = 0.08 (see Table 3 and Fig. 2).

The association between muscular fitness and working memory. Hierarchical regression analysis indicated that muscular fitness was not associated with RT in the one-back condition (β = 0.21, pr = 0.23, t = 1.99, P = 0.051, Cohen's f^2 = 0.05). However, in the 2-back condition, analyses revealed that children with higher muscular fitness exhibited greater d', increased response accuracy, and longer RT, β's ≥ 0.22, pr$'$s ≥ 0.23, t's ≥ 2.03, P's ≤ 0.046, Cohen's f^2 ≥ 0.06 (see Table 3 and Fig. 1), after controlling for age, sex, grade, IQ, and SES.

The association between aerobic fitness, muscular fitness, and working memory. Given that response accuracy and d' in the 2-back condition were predicted by aerobic fitness and muscular fitness separately, two fitness measures were entered into step 2 or step 3 separately to determine their unique contribution to response accuracy and d' in the 2-back condition. After controlling for age, sex, grade, IQ, SES, and aerobic fitness, higher muscular fitness predicted greater response accuracy and d' in the 2-back condition, β's ≥ 0.25, pr$'$s ≥ 0.26, t's ≥ 2.24, P's ≤ 0.028, Cohen's f^2 ≥ 0.07 (see Table 4, Model 1). However, no such independent associations were observed for aerobic fitness, β's ≤ 0.20, pr$'$s ≤ 0.19, t's ≤ 1.67, P's ≥ 0.100, Cohen's f^2 ≤ 0.04 (see Table 4, Model 2).

DISCUSSION

The results of this study indicated that higher levels of aerobic and muscular fitness were associated with greater performance in task conditions that placed greater demand on working memory. Further, these results suggest that aerobic and muscular fitness have similar yet differential associations with working memory and academic achievement.

TABLE 3. N-back task and academic achievement test hierarchical regression values for fitness-domains.

Measure	Step 1 R^2	Step 2 $\triangle R^2$	B	SE B	β	t
			$\dot{V}O_{2max}$			
2-back response accuracy (%)	0.174*	0.045*	0.277	0.136	0.23	2.04*
2-back d'	0.123	0.058*	0.021	0.009	0.26	2.26*
2-back false alarm rate (%)	0.103	0.024	−0.159	0.113	−0.17	−1.41
Algebra and functions (%)	0.351**	0.047*	0.010	0.004	0.24	2.36*
Mathematics (%)	0.346**	0.023	0.005	0.003	0.17	1.60
			Strength			
2-back response accuracy (%)	0.174*	0.077**	0.508	0.187	0.29	2.72**
2-back d'	0.123	0.082**	0.035	0.013	0.30	2.72**
1-back RT (ms)	0.229**	0.040	7.088	3.570	0.21	1.99
1-back RT (ms)	0.151*	0.046*	9.233	4.543	0.22	2.03*

Step 1 included demographic variables (age, sex, grade, IQ, SES), and step 2 included $\dot{V}O_{2max}$ or strength.
*$P \leq 0.05$.
**$P \leq 0.01$.

