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KEY WORDS

cognition, physical activity, aerobic fitness, randomized controlled trial

ABBREVIATIONS

ANOVA—analysis of variance
CI—confidence interval
ERP—event-related brain potential
FITKids—Fitness Improves Thinking in Kids
HR—heart rate
MVPA—moderate to vigorous physical activity
SES—socioeconomic status
RT—reaction time
Vo_{2peak}—maximal oxygen consumption

Dr Hillman conceptualized and designed the study, drafted the initial manuscript, and critically reviewed the manuscript; Dr Pontifex coordinated and supervised data collection and reduction. He assisted in revising the initial manuscript and critically reviewed the manuscript; Dr Castelli conceptualized and designed the physical activity intervention, assisted in revising the initial manuscript, and critically reviewed the manuscript; Dr Khan, Ms Raine, Mr Scudder, Mr Drollette, Mr Moore, Dr Wu, and Dr Kamijo coordinated and supervised data collection and reduction. They also assisted in revising the initial manuscript and critically reviewed the manuscript; and all authors approved the final manuscript as submitted.

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WHAT'S KNOWN ON THIS SUBJECT: Physical activity programs have been shown to have positive implications for children's cognitive performance and brain structure and function. However, additional randomized controlled trials are needed to determine whether daily physical activity influences executive control and its neural underpinnings.

WHAT THIS STUDY ADDS: The randomized controlled trial, designed to meet daily physical activity recommendations, used behavioral and electrophysiological measures of brain function to demonstrate enhanced attentional inhibition and cognitive flexibility among prepubertal children.

abstract

OBJECTIVE: To assess the effect of a physical activity (PA) intervention on brain and behavioral indices of executive control in preadolescent children.

METHODS: Two hundred twenty-one children (7–9 years) were randomly assigned to a 9-month afterschool PA program or a wait-list control. In addition to changes in fitness (maximal oxygen consumption), electrical activity in the brain (P3-ERP) and behavioral measures (accuracy, reaction time) of executive control were collected by using tasks that modulated attentional inhibition and cognitive flexibility.

RESULTS: Fitness improved more among intervention participants from pretest to posttest compared with the wait-list control (1.3 mL/kg per minute, 95% confidence interval [CI]: 0.3 to 2.4; d = 0.34 for group difference in pre-to-post change score). Intervention participants exhibited greater improvements from pretest to posttest in inhibition (3.2%, 95% CI: 0.0 to 6.5; d = 0.27) and cognitive flexibility (4.8%, 95% CI: 1.1 to 8.4; d = 0.35 for group difference in pre-to-post change score) compared with control. Only the intervention group increased attentional resources from pretest to posttest during tasks requiring increased inhibition (1.4 μV, 95% CI: 0.3 to 2.6; d = 0.34) and cognitive flexibility (1.5 μV, 95% CI: 0.6 to 2.5; d = 0.43). Finally, improvements in brain function on the inhibition task (r = 0.22) and performance on the flexibility task correlated with intervention attendance (r = 0.24).

CONCLUSIONS: The intervention enhanced cognitive performance and brain function during tasks requiring greater executive control. These findings demonstrate a causal effect of a PA program on executive control, and provide support for PA for improving childhood cognition and brain health. *Pediatrics* 2014;134:e1063–e1071

The pandemic of physical inactivity is a serious threat to global public health[1] accounting for ~10% of all premature deaths from noncommunicable diseases.[2] Despite evidence that such inactivity detrimentally affects brain health and aspects of cognition known as executive control (also called cognitive control) in older adult populations,[3,4] this area remains understudied in children. This is concerning because childhood is characterized by extensive changes in brain structure, function, and connectivity.[5] Thus, an active lifestyle during childhood may have protective effects on brain health across the lifespan, as is the case for physical health. However, the specific effects of physical activity (PA) on key cognitive processes and their neural underpinnings remain unknown.

