

Exercise Improves Executive Function and Achievement and Alters Brain

Activation in Overweight Children: A Randomized, Controlled Trial

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Objective: This experiment tested the hypothesis that exercise would improve executive function.

Design: Sedentary, overweight 7- to 11-year-old children (N = 171, 56% girls, 61% Black, M SD age = 9.3 ± 1.0 years, body mass index [BMI] = 26.4 ± 4.6 kg/m², BMI z-score = 2.1 ± 0.4) were randomized to 13 ± 1.6 weeks of an exercise program (20 or 40 min/day), or a control condition.

Main Outcome Measures: Blinded, standardized psychological evaluations (Cognitive Assessment System and Woodcock-Johnson Tests of Achievement III) assessed cognition and academic achievement. Functional MRI measured brain activity during executive function tasks. **Results:** Intent to treat analysis revealed dose-response benefits of exercise on executive function and mathematics achievement. Preliminary evidence of increased bilateral prefrontal cortex activity and reduced bilateral posterior parietal cortex activity attributable to exercise was also observed. **Conclusion:** Consistent with results obtained in older adults, a specific improvement on executive function and brain activation changes attributable to exercise were observed. The cognitive and achievement results add evidence of dose-response and extend experimental evidence into childhood. This study provides information on an educational outcome. Besides its importance for maintaining weight and reducing health risks during a childhood obesity epidemic, physical activity may prove to be a simple, important method of enhancing aspects of children's mental functioning that are central to cognitive development. This information may persuade educators to implement vigorous physical activity.

Keywords: cognition, aerobic exercise, obesity, antisaccade, fMRI

Executive function appears more sensitive than other aspects of cognition to aerobic exercise training (Colcombe & Kramer, 2003). Executive function constitutes supervisory control of cognitive functions to achieve a goal and is mediated via prefrontal cortex circuitry. Planning and carrying out action sequences that make up goal directed behavior requires allocation of attention and memory, response selection and inhibition, goal setting, self-control, self-monitoring, and skillful and flexible use of strategies (Eslinger, 1996; Lezak, Howieson, & Loring, 2004). The executive function hypothesis was proposed based on evidence that aerobic exercise selectively improves older adults' performance on executive function tasks and leads to corresponding increases in prefrontal cortex activity (Colcombe et al., 2004; Kramer et al., 1999). Children's cognitive and neural development may be sensitive to physical activity (Diamond, 2000; Hillman, Erickson, & Kramer, 2008; Kolb & Whishaw, 1998). Theoretical accounts of the links between motor behavior

and cognitive development during childhood have ranged from hypothesized brain networks to the construction of perception-action representations (Rakison & Woodward, 2008; Sommerville & Decety, 2006). A meta-analysis of exercise studies in children showed improved cognition with exercise; however, randomized trial results were inconsistent (Sibley & Etnier, 2003). A selective effect of exercise on executive function may explain mixed experimental results obtained in children (Tompsonowski, Davis, Miller, & Naglieri, 2008). Studies utilizing cognitive tasks requiring executive function showed benefits of exercise (Davis et al., 2007; Tuckman & Hinkle, 1986), while those using less sensitive measures did not (Lezak et al., 2004, pp. 36, 611–612; e.g., Ismail, 1967; Zervas, Apostolos, & Klissouras, 1991). A preliminary report from this Accepted under the editorial term of Robert M. Kaplan.

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study, with a smaller sample, showed a benefit of exercise on executive function (Davis et al., 2007). The final results are presented here. In children, vigorous physical activity has been associated with better grades (Coe, Pivarnik, Womack, Reeves, & Malina, 2006; Taras, 2005), physical fitness with academic achievement (Castelli, Hillman, Buck, & Erwin, 2007; Dwyer, Sallis, Blizzard, Lazarus, & Dean, 2001; Wittberg, Northrup, Cottrell, & Davis, 2010), and overweight with poorer achievement (Castelli et al., 2007; Datar, Sturm, & Magnabosco, 2004; Dwyer et al., 2001; Shore et al., 2008; Taras & Potts-Datema, 2005). The strongest conclusion to be drawn regarding the effect of physical activity on academic achievement, however, is that it does not impair achievement, even when it takes away classroom time (Dwyer, Coonan, Leitch, Hetzel, & Baghurst, 1983; Sallis et al., 1999; Shephard et al., 1984). Because overweight is a marker of chronic inactivity (Must & Tybor, 2005), overweight, sedentary children may be more likely to benefit from exercise than lean children. The primary hypothesis of this study was that sedentary, overweight children assigned to exercise would improve more than children in a control condition on executive function, but not other cognitive processes such as resistance to distraction, spatial and logic processes, and sequencing. A secondary hypothesis was that a dose-response relation would be observed between exercise and cognition. Effects on academic achievement were explored. Based on previous studies in adults showing exercise related changes in brain function, effects on activity in prefrontal cortex circuitry were explored using functional MRI (fMRI) in a subgroup of participants.