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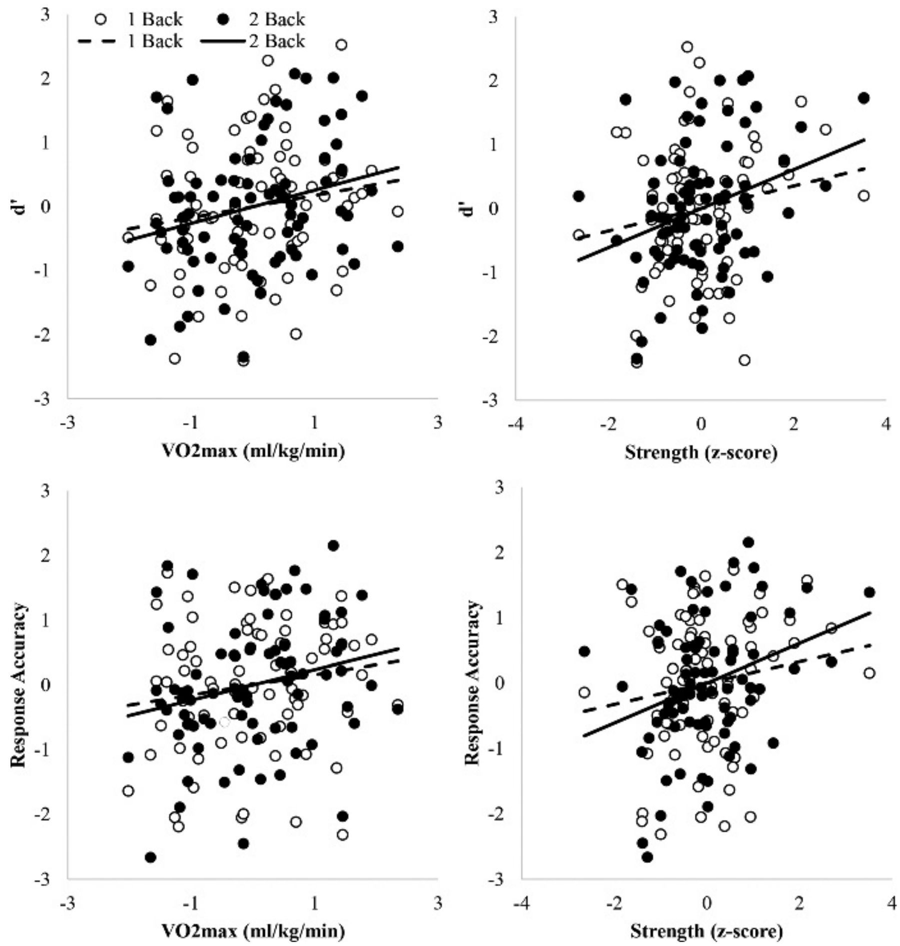

FIGURE 1—Partial regression plots depicting the relationship of aerobic and muscular fitness with response accuracy and d' in the 1- and 2-back conditions.

The positive association between muscular fitness and task performance in the 2-back condition was independent of aerobic fitness. Aerobic fitness was associated with greater mathematic performance in the category of algebraic functions, whereas no association between muscular fitness and academic achievement was observed.

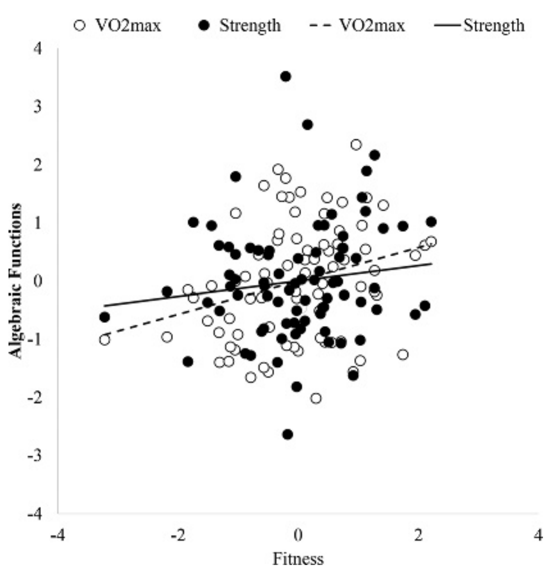

FIGURE 2—Partial regression plots depicting the relationship of aerobic and muscular fitness with performance in the category of algebraic functions.

This study replicated previous findings suggesting that children with higher aerobic fitness are better able to discriminate target from nontarget trials during task conditions imposing greater demands on working memory (16,38), as evidenced by a positive association between aerobic fitness and task performance (i.e., response accuracy and d') in the 2-back condition of a n-back task. The counterbalanced

TABLE 4. Summary of hierarchical regression analysis for response accuracy and d' in the 2-back condition.

