Published in final edited form as:

Health Psychol. 2016 September ; 35(9): 967–978. doi:10.1037/hea0000343.

Tracking the Relationship between Children's Aerobic Fitness and Cognitive Control

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Abstract

Objective—To investigate if changes in aerobic fitness over a three-year period are associated with modulations in children's cognitive control.

Methods—A sample of 2nd/3rd grade children (N = 290) completed baseline measures in Fall of 2011, and again in Spring of 2014 at the end of 4th/5th grade. Children completed the Progressive Aerobic Cardiovascular Endurance Run (PACER) test to measure aerobic capacity, a flanker task to evaluate inhibitory control, and an *n*-back task to assess working memory. Aerobic fitness was included as an independent variable in hierarchical regression analyses conducted at both time points, in addition to analyses examining changes in cognition over time.

Results—At baseline, higher fit children exhibited shorter overall flanker reaction time, as well as superior accuracy and d' scores (i.e., target discrimination) for both 1- and 2-back conditions. Approximately three years later, higher levels of fitness were associated with better performance for only the most difficult conditions of each task, including greater incongruent flanker accuracy and less interference during the compatible condition, as well as better accuracy and target discrimination for the 2-back condition of the *n*-back task. Importantly, increases in fitness were independently related to improvements in incongruent flanker accuracy and 2-back d' scores.

Conclusions—The current findings indicate that both higher aerobic fitness levels, as well as increases in children's fitness, are associated with better performance for task conditions eliciting greater cognitive demand. Such evidence is vital for implementing future health recommendations intended to foster improved cognitive performance in children.

Keywords

PACER; *n*-back; working memory; physical activity; inhibitory control

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Author Disclosure Statement

No conflicting financial, consultant, institutional, or other interests exist.

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Introduction

Adverse health trends among industrialized nations, including the global decline of children's aerobic fitness levels (Tomkinson, Léger, Olds, & Cazorla, 2003; Tomkinson, Olds, Kang, & Kim, 2007), have received considerable attention as concerns for the well-being of future generations continue to mount (Finkelstein et al., 2010; Olshansky et al., 2005). Such health risks are largely attributed to decreases in children's physical activity (PA) levels, and have been related to increased screen time as well as reductions in active transportation to school (e.g., walking, biking; Owen, Sparling, Healy, Dunstan, & Matthews, 2010). Additionally, the increased emphasis on standardized academic achievement scores has further complicated matters by encouraging schools to eliminate PA opportunities during the school day, including recess and physical education (Institute of Medicine, 2013). Thus, many have questioned whether the allocation of additional time to classroom instruction at the expense of children's opportunities for increased energy expenditure is a viable method for improving academic performance (Sallis, 2010).

Several studies have recently highlighted the importance of aerobic fitness for promoting optimal functioning and overall well-being in children, and have revealed beneficial relationships between aerobic fitness and aspects of mental health (e.g., depression, anxiety), as well as academic performance (Lambourne et al., 2013; Ortega, Ruiz, Castillo, & Sjostrom, 2008). In fact, investigations of children's fitness and academic achievement have revealed that superior math and reading performance are primarily associated with higher levels of aerobic fitness as compared to muscular strength/endurance or aspects of body composition (Castelli, Hillman, Buck, & Erwin, 2007; Wittberg, Northrup, & Cottrel, 2009). However, one limitation found throughout the literature is the reliance on standardized academic measures, which provides limited information about the relation between aerobic fitness and the underlying cognitive processes supporting academic performance. Fortunately, multiple cross-sectional investigations across the early childhood years and adolescence have now documented the importance of cognitive control (including aspects of inhibitory control, working memory, and cognitive flexibility) for both math and language skills (Blair & Razza, 2007; Gathercole, Pickering, Knight, & Stegmann, 2004), with prospective studies further demonstrating that superior cognitive control during the pre-kindergarten years predicts better math and reading performance in primary school (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Bull, Espy, & Wiebe, 2008). Accordingly, researchers interested in understanding the influence of aerobic fitness on children's academic achievement and overall brain health/function have expanded their efforts to include additional measures of cognitive processing.

Several cross-sectional studies have now documented corroborating results with respect to the positive link between children's aerobic fitness and aspects of cognitive control (Mokgothu & Gallagher, 2010; Niederer et al., 2011), with additional evidence indicating that more aerobically fit children exhibit greater improvements in learning on memory tasks compared to their lesser fit peers (Herting & Nagel, 2012; Raine et al., 2013). Still, much less is known about the utility of increasing children's aerobic fitness levels as an effective means for improving cognitive performance. Given the potential of improving aerobic fitness (and other important health factors) through a variety of school-based contexts

(Carrel et al., 2005; Dobbins, Husson, DeCorby, & LaRocca, 2013), it is of considerable importance to understand the implications these fitness changes might hold for children's cognitive performance. For instance, findings from an after-school PA intervention in overweight children revealed a dose-response relationship between the amount of aerobic exercise received and improvements in math and cognitive control performance, with accompanying increases in bilateral prefrontal cortex activation and reduced activity in the posterior parietal cortex (Davis et al., 2011). More recent studies have extended these findings by observing greater accuracy improvements on tasks of inhibitory control (i.e., a modified flanker task) and cognitive flexibility (i.e., a switch task) among children participating in an after-school PA intervention, along with significant increases in aerobic fitness (~ 5.5 % increase over 9 months) compared to the control group (~ 1.9 %; Hillman et al., 2014). The results further indicated that attendance in the intervention was positively related to larger increases in a neuroelectric index of attentional resource allocation (i.e., the P3 component of an event-related brain potential), particularly under task conditions requiring increased cognitive control (Hillman et al., 2014).