Executive control, which consists of inhibition (resisting distractions or habits to maintain focus), working memory (mentally holding and manipulating information), and cognitive flexibility (multitasking), is vital to success in school, vocation, and life.[6] Cross-sectional studies[7,8] have demonstrated that aerobic fitness is positively related to executive control, with more fit children exhibiting superior attention, decision-making ability, and differential brain function compared with their lesser-fit peers. In particular, event-related brain potentials (ERPs), derived from an EEG, allow for the real-time measurement of changes in electrical activity in brain function while children performed cognitive tasks. The most common way that brain activity is captured in an ERP is through the measurement of the various peaks of the waveform. A peak commonly used to assess brain activity is the P3, which has been robust in demonstrating differences between individuals of higher and lower fitness during tasks that tap executive control. The P3 reflects neuronal activity thought to be associated with the processes of attention and working memory,[9] and can be assessed relative to its size (measured in amplitude) and its timing (measured in latency). That is, larger P3 amplitude reflects greater allocation of attentional resources,[10] and faster P3 latency reflects faster cognitive processing speed.[11] Our laboratory has previously demonstrated fitness-related differences in P3 such that higher-fit children exhibited larger P3 amplitude and shorter P3 latency, indicating greater attentional resource allocation and faster cognitive processing speed, respectively.[7,8] Therefore, differences in fitness account for a portion of the variability observed in executive control and underlying brain function in preadolescent children.

Despite available correlational evidence, few have manipulated PA or aerobic fitness among children to investigate their effects on executive control and its neural underpinnings.[12–15] In addition, it remains unknown whether attendance in a PA program correlates with measures of executive control. Consequently, we investigated the effects of a 9-month randomized controlled PA trial (Fitness Improves Thinking in Kids [FITKids]) on brain and behavior during tasks requiring attentional inhibition and cognitive flexibility. We hypothesized that, relative to the wait-list control group, the FITKids intervention would result in (1) improvements in behavioral performance, (2) increased attention allocation (measured via P3 amplitude), and (3) faster cognitive processing speed (measured via P3 latency). Finally, we predicted a positive correlation between participation in the intervention and improvements in the cognitive outcomes.

METHODS

Study Design

Participants were randomly assigned to either the FITKids afterschool PA program (intervention group) or a wait-list control group. Randomization was performed by a staff member who was not involved in the data collection. The randomization procedure was performed only after all participants had been recruited and group allocation was concealed from the research/data collection team. Due to the inclusion of siblings among 10 families, nonindependent observations were included. As such, analyses were rerun by using a randomly selected sibling from each family. The findings remained unchanged from those included in the results section. After baseline testing, pairs of participants were matched for age, gender, race, socioeconomic status (SES), and $\text{V}\text{O}_{2\text{max}}$, and a coin was flipped by the independent researcher to determine group assignment. All participants completed a 2-day protocol of testing at baseline (pretest) and postintervention (posttest). The study was conducted over the fall and spring semesters of the school years between 2009 and 2013. The institutional review board at the University of Illinois approved the study protocol. Parents provided written informed consent, and participants provided written assent.

Participants

Eligible participants were 8- to 9-year-olds residing in East Central Illinois. This age range was chosen based on preliminary research investigating fitness and preadolescent cognition, which found reliable differences in neuroimaging, behavioral, and academic achievement test performance occur at, or before, this age range. Four hundred seventy-five children were screened, and 221 children were randomly assigned to either study group (Fig 1). The exclusion criteria included special educational services related to cognitive or attentional disorders, neurologic diseases, and physical disabilities.

Study Procedures

Outcome assessors were blinded to group assignment throughout all testing.