Variable		2-Back Response Accuracy (%) ΔR^2	B	SE B	β	2-Back d' ΔR^2	B	SE B	β
Model 1									
Step 1		0.174*				0.123			
Step 2	$\dot{V}O_{2max}$	0.045*	0.277	0.136	0.23*	0.058*	0.021	0.009	0.26*
Step 3	Strength	0.053*	0.437	0.192	0.25*	0.054*	0.029	0.013	0.25*
Model 2									
Step 1		0.174*				0.123			
Step 2	Strength	0.077*	0.508	0.187	0.29**	0.082**	0.035	0.013	0.30**
Step 3	$\dot{V}O_{2max}$	0.021	0.197	0.137	0.17	0.030	0.016	0.009	0.20

Age, sex, grade, IQ, and SES were entered into Step 1 in both models.
*$P \leq 0.05$.
** $P \leq 0.01$.

order of the 1- and 2-back conditions and the lack of any findings relating to order suggest that this selective association was not simply a function of the order of task administration. The current results also suggest that muscular fitness, similar to aerobic fitness, has a beneficial association with working memory as evidenced by a positive association of muscular fitness on response accuracy and d' in the two-back condition. Although no direct evidence has suggested such association, examination into the effect of muscular fitness on health outcomes has indicated that superior muscular fitness is associated with a variety of health benefits (7,39), which may be beneficial for cognition (24,37). That is, decreased adiposity (4), improved metabolic control (36), and reduced insulin resistance (20) have been associated with enhanced working memory.

More importantly, the current findings revealed that muscular fitness may have unique contributions to working memory independent of aerobic fitness. Although the interpretation of this unique contribution is unclear, resistance exercise targeting improvement of muscular fitness is potentially associated with enhancement of working memory through mechanisms that differ from aerobic fitness (31,45). Given that skeletal muscle has recently been found to serve as an endocrine organ exerting influence on brain metabolism through cytokines and peptides that are produced, expressed, and released by muscle contractions (34), it is plausible that this influence on brain metabolism may be greater in individuals with higher levels of muscular fitness. Collectively, although aerobic and muscular fitness were similarly associated with enhanced working memory, this beneficial association may also be uniquely attributable to muscular fitness.

In addition, this study indicated that aerobic and muscular fitness may have differential associations with the employment of a speed–accuracy tradeoff strategy. That is, findings from the present investigation and others within the literature have observed a positive association between aerobic fitness and response accuracy (16,38), with either no relationship observed for RT (16) or additional facilitations in RT associated with increased aerobic fitness (38). Muscular fitness, in contrast, was associated with increased response accuracy at the cost of longer RT in the 2-back condition within the present investigation. Such findings could suggest that higher levels of muscular fitness are associated with a less impulsive response strategy when greater amounts of working memory are required. Alternatively, these findings may indicate delays in cognitive processing associated with higher levels of muscular fitness. Clearly, this is an area for future research to begin to address in order to understand the differential relationships between aerobic and muscular fitness, particularly relative to such differences in optimizing speed and accuracy.

Relative to academic achievement, the findings also demonstrated a differential relationship between aerobic and muscular fitness. That is, aerobic fitness was positively associated with superior mathematic performance in the category of algebraic functions while muscular fitness had no associations with any area of academic achievement. Although the extant literature has indicated beneficial associations between aerobic fitness and overall academic achievement (10,17,23), some findings have suggested that aerobic fitness has selective benefit for mathematics performance (12,14,28). This latter finding further suggests a selective benefit related to cortical gray matter thinning during brain maturation, as indexed by decreased gray matter thickness in the superior frontal cortex, superior temporal areas, and lateral occipital cortex (12). It is noteworthy that current findings only showed a positive association between aerobic fitness and performance in the category of algebraic functions, rather than an overall mathematics effect or for specific categories related to number sense or measurement and geometry. Among these categories, algebraic function is a higher-level domain of mathematics, which requires the ability to represent and operate on the unknowns (21), and associates with cognitive capacity such as working memory (41). Thus, it should not be unexpected that the beneficial association between aerobic fitness and mathematic performance may be mainly driven by more complex mathematical operations such as algebraic functions, given that aerobic fitness has a larger beneficial association with performance in task conditions that place greater demands on working memory for information representation and manipulation (16,38). Collectively, these findings suggest that performance of algebraic functions may particularly benefit from increased aerobic fitness because of its higher demand for working memory. However, further investigation is needed to confirm whether this selective association is related to changes in the brain regions and networks underlying working memory.