Despite the cognitive benefits associated with improvements in aerobic fitness, one of the limitations in previous investigations is the failure to assess the contribution of individual changes in aerobic fitness (as opposed to overall group differences) while controlling for baseline fitness levels. Given the likelihood that individual children may exhibit increased/decreased aerobic fitness levels due to a number of different factors over time (regardless of an intervention), regression-based analyses are well-suited for detailing the relationship between modulations in aerobic fitness and cognitive processing while controlling for important demographic factors (i.e., socioeconomic status, sex, etc.) that have been shown to relate to aspects of cognitive control (Kaufman, 2007; Mezzacappa, 2004). Such an approach would help provide a more comprehensive account of the independent association between modulations in aerobic fitness and cognitive performance, irrespective of the broad impact that an intervention may have on multiple areas of children's cognitive/physical development.

Accordingly, the current investigation examined the relationship between changes in children's aerobic fitness and cognitive control using two widely-administered tasks that assess inhibitory control (the flanker task) and working memory performance (the *n*-back task), which have been used in previous fitness studies among individuals of all ages (Hillman et al., 2014; Kramer et al., 2001; Stroth et al., 2009). Children's fitness levels and cognitive performance were measured at the beginning of $2^{nd}/3^{rd}$ grade and at the end of $4^{th}/5^{th}$ grade, which allowed for the examination of variations in children's aerobic fitness and associated modulations in cognitive performance. Consonant with previous research, it was predicted that higher fit children would exhibit superior cognitive performance for task conditions requiring greater amounts of cognitive control at both baseline and follow-up testing, yet this pattern of results was expected to shift between time points as children became more proficient at each task. Further, it was hypothesized that greater increases in aerobic fitness would be independently associated with improvements in task performance for conditions/trials eliciting greater cognitive demands. Such findings regarding the role of aerobic fitness, and specifically changes in fitness, for aspects of children's cognitive control have important implications for guiding school policy to promote children's overall health and cognitive/academic performance.

Method

Participants

Children in the current investigation (n = 290) stemmed from a cluster-randomized controlled trial that examined the influence of classroom-based PA on preventing increased body mass index (BMI) and promoting academic success (masked for review). The primary focus of the larger study was to have teachers in the intervention schools include two 10 min. bouts of physically active academic lessons during each school day, which was modeled after other school-based physical activity interventions including: the Sports, Play, and Active Recreation for Kids (SPARK; McKenzie & Rosengard, 1993), and the Child and Adolescent Trial for Cardiovascular Health (CATCH; McGraw et al., 1994). The (masked for review) Human Subjects Committee approved the study. Fliers describing the study and assessment procedures were mailed to the guardians of 2nd and 3rd grade children, and those who were interested in participating provided their contact information to the school. Due to a large response, a random sample of children stratified by grade and sex were selected from those who provided written parental consent and child assent. Schools partaking in the study received monetary compensation, and all children received a water bottle for their participation. Participant demographics are provided in Table 1.

Secondary measures included in the study consisted of aerobic fitness assessment and tests of cognitive control, which permitted the current investigation of changes in children's aerobic fitness and cognitive performance. Measures were collected during baseline testing at the start of 2nd or 3rd grade in Fall of 2011, and three other testing phases occurring in Spring at the end of the school year, until the completion of 4th or 5th grade (ending in 2014). However, nearly half (6/15) of the participating schools were unable to accommodate the cognitive assessment during the second-to-last phase due to interference with year-end standardized testing (two additional schools withdrew from the study prior to this point). Accordingly, aerobic fitness levels and cognitive performance at baseline (T1) and the end of 4th/5th grade (T2), as well as the ~3 year change between these two time points, were the main focus of the current investigation.[1]

Aerobic fitness was represented by the number of laps run on the 20 meter Progressive Aerobic Cardiovascular Endurance Run (PACER) subtest of the FitnessGram®. Additional demographic variables that were collected included: BMI (kg/m^2), age, grade, sex (coded as 0 = female, 1 = male), household income (coded as 1: < $10,000 per year, through 11: > $100,000 per year, with $10,000 increments), and mother's level of education (coded as 1–6: less than high school; some high school; completed high school; some college/associate's degree; bachelor's degree; advanced degree). Change scores for BMI, aerobic fitness, and cognitive variables were calculated by subtracting T1 from T2. Since changes in fitness

[1]A total of 424 children completed testing at both time points. Children were excluded from the current analyses due to reported ADHD, dyslexia, or a learning disability (n = 31). Participants were also excluded from the current analyses if their average flanker performance was below chance (i.e., 50%) across compatible and incompatible conditions (n = 75), or if their mean d' score was ≤ 0 across 1- and 2-back conditions (n = 28) at either T1 or T2.

(Δfitness) and cognitive performance were the primary outcome measures in the current investigation, independent t-tests were conducted to analyze whether children in the control and intervention groups differed on any of the included variables. Preliminary analyses revealed no significant differences as a function of the intervention in fitness level (at either T1 or T2), Δfitness, or any demographic factors, t's(288) ≤ 1.7, p's ≥ .10, except household income (intervention: M = 7.8, SE = 0.3; control: M = 6.8, SE = 0.3), $p = .003$. Additionally, inclusion of a group factor (i.e., control vs. intervention) in the regression analyses were non-significant, p's ≥ .13, and did not moderate any of the observed relationships between changes in fitness and cognitive performance reported in the findings. As such, children were collapsed across groups in the final set of analyses reported in the Results section.

Procedure

During the cognitive protocol (~ 15 min. per task) children were tested on an individual basis in a quiet environment free of distractions (e.g., an empty classroom or conference room) using a laptop and handheld response pad (model: TR-1×4-CR; Current Designs Inc., Philadelphia, PA) in their school's provided testing space. Research staff were trained and supervised by a qualified co-investigator. At each time point, testing was completed over the course of two separate days with fitness and cognitive assessments always occurring on separate days. Due to the limited time constraints for cognitive testing, staff were unable to complete testing at the same time of day for all children. However, when time of testing (coded as 1: 8:00 – 10:30am; 2: 10:30am – 1:00pm; 3: 1:00 – 3:30pm) was included in the final regression analyses, it held a non-significant relationship with all of the reported outcomes.