Method

Main Study Participants. Students were recruited from schools during 2003–2006 for a trial of aerobic exercise on children's health. Children were eligible if they were overweight (85th percentile body mass index [BMI]; Ogden et al., 2002), inactive (no regular physical activity program—1 hr/wk), and had no medical condition that would affect study results or limit physical activity. One hundred seventyone

children 7–11 years of age were randomized (56% female, 61% Black, 39% White, M SD age 9.3 1.0 years, BMI 26.0 4.6 kg/m², BMI z-score 2.1 0.4, parent (i.e., primary caregiver) education level 5.0 1.1, where 1 less than 7th grade, 2 8th or 9th, 3 10th or 11th, 4 high school graduate, 5 some college, 6 college graduate, 7 postgraduate). One child was excluded from posttest because of a psychiatric hospitalization that occurred after randomization. Children were encouraged to posttest regardless of adherence to the intervention. Eleven children taking medication for attention deficit disorder were included (and took their medication as usual; n 4 in control, n 4 in low-dose, and n 3 in high-dose group) to maximize generalizability. Children and parents completed written informed assent and consent. The study was reviewed and approved by the Institutional Review Board of the Medical College of Georgia. Testing and intervention occurred at the Medical College of Georgia. The participant flow diagram is presented in Figure 1. Study design. Children were assigned randomly by the statistician to low-dose (20 min/day) or high-dose (40 min/day) aerobic exercise, or a no exercise control. Randomization was stratified by race and gender. Assignments were concealed until baseline testing was completed, then communicated to the study coordinator, who informed the subjects. The control condition did not provide any after school program or transportation. The exercise conditions were equivalent in intensity, and differed only in duration (i.e., energy expenditure). Five cohorts participated in the study over 3 years.

Aerobic exercise intervention. Children assigned to exercise were transported to an after school exercise program each school day (student:instructor ratio about 9:1). The emphasis was on intensity, enjoyment, and safety, not competition nor skill enhancement. Activities were selected based on ease of comprehension, fun, and eliciting intermittent vigorous movement, and included running games, jump rope, and modified basketball and soccer (Gutin, Riggs, Ferguson, & Owens, 1999). The program handbook is available on request. Heart rate monitors (S610i; Polar Electro, Oy, Finland; 30-s epoch) were used to observe the dose. Each child's average heart rate during the sessions was recorded daily, and points awarded for maintaining an average _____ 150 beats per minute. Points were redeemed for weekly prizes. Children assigned to the high-dose condition completed two 20-min bouts each day. Children in the low-dose condition completed one 20-min bout, and then a 20-min period of sedentary activities (e.g., board games, card games, drawing) in another room. No tutoring was provided during this period. Each session began with a 5-min warm-up (moderate cardiovascular activity, static and dynamic stretching). Bouts ended with a water break, light cool down

cardiovascular activity, and static stretching. During the 13 1.6 weeks of intervention (13 1.5, 13 1.7 in low- and high-dose conditions, respectively), attendance was 85 13% (85 12, 85 14). Average heart rate was 166 8 beats per minute (167 7, 165 8). Children achieved an average heart rate _____ 150 beats per minute on most days (87 10% overall; 89 8, 85 12 in low- and high-dose conditions, respectively). The duration of the intervention period, average attendance, heart rate, and proportion of the time the heart rate goal was achieved were similar across exercise conditions, and the time between baseline and posttest was similar across all experimental conditions (19 3.3, 18 2.6, 18 2.5 weeks in control, low-, and high-dose conditions, respectively).