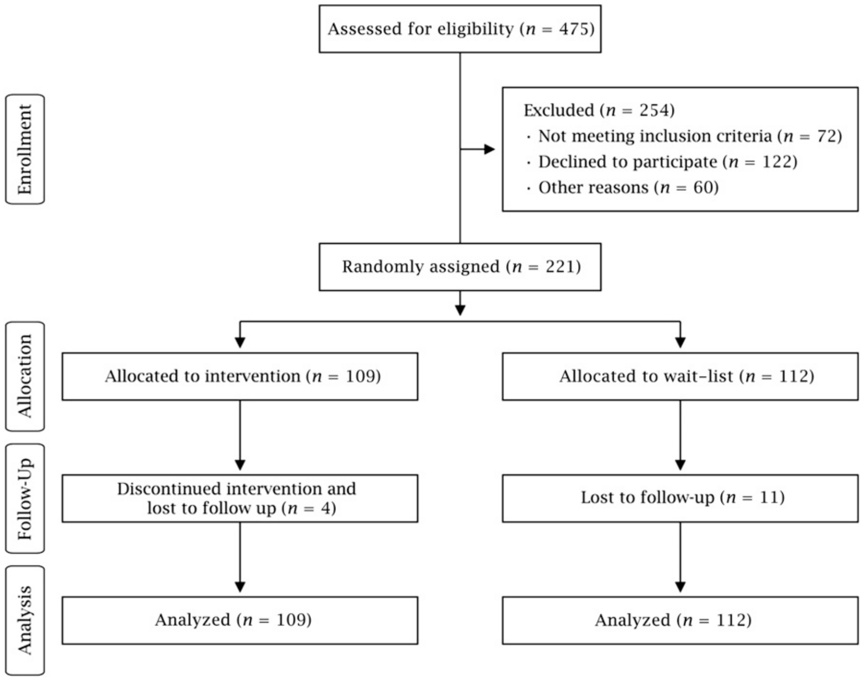

FIGURE 1

Flow diagram of the FITKids intervention.

On the first visit, demographic information, including age, gender, race/ethnic group, and SES were collected.[16] SES was determined by using a trichotomous index based on the following: (1) participation in free or reduced-price meal program at school, (2) the highest level of education obtained by the mother and father, and (3) number of parents who worked full-time.[16] Participants completed the Kaufman Brief Intelligence Test[17] to assess IQ, a Tanner Staging System questionnaire to assess pubertal status,[18] and the PA Readiness Questionnaire[19] to screen for health issues exacerbated by physical exercise. Participants were then fitted with a Polar heart rate (HR) monitor (Model A1, Polar Electro, Finland), had their height and weight measured by using a Tanita WB-300 Plus digital scale and stadiometer (Tanita Corp, Tokyo, Japan), and completed a maximal exercise test to assess aerobic fitness. On the second visit, participants performed cognitive tasks assessing attentional inhibition and cognitive flexibility while fitted with an EEG cap (Compumedics, Inc, Charlotte, NC). Participants were then randomly assigned to the FITKids intervention or the wait-list as described earlier. After completion of the intervention, participants returned to the laboratory for their posttest assessments, which was identical to the baseline assessment.

Aerobic Fitness Assessment

Aerobic fitness was assessed by using a test of maximal oxygen consumption ($\text{VO}_{2\text{peak}}$; see Supplemental Information). This test employed a computerized indirect calorimetry system while participants ran/walked on a motor-driven treadmill at a constant speed with incremental grade increases every 2 minutes until volitional exhaustion.[20] Aerobic fitness percentiles were determined by using normative values for $\text{VO}_{2\text{peak}}$.[21]

Cognitive Tasks

Response accuracy and reaction time (RT) were collected to assess behavioral performance on the attentional inhibition and cognitive flexibility tasks. Attentional inhibition was assessed by using a modified flanker task,[22,23] and cognitive flexibility was assessed by using a color-shape switch task.[24] A modified flanker task is a method to measure inhibition in which children are engaged in a series of trials that, in this case, have arrays of fish that either match (ie, congruent arrays) or do not match (ie, incongruent arrays). The task is to press either the right or left button as quickly and accurately as possible based on the direction in which the middle fish is facing. Task difficulty is manipulated by whether the flanking fish face the same direction or the opposite direction to the middle fish. The color-shape switch task is a measure of cognitive flexibility, in which children are shown characters of different shapes (ie, square, circle) and color (ie, blue, green), and are asked to make a single judgment (ie, homogeneous task condition) via a button press about either shape or color. Next, they are asked to flexibly switch their decisions around both shape and color creating a more difficult decision process (ie, heterogeneous task condition). The task conditions that require the greatest amount of executive control are the incongruent condition in the flanker task and the heterogeneous condition in the switch task (see Supplemental Information). In addition to behavioral measures, EEG activity was collected during the cognitive tasks from 64 electrode sites to derive the P3 amplitude and latency measures (see Supplemental Information).