Aerobic Fitness Assessment

The PACER test was administered at each school in small groups (8–12 students) with a 1:3 staff to child ratio, and an additional staff member supervising the testing. During testing, children were instructed to run back and forth between two lines, spaced 20-meters apart, and were paced by a tone signaling the time at which students must reach the opposite side. The pace began slowly and became progressively faster until each child was unable to traverse the 20-meter distance on two separate occasions, at which point the test ended (Welk & Meredith, 2008). Higher levels of fitness are denoted by a greater number of completed laps. The PACER was used over other measures of aerobic fitness due to the ability to collect data in multiple participants at once, thereby facilitating data collection in the large sample of children. There is also considerable work in adults and children (Léger & Lambert, 1982; Léger, Mercier, Gadoury, & Lambert, 1988; Mahar, Guerieri, Hanna, Kemble, 2011) detailing the high reliability and validity of the PACER, which has been administered worldwide and in children as young as 6 years old (Olds, Tomkinson, Léger, & Cazorla, 2006).

Cognitive Control Tasks

Flanker—Cognitive assessment began with administration of a modified Eriksen flanker task to assess inhibitory control (masked for review). This version required participants to make a thumb press, as quickly and accurately as possible, according to the direction (i.e., left or right) of a centrally presented "goldfish". Each goldfish was accompanied by lateral flanking goldfish that either matched (i.e., congruent trials), or mismatched (i.e., incongruent trials) directionality. Children first completed a compatible stimulus-response condition (e.g., right target goldfish required a right thumb response), and were then introduced to an incompatible stimulus-response condition wherein the response-mappings were reversed (e.g., right target goldfish required a left thumb response). Stimuli were 2 cm tall yellow goldfish presented focally for 200 ms on a light blue background with a fixed inter-stimulus interval (ISI) of 1700 ms. Prior to testing, children received a 40-trial practice block and were allowed to ask questions before completing a 100-trial block in both compatibility conditions. Each block was evenly divided among congruent and incongruent trials with equiprobable directionality of the central target stimulus. In addition to measuring reaction time (RT) and accuracy for each trial type, interference scores were calculated within each compatibility condition by subtracting incongruent from congruent accuracy, and congruent from incongruent RT. Thus, larger and more positive scores indicate greater interference (i.e., poorer performance) as cognitive demand increased.[2]

***n*-back—**Following the flanker task, participants completed a modified version of a spatial *n*-back task (all participants completed the same testing order; masked for review) to examine variable demands in working memory. The display screen consisted of six white-framed 4 × 4 cm boxes 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 pseudo-randomly inside one of the six boxes (i.e., "Tab" appeared in each box an equal number of times, but order of presentation was randomized). 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 (i.e., target trials). In both conditions, participants were also instructed to press the left button when Tab appeared in any of the other five locations (i.e., correct rejection of nontarget trials). Errors of commission were deemed "false alarms" when participants incorrectly identified a nontarget trial with a right button press, and a "miss" when target trials resulted in a left button response. Prior to completion of each condition, participants received 30 practice trials that were administered using the same task parameters as the larger test blocks, which each consisted of 72 total trials. That is, all trials were presented for 250 ms at a fixed ISI of 2500 ms, with target trials presented at 33.3% probability in each condition. Measures of RT and accuracy were collected for both target and nontarget trials during the 1- and 2-back conditions, in addition to false alarm rate. To provide an index of children's target discrimination performance, d' scores were calculated as z(adjusted target accuracy) – z(adjusted false alarm rate) in accordance with the formula provided by Sorkin (1999). Larger (positive) values of d' indicate an increased ability to accurately detect target from nontarget stimuli, with a score of 0 reflecting chance level performance (Dawkins, Powell, West, Powell, & Pickering, 2007; Sorkin, 1999).

[2]For analyzing changes in flanker interference, change scores were calculated by subtracting T2 from T1 considering larger interference scores were expected at T1 due to greater task difficulty at younger ages. Thus, larger positive change scores indicated greater reductions in interference (i.e., better performance) over time.

Statistical Analysis

Analyses were conducted using SPSS v.21 (IBM Corp., Armonk, NY) and significance levels were set at $p = .05$. Children's flanker performance was also investigated across time using separate 2 (Time: T1 and T2) × 2 (Compatibility: compatible and incompatible conditions) × 2 (Congruency: congruent and incongruent trials) repeated measures analysis of variance (RM-ANOVA) for RT and accuracy. Flanker RT and accuracy interference scores were entered separately into a 2 (Time) × 2 (Compatibility) analysis. As for the *n*-back task, RT and accuracy were separately entered in a 2 (Time) × 2 (Trial: target and nontarget) RM-ANOVA for both 1- and 2-back conditions. False alarm rate and d' scores were compared across time within each condition. Post-hoc comparisons were conducted using paired-samples *t*-tests and Bonferroni correction. Cohen's *d* is reported to indicate effect size.

Pearson correlations were conducted among all demographic variables and dependent cognitive measures at each time point to identify potential demographic predictors that warranted inclusion in Step 1 of the hierarchical regression analyses. To assess the unique contribution of fitness, the number of PACER laps was entered in Step 2. When changes in cognition were regressed on Δfitness, baseline fitness and cognitive performance were included in Step 1 along with any significant T2 demographic variables. Assumptions of independent errors, homoscedasticity of the residual terms, and normally distributed errors were plotted, inspected, and verified using studentized residuals. There were no concerns of multicollinearity as evidenced by variance inflation factors remaining ≤ 1.4.