Muscular fitness, in contrast, was neither associated with overall academic achievement nor any category of reading or mathematics performance. The literature to-date on the relationship between muscular fitness and academic achievement remains equivocal, with some investigations observing a positive relationship between muscular fitness and academic achievement (18,32,44), whereas other investigations have observed no such beneficial association (10,17,42). One possible explanation for the divergent findings in this area may be the different analytical approaches across studies with investigations treating muscular fitness either as a continuous or a discrete variable. For example, when muscular fitness indices were categorized by mean-split or interquintile difference, a positive association between muscular fitness and academic achievement was observed (32,44). However, when muscular fitness was categorized by quartiles (42) or used as a continuous variable, no independent relationship was observed between muscular fitness and academic achievement (10,17). Taken together, although there is some evidence in the literature for a positive association between muscular fitness and academic achievement, the association is less conclusive and appears to become attenuated as more variability is accounted in the statistical analyses. However, given the wide variety in measures of muscular fitness and academic achievement as well as inconsistency in controlling for potentially confounding variables within the existent body of literature, future investigation using comparable methodology is necessary to better understand the relationship between muscular fitness and academic achievement.

Although the current results are unable to reveal the mechanisms of the fitness-related associations with working memory and academic achievement, previous research has suggested that exercise benefits cognitive development across the life span through exercise-induced changes in growth factors and brain function, synaptic plasticity, neurogenesis and brain structure, angiogenesis, and genetics and epigenetics (45). Given that recent evidence has suggested that chronic resistance exercise has differential impacts on working memory and other domains of cognitive control compared with aerobic exercise (31), there is a need to investigate whether there are differential mechanisms for various types of exercise underlying the exercise-induced enhancement of cognitive health (45). In addition, from a contextual/environmental perspective, physical activities targeting improvement of muscular fitness may involve movements and strategic behavior that are different from activities with the aim of improving aerobic fitness. Such investigations may help explain the differential associations observed between aerobic and muscular fitness, working memory, and academic achievement in school-age children.

Given the correlational nature of the study design, one limitation of the present investigation is its inability to infer causality. For instance, although studies have demonstrated a neuroselection mechanism to explain the influence of childhood cognitive functioning on the association between fitness and cognition during midlife (6), the current study was unable to determine whether such a mechanism can be generalized to preadolescent children. Accordingly, future research using longitudinal designs are necessary to assess the relation of aerobic and muscular fitness to optimal developmental trajectories of cognition during childhood. Although this study demonstrated that aerobic and muscular fitness are differentially associated with working memory, further investigations in this area are necessary to understand whether this differential association exists in other domains of cognitive control. Although aerobic and muscular fitness were the focus of the present investigation, recent evidence has demonstrated positive associations for other physical fitness domains such as motor fitness and agility relative to childhood cognitive health (42). Thus, further investigation comparing the associations between multiple aspects of physical fitness with cognitive health is necessary to better understand how these aspects of physical fitness should be differentially targeted to improve cognitive health during childhood.

In conclusion, the current study demonstrated similar associations between aerobic and muscular fitness with working memory. Specifically, muscular fitness exhibited a unique contribution to working memory and was associated with a speed–accuracy tradeoff strategy during the working memory task. In addition, mathematic achievement of algebraic functions was selectively predicted by aerobic fitness. These findings indicated a similar yet differential beneficial association between aerobic and muscular fitness with childhood cognitive health, suggesting the importance of developing multiple aspects of fitness for cognitive health in early life. Given that development of childhood aerobic fitness has become increasingly emphasized, these data suggest that activities targeting improvement of muscular fitness should also be integrated into school- and community-based youth programs for enhancing cognitive health.