PA Intervention

The 2-hour PA intervention occurred at a recreational facility on the University of Illinois campus after each school day, and focused on improvement of aerobic fitness through engagement in a variety of age-appropriate physical activities. Children intermittently participated in at least 70-minutes of moderate-to-vigorous PA (recorded by E600 Polar HR monitors; Polar Electro). Specifically, the intervention included ~30 to 40 minutes at PA stations. Next, a healthy snack and educational component were provided as a rest period, and children then engaged in low organizational games (45–55 minutes) centered on a skill theme (see Supplemental Information). The activities were aerobically demanding, but simultaneously provided opportunities to refine motor skills. The program was offered 150 days of the 170-day school year.

Statistical Analysis

Assuming a small effect size ($d = 0.3$), reliability of the within-subjects factor ($\rho = 0.8$), 2-sided α of 0.05, and 80% power, the required sample size was 90 to 100 participants per group. The primary outcomes assessed were behavioral and brain function indices of performance in response to the flanker and switch tasks. Analyses were conducted by using a 2 (group: intervention, wait-list) × 2 (time: pretest, posttest) multivariate repeated measures analysis of variance (ANOVA) with additional variables nested within the primary analytical procedure based on the outcome variable. Analysis of behavioral measures (response accuracy, RT) was conducted separately within 2 conditions (congruency: congruent, incongruent) for the flanker task and within 2 conditions (switch: homogeneous, heterogeneous) for the switch task. The P3 ERP component was assessed separately for amplitude and latency within the same 2 conditions for each task. To account for missing data, multiple imputation was performed by using PASW Statistics, 19.0 to impute 20 values for each missing observation. Analyses were performed by using the combined multivariable modeling estimates. All statistical analyses were conducted with $\alpha = 0.05$ by using the Greenhouse-Geisser statistic with subsidiary univariate ANOVAs and Tukey's honest significant difference tests for posthoc comparisons. Findings reported herein are restricted to only those related to the intervention. For a more complete statistical summary, please refer to the Supplemental Information.

RESULTS

Participants

Demographic data are provided in Table 1. Over half of the participants in both groups were white, and over 40% of the participants were categorized as low SES. At baseline, there were no significant differences between intervention and wait-list control groups relative to age (−0.08 years, $P = .32$), pubertal timing (−0.05, $P = .48$), aerobic fitness (−1.73 mL/kg per minute, $P = .07$), BMI (0.2, $P = .73$), or IQ (−2.5, $P = .17$).

Intervention Participation

Participants in the FITKids afterschool program attended 80.6% (±15.1) of the sessions. Mean HR during these sessions was ~137 beats per minute (±8.3) with children taking ~4246 steps (±1039.9; see Supplemental Information).

Changes in Aerobic Fitness and Weight Status

Although both groups increased in aerobic fitness, the intervention group demonstrated a greater improvement from pretest to posttest than the wait-list control group (1.5 mL/kg per minute, 95% confidence interval [CI]: 0.5 to 2.5, $d = 0.39$ for group difference in pre-to-post change score). Furthermore, pre- to posttest change in aerobic fitness percentile was significant only among intervention participants (5.5 percentile, 95% CI: 1.9 to 9.1, $d = 0.42$ for intervention group pre-to-post change score) and not among wait-list participants