Results

Bivariate Correlations

Pearson correlations (all p's < .05) indicated that aerobic fitness was positively related to age ($r = .20$) and grade ($r = .23$) at T1, in addition to sex ($r \geq .16$) and household income ($r \geq .19$) at both time points. Fitness was negatively related to BMI ($r \geq -.28$) at both time points. Thus, children who were male, older, lived in higher income households, and had lower BMI values tended to be higher fit. Males also demonstrated larger Δfitness ($r = .24$). Upon inspection of demographic correlations with the cognitive outcomes at each time point, grade exhibited stronger associations than age, whereas mother's level of education was more strongly related to the cognitive measures compared to household income. To avoid issues of multicollinearity in the regression models, grade (instead of age, $r = .90$) and mother's level of education (instead of household income, $r = .51$) were included in Step 1 of the regression analyses in addition to sex and BMI at each respective time point. Additional regression analyses were conducted in which household income, hand dominance, and school district (to account for clustering) were separately included in Step 1. None of the factors were significant in the model, nor did they influence any of the fitness/cognition relationships reported below.

Cognitive Performance over Time

Flanker

Reaction time: The RM-ANOVA for flanker RT revealed main effects of Time, F(1, 289) = 267.0, $p < .001$, $\eta^2 = .48$, Compatibility, F = 176.4, $p < .001$, $\eta^2 = .38$, and Congruency, F = 316.8, $p < .001$, $\eta^2 = .52$, which were superseded by interactions of Time × Compatibility, F = 7.2, $p < .01$, $\eta^2 = .02$, and Compatibility × Congruency, F = 9.7, $p < .01$, $\eta^2 = .03$. The Time × Compatibility post-hoc comparisons indicated that RTs were shorter in the compatible condition compared to the incompatible condition at both time points, *t*'s(289) ≥ 9.4, *p*'s ≤ .001, *d*'s ≥ 0.4 (see Figure 1a). RTs in the compatible and incompatible conditions were also shorter at T2 compared to T1, *t*'s ≥ 13.3, *p*'s ≤ .001, *d*'s ≥ 0.9. Decomposition of the Compatibility × Congruency interaction further revealed that congruent trials resulted in shorter RTs compared to incongruent trials in both compatibility conditions, *t*'s ≥ 10.6, *p*'s ≤ .001, *d*'s ≥ 0.2. Lastly, analysis of flanker RT interference scores indicated a significant main effect of Compatibility, F = 9.7, $p < .01$, $\eta^2 = .03$, such that RT interference was greater in the compatible compared to the incompatible condition, $d = 0.3$ (see Figure 1b).

Accuracy: The results for flanker accuracy revealed main effects of Time, F = 335.2, $p < .001$, $\eta^2 = .54$, and Congruency, F = 476.0, $p < .001$, $\eta^2 = .62$, as well as interactions of Compatibility × Congruency, F = 126.9, $p < .001$, $\eta^2 = .31$, and Time × Compatibility × Congruency, F = 19.7, $p < .001$, $\eta^2 = .06$. Separate Compatibility × Congruency RM-ANOVA's at each time point yielded significant interactions, F's ≥ 25.6, *p*'s ≤ .001, η^2's ≥ .08. The Compatibility × Congruency decomposition at T1 indicated that accuracy was higher for congruent compared to incongruent trials in both compatibility conditions, *t*'s ≥ 4.1, *p*'s ≤ .001, *d*'s ≥ 0.2 (see Figure 1c). However, whereas congruent trial accuracy was greater in the compatible versus incompatible condition, $t = 3.8$, $p < .001$, $d = 0.2$, incongruent trial accuracy was greater in the incompatible versus the compatible condition, $t = 4.1$, $p < .001$, $d = 0.2$. The Compatibility × Congruency decomposition at T2 exhibited the same trends as T1, *t*'s ≥ 4.6, *p*'s ≤ .001, *d*'s ≥ 0.2, except there was no difference between incongruent trials across compatibility conditions, $t = 0.2$, $p = .829$. Each trial type was also separately compared across time, which confirmed that accuracy was higher at T2 for all trial types, *t*'s ≥ 11.2, *p*'s ≤ .001, *d*'s ≥ 0.8. Lastly, the RM-ANOVA for flanker accuracy interference indicated a significant main effect of Compatibility, F = 126.9, $p < .001$, $\eta^2 = .30$, and an interaction of Time × Compatibility, F = 19.7, $p < .001$, $\eta^2 = .06$. Decomposition of the interaction confirmed that accuracy interference was higher during the compatible condition compared to the incompatible condition at both time points, *t*'s ≥ 5.1, *p*'s ≤ .001, *d*'s ≥ 0.4 (see Figure 1d). However, while accuracy interference was higher in the compatible condition at T1 compared to T2, $t = 2.7$, $p < .01$, $d = 0.2$, interference during the incompatible condition was higher at T2, $t = 3.2$, $p < .01$, $d = 0.3$.

n-back

Reaction time: The RM-ANOVA for 1-back RT revealed main effects of Time = 63.9, $p < .001$, $\eta^2 = .18$, and Trial, F = 253.1, $p < .001$, $\eta^2 = .47$, which were superseded by an interaction of Time × Trial, F = 9.6, $p < .01$, $\eta^2 = .03$. Post-hoc comparisons demonstrated that nontarget trials resulted in longer RTs compared to target trials at both time points, *t*'s ≥

10.6, *p*'s ≤ .001, *d*'s ≥ 0.4 (see Figure 2a). Comparisons across time further indicated that both trial types exhibited longer RTs at T1, *t*'s ≥ 6.7, *p*'s ≤ .001, *d*'s ≥ 0.5. The RM-ANOVA for 2-back RT revealed a main effect of Trial, F = 26.0, $p < .001$, $\eta^2 = .08$, indicating that nontarget trials elicited longer RTs than target trials at both time points, *d*'s ≥ 0.2.