Measures. A standardized psychological battery assessed cognition and achievement at baseline and posttest. Most children (98%) were evaluated by the same tester, at the same time of day, and in the same room at baseline and posttest. Testers were unaware of the child's experimental condition. Standard scores were analyzed. Altogether, 5 cohorts provided data for cognition and 4 cohorts for achievement. The means fell in the normal range (Table 1).

A standardized, theory-based (Das, Naglieri, & Kirby, 1994; Naglieri, 1999) cognitive assessment with excellent psychometric qualities, the Cognitive Assessment System, was utilized (Naglieri & Das, 1997). The Cognitive

Assessment System was standardized on a large representative sample of children aged 5–17 years who closely match the U.S. population on a number of demographic variables (e.g., age, race, region, community setting, educational classification, and parental education). It is strongly correlated with academic achievement ($r = .71$), though it does not contain achievement-like items (Naglieri & Rojahn, 2004). It is known to respond to educational interventions (Das, Mishra, & Pool, 1995), and it yields smaller race and ethnic differences than traditional intelligence tests, making it more appropriate for the assessment of disadvantaged groups (Naglieri, Rojahn, Aquilino, & Matto, 2005).

The Cognitive Assessment System measures children's mental abilities defined on the basis of four interrelated cognitive processes: Planning, Attention, Simultaneous, and Successive. Each of the four scales is comprised of three subtests. Only the Planning scale measures executive function (i.e., strategy generation and application, self-regulation, intentionality, and utilization of knowledge; internal reliability $r = .88$). The Planning scale has better reliability than neuropsychological tests of executive function (Rabbitt, 1997). The remaining scales measure other aspects of cognitive performance, and thus can determine whether the effects of exercise in children are stronger for executive function than for other cognitive processes. The Attention tests require focused, selective cognitive activity and resistance to distraction (internal reliability $r = .88$). The Simultaneous subtests involve spatial and logical questions that contain nonverbal and verbal content (internal reliability $r = .93$). The Successive tasks require analysis or recall of stimuli arranged in sequence, and formation of sounds in order (internal reliability $r = .93$). Preliminary results on this measure have been published (Davis et al., 2007). One child was erroneously administered the 8-year-old version of the test at baseline when the child was 7 years old. Children's academic achievement was measured using two interchangeable forms of the Woodcock-Johnson Tests of Achievement III (McGrew & Woodcock, 2001) which were randomly counterbalanced. The Broad Reading and Broad Mathematics clusters were the outcomes of interest. One hundred forty-one children in 4 cohorts provided achievement data.

Statistical analysis. Intent to treat analysis of covariance tested group differences on cognition and achievement at posttest, adjusting for baseline score. Analyses were conducted using the last observation carried forward imputation for the 7 children who

Control group ($n = 60$)
Low-dose exercise group ($n = 55$)
High-dose exercise group ($n = 56$)

Assessed for eligibility ($n = 840$)

Randomized ($N = 171$)

Excluded ($n = 668$)

. Not meeting inclusion criteria ($n = 355$):

<85th percentile BMI ($n = 194$)

School not included ($n = 90$)

Age > 11 or < 7 years ($n = 9$)

Sibling a subject ($n = 8$)

Medical Condition ($n = 3$)

Participating in another study ($n = 1$)

Medications ($n = 1$)

Other reasons ($n = 49$)

. Refused to participate ($n = 223$)

. Unsuccessful blood draw ($n = 39$)

. Unable to schedule for testing ($n = 8$)

. School district refused permission to test ($n = 41$)

. Conners Oppositional Score >85 ($n = 2$)

Lost to follow-up ($n = 4$)

. Refused posttest (n=3)
 . Excluded, psychiatric illness (n=1)
 . Posttest data imputed (n=4)
 Lost to follow-up (n=1)
 . Refused posttest (n=1)
 . Posttest data imputed (n=1)
 Lost to follow-up (n=2)
 . Refused posttest (n=2)
 . Posttest data imputed (n=2)
 Analyzed (n=60) Analyzed (n =55) Analyzed (n =56)
 Analysis Follow-up Allocation Enrollment

Figure 1. Participant flow diagram.