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The results of the present study do not constitute endorsement by the American College of Sports Medicine. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

APPLIED SCIENCES

REFERENCES

1. Alloway TP, Alloway RG. Investigating the predictive roles of working memory and IQ in academic attainment. *J Exp Child Psychol*. 2010;106(1):20–9.
2. American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription*. 9th ed. Lippincott Williams & Wilkins; 2014. pp. 1–456.
3. Baddeley A. Working memory. *Science*. 1992;255(5044):556–9.
4. Bauer LO, Manning KJ. Challenges in the detection of working memory and attention decrements among overweight adolescent girls. *Neuropsychobiology*. 2016;73(1):43–51.
5. Belsey DA, Kuh E, Welsch RE. *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*. John Wiley; 1980. pp. 22–4.
6. Belsky DW, Caspi A, Israel S, Blumenthal JA, Poulton R, Moffitt TE. Cardiorespiratory fitness and cognitive function in midlife: neuroprotection or neuroselection? *Ann Neurol*. 2015;77(4):607–17.
7. Benson AC, Torode ME, Fiatarone Singh MA. Muscular strength and cardiorespiratory fitness is associated with higher insulin sensitivity in children and adolescents. *Int J Pediatr Obes*. 2006;1(4): 222–31.
8. Birnbaum AS, Lytle LA, Murray DM, Story M, Perry CL, Boutelle KN. Survey development for assessing correlates of young adolescents' eating. *Am J Health Behav*. 2002;26:284–95.
9. Boddy LM, Fairclough SJ, Atkinson G, Stratton G. Changes in cardiorespiratory fitness in 9- to 10.9-year-old children: SportsLinx 1998–2010. *Med Sci Sports Exer*. 2012;44(3):481–6.