Accuracy: Results for 1-back accuracy revealed main effects of Time = 53.5, $p < .001$, $\eta^2 = .16$, and Trial, F = 635.2, $p < .001$, $\eta^2 = .69$, which indicated that overall accuracy was greater at T2 compared to T1, $t = 7.3$, $p < .001$, $d = 0.5$ (see Figure 2b), and that nontarget trials resulted in higher accuracy than target trials, $t = 25.2$, $p < .001$, $d = 1.4$. As for 2-back accuracy, the RM-ANOVA exhibited main effects of Time = 208.6, $p < .001$, $\eta^2 = .42$, and Trial, F = 110.2, $p < .001$, $\eta^2 = .28$, which mirrored the effects observed with 1-back accuracy. Thus, overall accuracy was greater at T2 compared to T1, $t = 14.4$, $p < .001$, $d = 1.1$, and for nontarget compared to target trials, $t = 10.5$, $p < .001$, $d = 0.8$.

False alarm rate & d′: Separate RM-ANOVA's for 1- and 2-back false alarm rate and *d′* yielded significant main effects of Time, F's ≥ 4.8, *p*'s ≤ .03, η^2's ≥ .02. These effects revealed that false alarm rates were lower at T2 compared to T1 for both 1- and 2-back conditions, *d*'s ≥ 0.2 (see Figure 2c), and that *d′* scores were higher at T2 compared to T1 for both conditions, *d*'s ≥ 0.5 (see Figure 2d).

Regression Analyses

Due to the *a priori* interests of the current investigation, only results exhibiting significant effects of fitness or Δfitness are reported below.

Flanker—Table 2 provides a summary of the flanker regression analyses for the observed fitness findings. At T1, higher fit children exhibited shorter RTs for each trial type in both compatibility conditions (partial correlation: [*pr*'s] ≥ −.16). Additionally, males had shorter RTs (β's ≥ −.13, *p*'s ≤ .03) for all trial types except incongruent trials in the incompatible condition. Children in higher grade levels also demonstrated shorter RTs for all trial types (β's ≥ −.22, *p*'s ≤ .001). At T2 higher fit children demonstrated superior accuracy for incongruent trials in the compatible condition ($pr = .17$). Females ($\beta > -.17$, $p < .01$) and children in higher grade levels ($\beta > .14$, $p < .02$) also demonstrated higher accuracy. Further, higher fit children ($pr = -.14$) and females exhibited less accuracy interference ($\beta > .15$, $p < .02$) only during the compatible condition (the condition eliciting greater overall interference at T1 and T2).

***n*-back—**Table 3 provides the *n*-back regression analyses with the observed fitness findings. At T1, higher fit children had greater target and nontarget accuracy in both 1-and 2-back conditions, in addition to larger *d′* scores (*pr*'s ≥ .15). Mother's level of education was also positively related to accuracy performance for all trials (β's ≥ .13, *p*'s ≤ .03) except 2-back nontarget trials. Lastly, children in higher grade levels exhibited greater accuracy for 2-back nontarget trials ($\beta = .21$, $p = .001$). At T2 higher fit children demonstrated better performance on target and nontarget trials for the 2-back condition only, as well as superior *d′* scores (*pr*'s ≥ .12). Higher fit children also had lower false alarm rates in the 2-back condition ($pr = -.15$). Furthermore, mother's level of education was positively related to target accuracy and d' scores in the 2-back condition (β's ≥ .15, p's ≤ .02).

Changes in Cognition—Increases in aerobic fitness over the three year period were positively related to larger changes in flanker accuracy for incongruent trials in the compatible condition ($pr = .17$, see Table 2), and greater reductions in compatible accuracy interference ($pr = .15$, see Table 2). Females also exhibited greater positive changes in accuracy for incongruent trials in the compatible condition ($\beta = -.11$, $p < .02$), as well as larger reductions in compatible accuracy interference ($\beta = -.10$, $p < .02$). Children in higher grade levels ($\beta = .11$, $p < .02$) demonstrated greater improvements in accuracy for incongruent trials in the compatible condition. Lastly, a positive relationship was observed between larger increases in fitness and 2-back d' scores ($pr = .15$, see Table 3).

Discussion

The current study examined the relationship between changes in children's aerobic fitness and aspects of cognitive control that have been previously shown to support academic performance. As hypothesized, higher fit children demonstrated better inhibitory control and working memory performance at both time points, particularly for task conditions eliciting greater cognitive demand. Higher fit children demonstrated overall shorter flanker RT at T1, whereas superior incongruent accuracy and less interference were observed at T2. Similarly, higher fitness levels were related to superior working memory accuracy and target discrimination in both 1- and 2-back conditions at T1, yet this effect was only observed for the more difficult 2-back condition at T2. Critically, larger increases in fitness over the three year period were related to greater improvements in flanker incongruent accuracy, larger reductions in compatible accuracy interference, and increased 2-back target discrimination, even after controlling for baseline task performance, fitness level, and other significant demographic factors. It should also be mentioned that the current findings align closely with previous studies investigating the impact of socio-demographic variables on children's cognitive control, such that older participants and males exhibited shorter flanker RT at T1 (Mezzacappa, 2004), yet it was interesting to note that females demonstrated greater changes in flanker accuracy over the three year period. Further, superior working memory performance was witnessed among more socially advantaged children (i.e., higher parental education status), which is also consonant with previous research (see Hackman & Farah, 2009, for review). Although the current study does not permit a mechanistic account for these socio-demographic influences, it is encouraging that the current measures produce a well-replicated pattern of results that are consistent among the wider literature. Most importantly, the significant findings highlight the necessity of including and controlling for such variables when investigating the relationship between aerobic fitness and cognitive performance.

Tracking the development of children's inhibitory control has received ample attention and is well-documented within the literature (Davidson, Amso, Andersen, & Diamond, 2006). This work has revealed that children of similar age to those in the current study experience considerable difficultly regulating such processes, and that the development and refinement of inhibitory control continues well into adolescence and young adulthood (Diamond, 2013).