TABLE 1 Mean (95% CI) Values for Participant Demographic Data

Measure	Intervention			Wait-list		
	Pretest	Posttest	Change	Pretest	Posttest	Change
N	109	—	—	112	—	—
Gender (% girls)	53 (49)^{a}	—	—	49 (44)^{a}	—	—
Race, *n* (%)						
Asian	17 (15)^{a}	—	—	12 (11)^{a}	—	—
African American	25 (23)^{a}	—	—	28 (25)^{a}	—	—
White	51 (47)^{a}	—	—	59 (53)^{a}	—	—
Other or mixed-race	16 (15)^{a}	—	—	13 (11)^{a}	—	—
Hispanic	10 (9.2)^{a}	—	—	5 (4.5)^{a}	—	—
Low SES	43 (39.5)^{a}	—	—	49 (43.8)^{a}	—	—
Age, y	8.8^{a} (8.7 to 8.9)	9.5^{b} (9.4 to 9.6)	0.7^{a} (0.6 to 0.7)	8.8^{a} (8.7 to 8.9)	9.5^{b} (9.4 to 9.7)	0.7^{a} (0.7 to 0.8)
Pubertal timing	1.4^{a} (1.3 to 1.5)	1.5^{b} (1.4 to 1.6)	0.1^{a} (0.0 to 0.2)	1.5^{a} (1.4 to 1.6)	1.6^{b} (1.5 to 1.7)	0.1^{a} (0.0 to 0.2)
IQ (K-BIT composite)	109.8^{a} (107.2 to 112.4)	111.8^{b} (109.2 to 114.3)	2.0^{a} (0.3 to 3.6)	112.6^{a} (109.9 to 115.4)	116.5^{b} (113.7 to 119.3)	3.9^{a} (2.0 to 5.8)
Attention-deficit/hyperactivity disorder-IV composite	42.8^{a} (37.0 to 48.5)	42.3^{a} (36.6 to 47.9)	−0.5^{a} (−5.8 to 4.8)	44.3^{a} (38.7 to 49.8)	46.2^{a} (40.4 to 51.9)	1.9^{a} (−2.7 to 6.5)
BMI	19.1^{a} (18.3 to 19.9)	19.3^{a,b} (18.4 to 20.2)	0.2^{a} (0.0 to 0.5)	18.9^{a} (18.1 to 19.7)	19.8^{b} (18.9 to 20.7)	0.9^{b} (0.6 to 1.2)
Vo_{2peak} (mL/kg/min)	37.5^{a} (36.2 to 38.8)	39.5^{b} (38.2 to 40.8)	2.1^{a} (1.2 to 2.9)	39.2^{a} (37.9 to 40.5)	39.9^{b} (38.6 to 41.3)	0.7^{b} (0.1 to 1.4)
Vo_{2peak} percentile	17.5^{a} (13.8 to 21.3)	23.2^{b} (18.5 to 27.8)	5.6^{a} (2.0 to 9.3)	21.9^{a,c} (17.7 to 26.2)	22.8^{b,c} (18.5 to 27.0)	0.8^{b} (−1.8 to 3.4)

K-BIT, Kaufman Brief Intelligence Test. Data are presented as mean (95% CI) unless noted otherwise. Values sharing a common superscript are not statistically different at $\alpha = 0.05$.

(0.5 percentile, 95% CI: −2.0 to 3.0, *d* = 0.06 for wait-list group pre-to-post change score). Both groups also increased in BMI; however, the wait-list group demonstrated a greater increase than the intervention group (0.5 kg/m^2, 95% CI: 0.2 to 0.9, *d* = 0.37 for group difference in pre-to-post change score).

Changes in Attentional Inhibition

Pre- and posttest performance is summarized in Table 2. Although response accuracy increased in both groups, the intervention group demonstrated greater improvement from pretest to posttest than the wait-list control group (3.2%, 95% CI: 0.0 to 6.5, *d* = 0.27 for group difference in pre-to-post change score; Fig 2). However, there was no influence of group assignment on RT ($P \geq .18$).

Only the intervention group demonstrated increased P3 amplitude from pretest to posttest on incongruent trials (1.4 μV, 95% CI: 0.3 to 2.6, *d* = 0.34 for intervention group pre-to-post change score; Fig 3; also Supplemental Fig 9 in the Supplemental Information), and a greater change in P3 amplitude on incongruent trials from pretest to posttest relative to the wait-list group (1.9 μV, 95% CI: 0.3 to 3.5, *d* = 0.31 for group difference in pre-to-post change score). The intervention group demonstrated faster P3 latency for incongruent trials at posttest relative to pretest (20.1 milliseconds, 95% CI: 2.6 to 37.6, *d* = 0.31 for intervention group pre-to-post change score), and a greater change in P3 latency from pretest to posttest relative to the wait-list group (32.0 milliseconds, 95% CI: 6.9 to 57.2, *d* = 0.34 for group difference in pre-to-post change score).