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did not provide posttest data. Covariates (cohort, race, gender, parent education) were included if they were related to the dependent variable. The Planning, Simultaneous, Attention, and Successive scales, as well as Broad Reading and Broad Math clusters, were examined. A priori contrasts testing a linear trend, and comparing the control group to the two exercise groups, were performed, along with orthogonal quadratic and low-versus highdose contrasts. Statistical significance was assessed at _____

.05. Significant analyses were repeated excluding the 11 children taking medications for attention deficit disorder, and excluding eighteen

7-year-olds, who because of their age were administered a slightly different version of the Cognitive Assessment System. A sample size of 62 subjects per group was estimated to provide 80% power to detect a difference between groups of 6.6 units. fMRI Substudy Participants. Twenty children in the last cohort of the study participated in an fMRI pilot study consisting of baseline (control n 9, exercise n 11) and posttest (control n 9, exercise n 10) brain scans. Left-handed children and those who wore glasses were excluded. One posttest session in the exercise group was refused. There were no significant differences in characteristics between this subset (9.6 1.0 years, 40% girls, 40% Black, BMI 25.3 6.0, BMI z-score 1.9 0.46) and the rest of the sample. Low- and high-dose exercise groups (14 1.7 weeks exercise) were collapsed for fMRI analyses. Design and procedure. Images were acquired on a GE Signa Excite HDx 3 Tesla MRI system (General Electric Medical Systems, Milwaukee, WI). Visual stimuli were presented using MRI compatible goggles (Resonance Technologies, Inc., Northridge, CA), and eye movements were monitored using an eye tracking system that allowed investigators to see that subjects were awake and engaged in the task. Subjects wore ear plugs and their heads were restrained using a vacuum pillow. Prior to the acquisition of MRI data, the magnetic homogeneity was optimized using an automated shimming procedure that determines low-order shim values by performing least squares fits of magnetic field maps and automatically applies the low-order shim values as DC offset currents in the X, Y, and Z gradient waveforms. Functional images were obtained using a spoiled gradient echo planar imaging sequence (time of repetition (TR) 2800 ms, echo time (TE) 35 ms, flip angle 90°, field of view (FOV) 280 280 mm², matrix 96 96, 34 slices, slice thickness 3.6 mm). Next, structural images were obtained using a 3-dimensional fast spoiled gradient echo sequence (TR 9.0 ms, TE 3.87 ms, flip angle 20°, FOV 240 240 mm², matrix 512 512, 120 slices, slice thickness 1.3 mm). The high resolution structural images were used to normalize functional images into a standard stereotaxic space for analyses (Talairach & Tournoux, 1988).

Antisaccade task. Functional imaging data were acquired while subjects completed another measure of executive function, an antisaccade task (McDowell et al., 2002). Correct antisaccade performance requires inhibition of a prepotent response to a visual cue and the generation of a response to the mirror image location of that cue (opposite side, same distance from central fixation). After an initial fixation period (25.2 s), a block paradigm alternated between baseline (N = 7 blocks; 25.2 s of a cross presented at central fixation) and experimental (N = 6 blocks; 25.2 s consisting of 8 antisaccade trials, 48 trials total) conditions (5.46 min run time; 117 volumes; the first 2 volumes were omitted from analysis to account for magnetization stabilization). During baseline subjects were instructed to stare at the cross. During antisaccade trials subjects were instructed to stare at a central cross until it went off, and then a cue in the periphery signaled subjects to look as quickly as possible to the mirror image location of the cue, without looking at the cue itself. Subjects had two separate practice sessions before each scanner session to ensure they understood instructions. Personnel interacting with the children during the scan were unaware of the child's assignment. Image analysis. Analyses were conducted as in previously published data from our laboratory (Camchong, Dyckman, Austin, Clementz, & McDowell, 2008; Camchong, Dyckman, Chapman, Yanasak, & McDowell, 2006; Dyckman, Camchong, Clementz, & McDowell, 2007; McDowell et al., 2002) using AFNI software (Cox, 1996). Briefly, for each session, volumes were registered to a representative volume to correct for minor head movement (and 6 regressors were calculated: 1 each for (a) rotational, and (b) translational head motion in each of 3 planes). A 4-mm full width

Table 1
Cognitive and Achievement Scores (M ± SE) by Group at Baseline and Posttest, and Adjusted Means at Post Assessment