Accordingly, it was intriguing to note the similarity between age-related trends of inhibitory control documented in previous work (Davidson et al., 2006; Luna, 2009), and those observed in the current study with respect to aerobic fitness. That is, previous studies have generally noted that early in development children increase the rate of correct inhibitory responses, but not necessarily the number of correct responses (Luna, 2009). As mentioned earlier, higher aerobic fitness levels at T1 were associated with overall shorter flanker RT, yet approximately three years later higher aerobic fitness levels were related to greater accuracy for incongruent trials in the compatible condition, as well as lower accuracy interference. These findings are consonant with previous fitness studies that have revealed selective benefits for flanker conditions engendering greater amounts of cognitive control (Chaddock et al., 2012; Hillman et al., 2014; Pontifex et al., 2011; Voss et al., 2011). As depicted in Figure 1, incongruent trials resulted in lower accuracy across both compatibility conditions at each time point, which indicated a need for elevated inhibitory control to ensure accurate performance. Similarly, interference scores for both accuracy and RT were greater in the compatible condition at both time points despite a general overall delay in RT during the incompatible condition. As such, a shift in global conflict elicited by the incompatible response manipulation may have caused children to adopt a general slowing-strategy to maintain accuracy; or conversely, the heighted response conflict may have triggered additional strategic control processes to facilitate overall correct responding (Bartholow et al., 2005).

Another primary outcome of the current study was that increases in aerobic fitness were related to greater improvements in compatible incongruent accuracy, which likely accounted for the observed fitness effect of larger reductions in compatible accuracy interference. These findings corroborate earlier work investigating changes in fitness and cognition, and are among the first depicting this relationship using a field test of aerobic fitness. Hillman et al. (2014) recently showed that children who demonstrated greater improvements in aerobic fitness following participation in a 9-month after-school PA program exhibited not only larger increases in flanker accuracy, but also greater increases in amplitude of the P3 event-related brain potential (a neural index of attention) for incongruent trials only. Although not specifically addressed in the current study, previous research has highlighted a number of other fitness-related differences with regards to brain structure/function that may account for the observed behavioral patterns. For example, Chaddock et al. (2010b) used magnetic resonance imaging (MRI) to reveal that more aerobically fit children had greater volumes of the dorsal striatum compared to lower fit individuals, and that this difference was associated with reduced behavioral interference during flanker performance. Similar work using functional MRI (fMRI) and the flanker task has revealed that higher and lower fit children demonstrate differential patterns of brain activation among regions involved in the top-down modulation of cognitive control, including the lateral anterior prefrontal cortex and the cingulo-opercular network. Interestingly, activation patterns were only associated with behavioral performance in the higher fit group, which may reflect the engagement of proactive (vs. reactive) cognitive control strategies to ensure optimal performance (Voss et al., 2011). Despite these differences, additional research will be necessary to fully elucidate the relationship between actual changes in children's aerobic fitness and cognitive performance, as opposed to comparing group differences between children residing at the highest and lowest fitness percentiles. However, the consistent finding of a select positive association between fitness and task conditions with elevated cognitive demand has important implications for designing and utilizing appropriate tasks in this area of research.

Similar to children's inhibitory control, the ability to manipulate and maintain larger amounts of information in working memory exhibits prolonged developmental progression (Diamond, 2013). Such a pattern was revealed in children's *n*-back performance, which demonstrated improvements (i.e., shorter RT, higher accuracy, fewer false alarms, and larger d' scores) from T1 to T2 for both 1- and 2-back conditions. It was also evident that the 2-back condition successfully engendered the greatest working memory demands, as indicated by lower performance at both time points. Consonant with the flanker results, the relationship between higher aerobic fitness and better working memory performance was observed primarily in the more demanding (2-back) condition. Analyses further revealed that increases in fitness were associated with greater improvements in target discrimination only for the more-difficult 2-back condition, which are among the first results to demonstrate a beneficial effect of aerobic fitness on measures of spatial working memory. Previous work incorporating brain-imaging methods have indicated that higher fit children exhibit greater bilateral hippocampal volume and better relational/associative memory performance compared to their lower fit peers (Chaddock et al., 2010a), thereby providing a potential mechanistic account for the current findings. Similar to the pattern of results in Voss et al. (2011), developmental fMRI studies have also shown that greater activation of the superior frontal and intraparietal cortex is observed with increasing age, and that such activation is related to better visuospatial working memory; however, measures of aerobic fitness were not included (Klingberg, Forssberg, & Westerberg, 2002). Accordingly, a limited number of investigations makes it difficult to determine if aerobic fitness is related to global improvements in memory performance, or associated with the selective demands of specific memory domains. It will be important for future studies to include multiple indices of memory performance to further dissociate the underlying factors that are responsible for beneficial associations between aerobic fitness and aspects of memory.

While the current study provides an important and unique perspective of the relation between changes in fitness and cognitive performance using well-established cognitive control measures, one of the limitations is a lack of academic achievement tests for further comparison. However, one of the weaknesses of standardized achievement tests is that they usually entail several aspects of cognition, thus not allowing for an understanding of individual aspects of cognitive control (i.e., inhibition, working memory, etc.). Still, there is considerable evidence throughout the literature indicating that aspects of cognitive control play a vital role in promoting academic success and school readiness (Diamond, Barnett, Thomas, Munro, 2007), and predict a number of beneficial health and economic outcomes in adulthood (Moffitt et al., 2011). Due to the limited amount of time allocated towards cognitive testing in the current study, measures of cognitive flexibility were not included, and therefore future investigations should include these measures to provide a more comprehensive understanding regarding other important aspects of cognitive control. Further, the sample of children included in study was predominately Caucasian, which prevents an account of how aerobic fitness levels or changes in fitness might influence cognitive performance across more diverse populations of children. Considering previous work using the flanker task has highlighted behavioral differences among select groups of ethnic/racial identification (Mezzacappa, 2004), future investigations will want to include children across a wide range of ethnic backgrounds to provide greater ecological validity regarding the benefits of increases in aerobic fitness for cognitive performance. Lastly, measures of children's extracurricular and habitual physical activity levels were not measured in the current study; thus, the potential reasons why individual children exhibited increased/decreased aerobic fitness levels remain unknown.