10. Castelli DM, Hillman CH, Buck SM, Erwin HE. Physical fitness and academic achievement in third- and fifth-grade students. *J Sport Exerc Psychol*. 2007;29(2):239–52.
11. Chaddock L, Pontifex MB, Hillman CH, Kramer AF. A review of the relation of aerobic fitness and physical activity to brain structure and function in children. *J Int Neuropsychol Soc*. 2011; 17(6):975–85.
12. Chaddock-Heyman L, Erickson KI, Kienzler C, et al. The role of aerobic fitness in cortical thickness and mathematics achievement in preadolescent children. *PLoS One*. 2015;10(8):e0134115.
13. Cohen J. *Statistical Power Analysis for the Behavior Science*. Routledge; 1988, pp. 474–81.
14. De Greeff JW, Hartman E, Mullender-Wijnsma MJ, Bosker RJ, Doolaard S, Visscher C. Physical fitness and academic performance in primary school children with and without a social disadvantage. *Health Educ Res*. 2014;29(5):853–60.
15. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135–68.
16. Drollette ES, Scudder MR, Raine LB, et al. The sexual dimorphic association of cardiorespiratory fitness to working memory in children. *Dev Sci*. 2016;19(1):90–108.
17. Esteban-Cornejo I, Tejero-González CM, Martinez-Gomez D, et al. Independent and combined influence of the components of physical fitness on academic performance in youth. *J Pediatr*. 2014; 165(2):306–12.
18. Eveland-Sayers BM, Farley RS, Fuller DK, et al. Physical fitness and academic achievement in elementary school children. *J Phys Act Health*. 2009;6(1):99–104.
19. Faigenbaum AD, Loud RL, O'Connell J, Glover S, O'Connell J, Westcott WL. Effects of different resistance training protocols on upper-body strength and endurance development in children. *J Strength Cond Res*. 2001;15:459–65.
20. Gonzales MM, Tarumi T, Miles SC, Tanaka H, Shah F, Haley AP. Insulin sensitivity as a mediator of the relationship between BMI and working memory-related brain activation. *Obesity*. 2010; 18(11):2131–7.
21. Herscovics N, Linchevski L. A cognitive gap between arithmetic and algebra. *Educational Studies in Mathematics*. 1994;27(1): 59–78.
22. Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. *Nat Rev Neurosci*. 2008;9(1):58–65.
23. Janak JC, Gabriel KP, Oluyomi AO, Peréz A, Kohl HW, Kelder SH. The association between physical fitness and academic achievement in Texas state house legislative districts: an ecologic study. *J Sch Health*. 2014;84(8):533–42.
24. Kamijo K, Khan NA, Pontifex MB, et al. The relation of adiposity to cognitive control and scholastic achievement in preadolescent children. *Obesity (Silver Spring)*. 2012;20(12):2406–11.
25. Kamijo K, Pontifex MB, O'Leary KC, et al. The effects of an afterschool physical activity program on working memory in preadolescent children. *Dev Sci*. 2011;14(5):1046–58.
26. Kaufman AS, Kaufman NL. *Kaufman Brief Intelligence Test*. John Wiley & Sons, Inc; 2004.
27. Khan NA, Hillman CH. The relation of childhood physical activity and aerobic fitness to brain function and cognition: a review. *Pediatr Exerc Sci*. 2014;26(2):138–46.
28. 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):165–71.
29. Mann JB, Stoner JD, Mayhew JL. NFL-225 test to predict 1RM bench press in NCAA Division I football players. *J Strength Cond Res*. 2012;26:2623–31.
30. Mayhew JL, Ware JS, Bemben MG, et al. The NFL-225 test as a measure of bench press strength in college football players. *J Strength Cond Res*. 1999;13:130–4.
31. Nagamatsu LS, Chan A, Davis JC, et al. Physical activity improves verbal and spatial memory in older adults with probable mild cognitive impairment: a 6-month randomized controlled trial. *J Aging Res*. 2013;2013:861893.
32. Padilla-Moledo C, Ruiz JR, Ortega FB, Mora J, Castro-Piñero J. Associations of muscular fitness with psychological positive health, health complaints, and health risk behaviors in Spanish children and adolescents. *J Strength Cond Res*. 2012;26(1):167–73.
33. Park CR. Cognitive effects of insulin in the central nervous system. *Neurosci Biobehav Rev*. 2001;25(4):311–23.
34. Pedersen BK, Febbraio MA. Muscles, exercise and obesity: skeletal muscle as a secretory organ. *Nat Rev Endocrinol*. 2012;8(8):457–65.
35. Pontifex MB, Parks AC, O'Neil PC, et al. Poorer aerobic fitness relates to reduced integrity of multiple memory systems. *Cogn Affect Behav Neurosci*. 2014;14(3):1132–41.
36. Ryan CM, Freed MI, Rood JA, Cobitz AR, Waterhouse BR, Strachan MW. Improving metabolic control leads to better working memory in adults with type 2 diabetes. *Diabetes Care*. 2006;29(2):345–51.
37. Scudder MR, Khan NA, Lambourne K, et al. Cognitive control in preadolescent children with risk factors for metabolic syndrome. *Health Psychol*. 2015;34(3):243–52.
38. Scudder MR, Lambourne K, Drollette ES, et al. Aerobic capacity and cognitive control in elementary school-age children. *Med Sci Sports Exerc*. 2014;46(5):1025–35.
39. Smith JJ, Eather N, Morgan PJ, et al. The health benefits of muscular fitness for children and adolescents: a systematic review and meta-analysis. *Sports Med*. 2014;44(9):1209–23.
40. Sorkin RD. Spreadsheet signal detection. *Behav Res Methods Instrum Comput*. 1999;31(1):46–54.
41. Tolar TD, Lederberg AR, Fletcher JM. A structural model of algebra achievement: computational fluency and spatial visualisation as mediators of the effect of working memory on algebra achievement. *Educational Psychol*. 2009;29(2):239–66.
42. Torrijos-Niño C, Martínez-Vizcaíno V, Pardo-Guijarro MJ, García-Prieto JC, Arias-Palencia NM, Sánchez-López M. Physical fitness, obesity, and academic achievement in schoolchildren. *J Pediatr*. 2014;165(1):104–9.
43. Utter AC, Roberson RJ, Nieman DC, et al. Children's OMNI scale of perceived exertion: walking/running evaluation. *Med Sci Sports Exerc*. 2012;34:139–44.
44. Van Dusen DP, Kelder SH, Kohl HW 3rd, Ranjit N, Perry CL. Associations of physical fitness and academic performance among schoolchildren. *J Sch Health*. 2011;81(12):733–40.
45. Voss MW, Vivar C, Kramer AF, van Praag H. Bridging animal and human models of exercise-induced brain plasticity. *Trends Cogn Sci*. 2013;17(10):525–44.