Control Low-dose High-dosed

Pre Post Adjusted post Pre Post Adjusted post Pre Post Adjusted post

Planning	99	1.6	102	1.7	102	1.0	98	1.6	102	1.7	103	1.1	101	1.6	107	1.4	105	1.1
Attention	97	1.5	104	1.5	104	1.1	96	1.5	103	1.7	104	1.1	100	1.8	106	2.0	104	1.1
Simultaneous	101	1.6	104	1.5	105	1.1	101	1.9	106	1.6	107	1.2	106	1.3	108	1.7	106	1.2
Successive	101	1.6	102	1.6	101	0.9	98	1.6	102	1.4	103	0.9	102	1.5	105	1.6	104	0.9
Broad Reading	98	1.2	98	1.4	100	0.8	100	1.6	100	1.6	101	0.8	103	1.9	102	2.1	100	0.8
Broad Math	104	1.7	104	1.4	104	0.8	104	1.8	105	1.6	105	0.8	106	1.6	107	1.4	107	0.8

Note. Covariates included baseline score and gender for Planning and Attention, baseline score and race for Simultaneous and Broad Math, and baseline score and parent education for Planning, Broad Reading, and Broad Math.

a Cognitive Assessment System Standard Scores; n in control group = 60, low-dose = 55, high-dose = 56. b

Woodcock-Johnson Test of Achievement

III Standard Scores; n in control group = 51, low-dose = 45, high-dose = 45. c Low-dose = 20 min/day aerobic

exercise. d High-dose = 40 min/day

aerobic exercise. e Linear contrast p = .013, contrast comparing control vs. both exercise groups, p = .03; control

vs. high-dose group p = .013. f Linear

contrast, p = .045; control vs. high-dose group, p = .045.

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at half maximum Gaussian filter was then applied to each dataset. For each voxel, the percent change in blood oxygenation level dependent signal from baseline was calculated for each time point. The resulting percent change across time was detrended for linear drift and correlated with a trapezoidal reference function modeling baseline (fixation) and experimental (antisaccade) conditions, using the 6 motion parameters as noise regressors. Data were then transformed into standardized space based on the Talairach and Tournoux Atlas (Talairach & Tournoux, 1988), and resampled to 4 × 4 × 4 mm voxels.

To identify the neural circuitry supporting antisaccade performance (Figure 2), the data were collapsed across groups and time points for analysis of variance. To protect against false positives, a cluster threshold method derived from Monte Carlo simulations (based on the geometry of the data set) was applied to the F map (Ward, 1997). Based on these simulations, the family wise alpha at $p = .05$ was preserved with an individual voxel thresholded at $p = .05$ and a cluster size of 40 voxels. The resulting clustered F map was used to identify regional blood oxygenation level dependent signal change.

Region of interest analyses. For each cortical region that showed significant activity in the clustered F map (frontal eye field, supplementary eye field, prefrontal cortex, posterior parietal cortex), a sphere (radius 8 mm, similar to Kiehl et al., 2005; Morris, DeGelder, Weiskrantz, & Dolan, 2001) was positioned at the center of mass, with bilateral activity collapsed across hemispheres. Mean percent signal changes at baseline and posttest were calculated for each region of interest for each participant, and difference scores analyzed. Because of nonnormal distributions of region of interest values, experimental conditions were compared using the Mann–Whitney U test (exact 2-tailed probabilities).

Results

Psychometric Data

Gender was related to posttest Planning (boys, 101.3 ± 12.1 vs. girls, 105.2 ± 12.7, $t = 2.0$, $p = .044$) and Attention (99.8 ± 12.2 vs. 107.5 ± 12.5, $t = 4.1$, $p = .001$) scores. Race was linked with posttest Simultaneous (White, 109.3 ± 13.6 vs. Black, 104.0 ± 10.9, $t = 2.9$, $p = .004$) and Broad Math (109.0 ± 9.3 vs. 102.0 ± 10.1, $t = 4.2$, $p = .001$) scores. Parent education was correlated with posttest Planning ($r = .18$, $p = .02$), Broad Reading ($r = .27$, $p = .001$) and Broad Math ($r = .27$, $p = .001$) scores. These covariates were included in corresponding analyses.