Changes in Cognitive Flexibility

Although both groups increased in pre- to posttest performance on homogenous and heterogeneous trials, the improvement in performance on the heterogeneous task was greater among intervention participants (4.8%, 95% CI:

TABLE 2 Mean (95% CI) Values for Task Performance

Measure	Intervention			Wait-list		
	Pretest	Posttest	Change	Pretest	Posttest	Change
Flanker task						
Response accuracy (%)						
Congruent trials	78.6^{a} (76.3 to 80.9)	85.8^{b} (84.0 to 87.5)	7.1^{a} (4.7 to 9.6)	82.3^{c} (80.2 to 84.5)	85.6^{b} (83.5 to 87.6)	3.2^{b} (1.0 to 5.5)
Incongruent trials	72.1^{a} (69.8 to 74.5)	78.9^{b} (76.9 to 81.0)	6.8^{a} (4.2 to 9.5)	75.5^{c} (73.5 to 77.6)	79.9^{b} (77.5 to 82.2)	4.3^{a} (2.0 to 6.7)
All trials	75.4^{a} (73.2 to 77.6)	82.4^{b} (80.6 to 84.2)	7.0^{a} (4.6 to 9.4)	79.0^{c} (77.0 to 81.0)	82.7^{b} (80.6 to 84.8)	3.8^{b} (1.6 to 5.9)
RT (ms)						
Congruent trials	504.0^{a} (481.8 to 526.3)	467.1^{b} (450.9 to 483.3)	−36.9^{a} (−54.6 to −19.3)	522.2^{a} (501.8 to 542.7)	478.1^{b} (459.5 to 496.7)	−44.2^{a} (−64.5 to −23.8)
Incongruent trials	531.6^{a} (507.4 to 555.9)	502.2^{b} (484.8 to 519.5)	−29.5^{a} (−49.7 to −9.2)	552.3^{a} (529.9 to 574.7)	508.2^{b} (489.0 to 527.5)	−44.1^{a} (−66.1 to −22.0)
All trials	517.2^{a} (494.2 to 540.1)	483.8^{b} (467.2 to 500.4)	−33.3^{a} (−51.9 to −14.7)	536.7^{a} (515.5 to 557.8)	492.5^{b} (473.7 to 511.2)	−44.2^{a} (−65.0 to −23.3)
Switch task						
Response accuracy (%)						
Homogeneous trials	87.7^{a} (86.3 to 89.0)	89.9^{b} (88.7 to 91.0)	2.2^{a} (0.7 to 3.8)	87.8^{a} (86.4 to 89.1)	90.2^{b} (89.1 to 91.3)	2.4^{a} (1.1 to 3.7)
Heterogeneous trials	65.9^{a} (63.2 to 68.6)	76.6^{b} (74.3 to 78.9)	10.7^{a} (8.2 to 13.3)	69.0^{a} (66.6 to 71.4)	75.0^{b} (72.6 to 77.4)	6.0^{b} (3.3 to 8.6)
RT (ms)						
Homogeneous trials	792.3^{a} (760.5 to 824.2)	754.9^{b} (721.2 to 788.7)	−37.4^{a} (−70.1 to −4.7)	816.8^{a} (786.0 to 847.6)	759.5^{b} (730.6 to 788.5)	−57.2^{a} (−90.2 to −24.3)
Heterogeneous trials	1385.4^{a} (1328.7 to 1442.1)	1407.1^{a} (1362.4 to 1451.9)	21.7^{a} (−39.2 to 82.7)	1475.4^{a} (1426.8 to 1524.1)	1435.1^{a} (1389.2 to 1481.0)	−40.4^{a} (−98.9 to 18.1)

Values sharing a common superscript are not statistically different at $\alpha = 0.05$.