In conclusion, the current findings are in agreement with a growing number of reports that have revealed a beneficial relationship between increases in aerobic fitness and improvements in children's cognitive performance; however, the use of regression-based analyses as opposed to reporting group-wide differences was a novel contribution to the literature. Given that the development of cognitive control unfolds rapidly and progresses well into young adulthood, one might predict that the positive association between aerobic fitness and cognition would change with maturation and the shifting of cognitive demands/ strategies, as witnessed in the current investigation. Therefore, additional longitudinal studies tracking these relationships throughout adolescence are needed, specifically those collecting multiple, well-established measures of cognitive control. Future PA interventions may also want to focus on engaging participants in activities that are sufficient in both duration and intensity for producing significant increases in aerobic fitness level (Kriemler et al., 2011). Such findings will have important implications for structuring the school curriculum to not only help students improve their physical health, but also promote aspects of cognitive performance and brain function to support greater academic success.

Acknowledgments

Funding Source: This study was supported by a grant from the National Institutes of Health masked for review.

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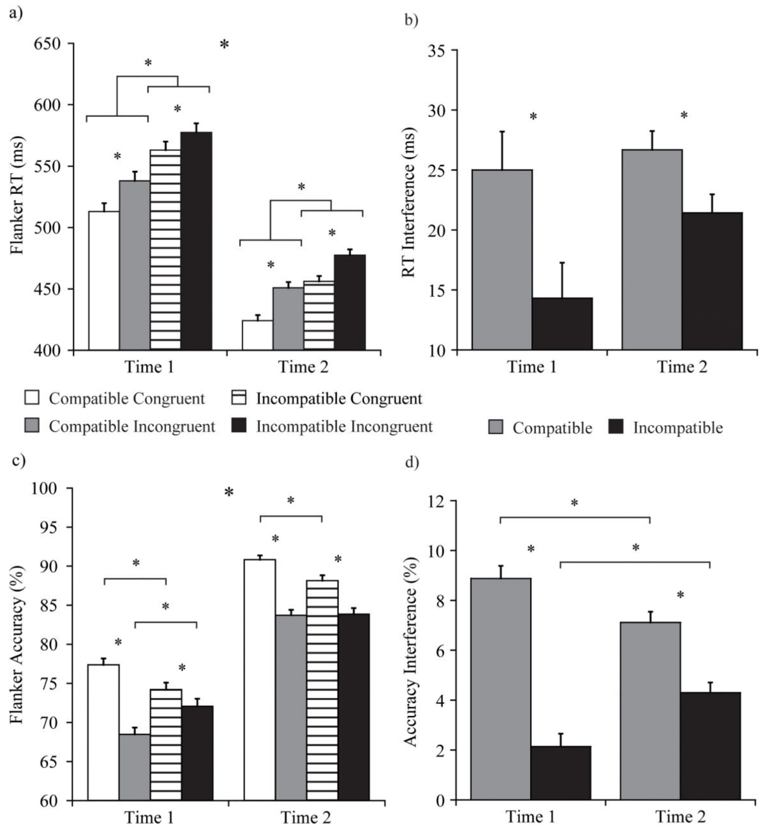

Figure 1.

a) Despite overall shorter RT at T2, similar trends were observed at each time point such that congruent trials resulted in shorter RT compared to incongruent trials in both compatibility conditions, and RT was shorter overall in the compatible condition. b) RT interference (incongruent - congruent RT) was greater in the compatible compared to the incompatible condition at both time points. c) Overall accuracy was higher at T2, yet similar trends were witnessed at each time point such that congruent trials resulted in greater accuracy compared to incongruent trials for each compatibility condition. However, congruent trial accuracy decreased in the incompatible (vs. compatible) condition at both time points, whereas incongruent accuracy increased at T1, and remained level at T2. d) Accuracy interference (congruent-incongruent accuracy) was larger in the compatible condition compared to the incompatible condition at both time points. Compatible interference decreased over time whereas incompatible interference increased.

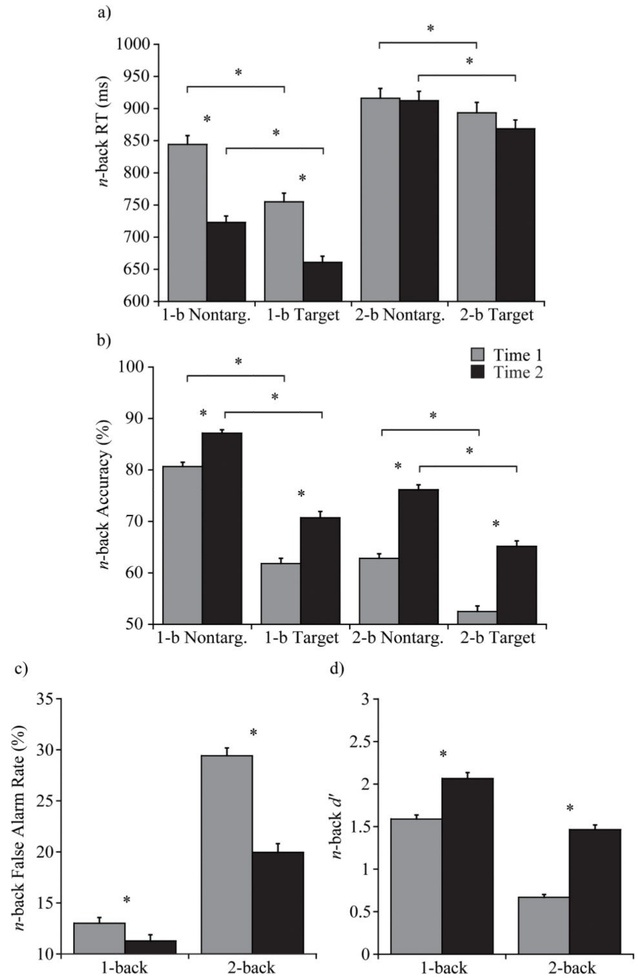

Figure 2.