A statistically significant a priori linear contrast indicated a dose-response benefit of exercise on executive function (i.e., Planning, Figure 3; $L = 2.7$, 95% confidence interval [CI] 0.6 to 4.8, $t(165) = 2.5$, $p = .013$). The a priori contrast comparing the control group to the exercise groups also was significant, showing that exposure to either the low- or high-dose of the exercise program resulted in higher Planning scores ($L = 2.8$, CI 1.5.3 to 0.2, $t(165) = 2.1$, $p = .03$). As expected, no effects were detected on the Attention, Simultaneous, or Successive scales. For the Broad Math cluster, a statistically significant a priori linear contrast indicated a dose-response benefit of exercise on mathematics achievement (Figure 3; $L = 1.6$, CI 0.04 to 3.2, $t(135) = 2.03$, $p = .045$). The contrast comparing the exercise conditions to the control condition was not statistically significant ($p = .10$). No effects were detected on the Broad Reading cluster.

The low- and high-dose conditions did not differ, and no quadratic trends were detected. Apart from baseline score, the only significant covariates in analyses of cognition or achievement were gender in the Attention analysis ($p < .001$) and race for Broad Math ($p < .03$). The results were similar when excluding children with attention deficit disorder (linear contrasts on Planning, $t(154) = 2.84, p < .005$, Broad Math, $t(125) = 2.12, p < .04$) and 7-year-olds (Planning, $t(147) = 2.92, p < .004$, Broad Math, $t(117) = 2.23, p < .03$).

Neuroimaging Data

The antisaccade-related blood oxygenation level dependent signal (collapsing across group and time point) revealed cortical saccadic circuitry (including frontal eye fields, supplementary eye fields, posterior parietal cortex, and prefrontal cortex; Figure 2), which is well defined in adults (Luna et al., 2001; Sweeney, Luna, Keedy, McDowell, & Clementz, 2007). Region of interest analyses demonstrated group differences in signal changes from baseline to posttest that were significant in two regions: bilateral prefrontal cortex (center of mass in Talairach coordinates (x,y,z): right 36, 32, 31; left 36, 32, 31) and bilateral posterior parietal cortex

Figure 2. Axial views displaying blood oxygenation level dependent percent signal change associated with antisaccade performance from one-sample analysis. Data from 39 sessions (20 children at baseline, 19 at posttest) are shown radiologically oriented (right hemisphere on left side). Colors from pink to yellow indicate increasing percent signal change. The background is an anatomical image averaged over 20 participants. FEF frontal eye field; SEF supplementary eye field; PFC prefrontal cortex; PPC posterior parietal cortex.

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(right 25, 74, 29; left 23, 70, 22). Specifically, the exercise group showed increased bilateral prefrontal cortex activity (Figure 4, left panel; $U = 20, p < .04$) and decreased activity in bilateral posterior parietal cortex (Figure 4, right panel; $U = 18, p < .03$) compared with controls. Region of interest analyses of motor regions (frontal and supplementary eye fields) did not show significant differences between groups.

Discussion

The experiment tested the effect of approximately 3 months of regular aerobic exercise on executive function in sedentary, overweight children using cognitive assessments, achievement measures, and fMRI. This multifaceted approach revealed convergent evidence that aerobic exercise improved cognitive performance. More specifically, blinded, standardized evaluations showed specific dose-response benefits of exercise on executive function and math achievement. Increased prefrontal cortex activity and reduced posterior parietal cortex activity due to the exercise program were observed. In sum, these results are consistent with those in adults regarding demonstrable behavioral and brain activity changes due to exercise (Colcombe et al., 2004; Pereira et al., 2007). They also add evidence of dose-response, which is particularly rare in exercise trials with children (Strong et al., 2005), and provide important information on an educational outcome. The high-dose condition resulted in mean Planning scores 3.8 points, or a quarter of a standard deviation ($SD = 15$), higher than

the control condition. Demographics did not contribute to the model. Similar results were obtained when children with attention deficit disorder or 7-year-olds were excluded. Therefore the results may be generalized to overweight Black or White 7- to 11-year-olds. Executive function develops in childhood, and is crucial for adaptive behavior and development (Best, Miller, & Jones, 2009; Eslinger, 1996). In particular, the capacity to regulate one's behavior (e.g., inhibiting inappropriate responses, delaying gratification) is important for a child to succeed in elementary school (Blair, 2002; Eigsti et al., 2006). This effect may have important implications for child development and educational policy. The finding of improved math achievement is remarkable, given that no academic instruction was provided, and suggests that a longer intervention period may result in more benefit. The improvement observed on achievement was specific to mathematics, with no benefit to reading. We hypothesize that regular vigorous physical activity promotes children's development via effects on brain systems that underlie cognition and behavior. Animal studies show that aerobic exercise increases growth factors such as brain derived neurotrophic factor, leading to increased capillary blood supply to the cortex and growth of new neurons and synapses, resulting in better learning and performance (Dishman et al., 2006). Experimental and prospective cohort studies conducted with adults demonstrate that long-term regular physical activity alters human brain function (Colcombe et al., 2004; Weuve et al., 2004). A randomized, controlled experiment revealed that 6 months of aerobic exercise led to improved cognitive performance in older adults (Kramer et al., 1999). An important paper reports clear evidence for the impact of aerobic exercise on brain activity in adults in two studies using fMRI techniques: A cross-sectional comparison of high-fit to low-fit individuals showed that prefrontal cortex activity was related to physical fitness, and an experiment showed that 6 months of aerobic exercise (walking) in sedentary 55- to 77-year-olds increased prefrontal cortex activity and led to improvements on a test of executive function (Colcombe et al., 2004). Of interest, a meta-analysis found no support for aerobic fitness as a mediator of the effect of physical activity on human cognition (Etnier, Nowell, Landers, & Sibley, 2006). Thus, rather than being mediated by cardiovascular benefits, the cognitive changes due to exercise may be a direct result of neural stimulation by movement. While the case has been made that physical activity may affect children's cognitive function directly via changes in neural integrity, Figure 3. Executive function (Planning) at posttest adjusted for gender, parent education, and baseline score, and math achievement means (SE) at posttest adjusted for race, parent education, and baseline score, showing dose-response effects of the aerobic exercise program.

Figure 4. Boxplots by experimental condition showing change in activation from baseline to posttest. Left panel: prefrontal cortex. Right panel: posterior parietal cortex.

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there are other plausible explanations, such as engagement in goal directed, effortful mental involvement (Tompsonski et al., 2008). This study has limitations. The results are limited to a sample of overweight Black and White 7- to 11-year-old children. Lean children and those of other ethnicities or age groups may respond differently. It is unknown whether cognitive benefits persist after a period of detraining. If benefits accumulate over time, however, this would be important for child development. There may be sensitive periods during which motor activity would exert a particularly strong effect on the brain (Knudsen, 2004). It remains to be determined whether other types of exercise, such as strength training or swimming, are also effective. Participants and intervention staff could not be blinded to experimental condition or the study hypothesis; however, the recruitment materials emphasized physical health benefits rather than cognitive ones. Another limitation is that the use of a no-intervention control condition does not allow the trial to rule out some alternative explanations (e.g., attention from adults, enjoyment). Psychological changes may occur in children who participate in exercise because of social interactions that occur during the sessions rather than due to

exercise per se. The dose-response pattern of results belies this explanation, however, because both exercise groups spent equal time at the research facility with instructors and peers. The study did not find a difference between the exercise dose groups. This does not conflict with the dose-response finding, which shows that the exercise intervention caused an improvement in cognition (Hill, 1965). Given that the linear contrast demonstrated a graded effect of treatment, a pairwise dose comparison asks a follow-up question, whether one specific dose is superior to another (Ruberg, 1995). The test of the dose-response benefit to achievement was significant, but the comparison of the control group to the two exercise groups was not, providing partial support to the hypothesis that exercise improves mathematics achievement. The fMRI results are limited by a small sample size and do not provide a test of dose-response, which renders them more subject to alternative explanations. Nevertheless, specific changes were observed, and the direction of changes differed in prefrontal and parietal regions, arguing against a global trend in brain activity. Although antisaccade performance and its supporting brain activity change with age (Luna et al., 2001), this is an unlikely confounder because the groups were of similar age. These experimental data offer evidence that a vigorous after school aerobic exercise program improved executive function in dose-response fashion among overweight children; social factors may have contributed to this effect. Changes in corresponding brain activation patterns were observed. These results also provide partial support of a benefit to mathematics performance. The assignment of conditions was randomized and outcome evaluations blinded, minimizing potential bias or confounding. Overweight children now constitute over a third of U.S. children and are overrepresented among disadvantaged populations. Besides its importance for reducing health risks during a childhood obesity epidemic (Ogden et al., 2006), aerobic activity may prove to be an important method of enhancing aspects of children's mental functioning that are central to cognitive development (Welsh, Friedman, & Spieker, 2006).

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