a) Target trials resulted in shorter RT compared to nontarget trials for both 1- and 2-back conditions at each time point. However, RT was lower at T2 compared to T1 for both trial types in the 1-back condition only. b) Target trials also resulted in lower accuracy for both 1- and 2-back conditions at each time point. Accuracy was greater for all trial types at T2. c) False alarm rates decreased over time in both 1- and 2-back conditions. d) d' scores increased over time in both conditions.

Table 1

Mean (SE) Values for Participant Demographics (N = 290).

Measure	Time 1	Time 2	Change
Age (year)	8.1 (0.04)	10.6 (0.04)	2.5 (0.01) *
Height (cm)	129.9 (0.4)	145.2 (0.4)	15.3 (0.1) *
Weight (kg)	30.0 (0.4)	41.3 (0.6)	11.3 (0.3) *
BMI (kg/m^2)	17.6 (0.2)	19.4 (0.2)	1.8 (0.1) *
BMI Percentile	39.7 (1.5)	38.7 (1.6)	−1.0 (0.8)
Fitness (# of PACER laps)	16.7 (0.5)	25.1 (0.7)	8.4 (0.6) *
Sex (% female)	175 (60.3)	-	-
Mother’s Education	4.7 (0.1)	-	-
Household Income	7.4 (0.2)	-	-
Grade, *n* (%)			
Grade 2/4 (T1/T2)	145 (50)	-	-
Grade 3/5 (T1/T2)	145 (50)	-	-
Race, *n* (%)			
White/Caucasian	232 (80.0)	-	-
Black/African American	8 (2.8)	-	-
Native Hawaiian/Pacific	1 (0.3)	-	-
Asian	7 (2.4)	-	-
American Indian/Alaska	4 (1.4)	-	-
Two or more races	30 (10.3)	-	-
Refused/unknown	8 (2.8)	-	-

Note:

* $p \leq .001$. Data are presented as mean (SE) unless noted otherwise.

BMI – Body mass index; PACER – Progressive Aerobic Cardiovascular Endurance Run; Household Income was coded as 1: < $10,000 per year, through 11: > $100,000 per year, with $10,000 increments; and Mother’s Education was coded as 1 – 6: less than high school, some high school, completed high school, some college/associate’s degree, bachelor’s degree, advanced degree.

Table 2

Flanker Regression Values for Fitness at Time 1 & 2 (T1/T2), and ΔFitness.

Variable	Step 1 R^2	Step 2 ΔR^2	*B*	*SE B*	β	*t*
T1 Compatible Congruent RT	.076**	.036**	−2.74	0.81	−.21	−3.4
T1 Compatible Incongruent RT	.070**	.032**	−2.86	0.90	−.20	−3.2
T1 Incompatible Congruent RT	.102**	.028**	−2.52	0.83	−.19	−3.0
T1 Incompatible Incongruent RT	.111**	.023**	−2.38	0.87	−.17	−2.7
T2 Compatible Incongruent Accuracy	.056**	.027**	0.18	0.06	.20	2.9
T2 Compatible Accuracy Interference	.027	.019*	−0.10	0.04	−.16	−2.4
Δ Comp. Incong. Acc. (ΔFitness)	.531**	.013**	0.21	0.08	.13	2.8
Δ Comp. Acc. Interference (ΔFitness)	.566**	.009*	0.12	0.05	.11	2.5

Note:

* $p \leq .05$,

** $p \leq .01$. Demographic variables were included in Step 1 (grade, sex, mother's education, BMI), and fitness (i.e., PACER laps) was entered in Step 2. Baseline fitness and cognitive performance were also entered in Step 1 when analyzing change (Δ) in fitness.

BMI – Body mass index; PACER – Progressive Aerobic Cardiovascular Endurance Run.

Table 3

n-back Regression Values for Fitness at Time 1 & 2 (T1/T2), and ΔFitness.

Variable	Step 1 R^2	Step 2 ΔR^2	*B*	*SE B*	β	*t*
T1 1-back Target Accuracy	.036**	.027**	.356	.124	.18	2.9
T1 1-back Nontarget Accuracy	.030	.031**	.315	.103	.20	3.1
T1 1-back *d′*	.032	.032**	.018	.006	.20	3.1
T1 2-back Target Accuracy	.033*	.021*	.333	.133	.16	2.5
T1 2-back Nontarget Accuracy	.044**	.032**	.338	.108	.20	3.1
T1 2-back *d′*	.048**	.046**	.015	.004	.24	3.8
T2 2-back Target Accuracy	.041*	.034**	.325	.101	.22	3.2
T2 2-back Nontarget Accuracy	.034*	.014*	.192	.093	.14	2.1
T2 2-back False Alarm Rate	.042*	.021*	−.201	.080	−.17	−2.5
T2 2-back *d′*	.052**	.052**	.021	.005	.27	4.0
Δ 2-back *d′* (ΔFitness)	.107**	.020*	.015	.006	.16	2.5

Note:

* $p \leq .05$,

** $p \leq .01$. Demographic variables were included in Step 1 (grade, sex, mother's education, BMI), and fitness (i.e., PACER laps) was entered in Step 2. Baseline fitness and cognitive performance were also entered in Step 1 when analyzing change (Δ) in fitness.

BMI – Body mass index; PACER – Progressive Aerobic Cardiovascular Endurance Run.