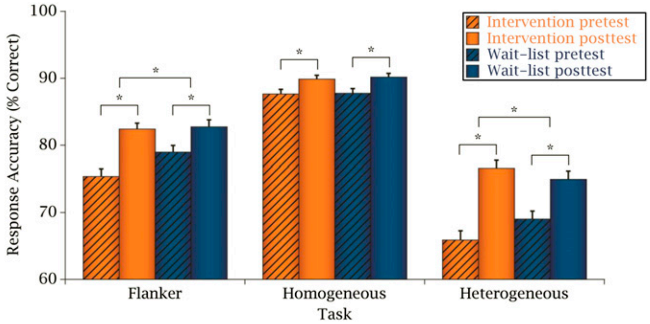

FIGURE 2
Change in response accuracy (mean ± SE) from pre- to posttest as a function of group and cognitive task.

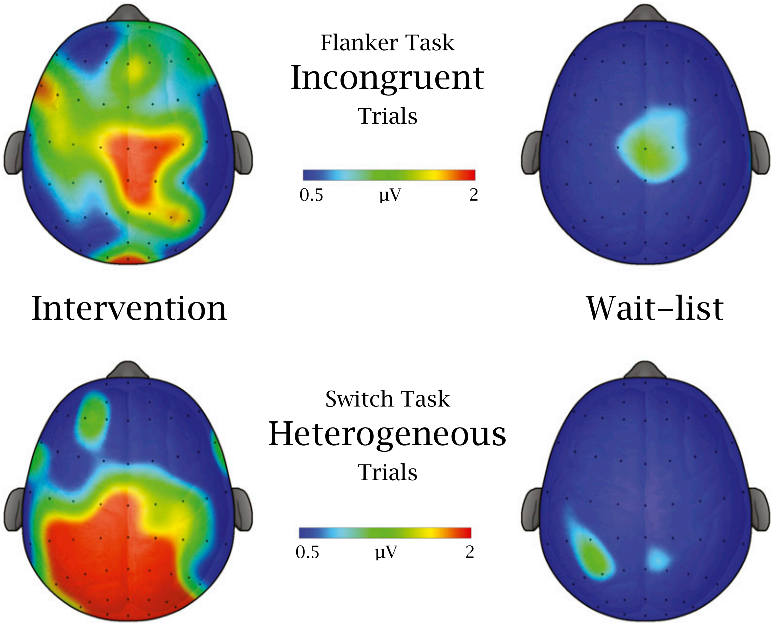

FIGURE 3
Topographic scalp distribution of the change in P3 amplitude (spectrum scale: blue to red) during the flanker task (top) and switch task (bottom) is illustrated for the intervention group (left) and wait-list group (right). As shown, P3 amplitude was greater in the intervention group at posttest only for the conditions that required the greatest amount of executive control across both tasks as denoted by the greater amount of red depicted in the electrophysiological plots representing brain function.

1.1 to 8.4, $d = 0.35$ for group difference in pre-to-post change score; Fig 2). An increase in P3 amplitude to the heterogeneous trials from pretest to posttest was observed only for the intervention group (1.5 μV, 95% CI: 0.6 to 2.5, $d = 0.43$ for intervention group pre-to-post change score), with a greater change in P3 amplitude relative to the wait-list group (1.4 μV, 95% CI: 0.0 to 2.7, $d = 0.27$ for group difference in pre-to-post change score; Fig 3; also Supplemental Fig 10 in the Supplemental Information). No influence of group assignment was observed for homogeneous trials or P3 latency ($P \geq .06$).

Attendance and Cognitive Task Performance

Attendance in the FITKids intervention was positively correlated with change in P3 amplitude ($r = 0.22$, $P = .02$) and negatively correlated with change in P3 latency ($r = -0.22$, $P = .02$) from pre- to posttest, only for incongruent flanker task trials requiring greater amounts of inhibitory control. No such relationship was observed for congruent flanker task trials requiring lesser amounts of inhibitory control. A similar relationship was observed for behavioral indices of the task-switching task, such that attendance was positively correlated with change in task performance on the more demanding heterogeneous condition necessitating increased inhibition, working memory, and cognitive flexibility ($r = 0.24$, $P = .01$), with no such effect realized for the homogeneous condition requiring lesser amounts of executive control (Fig 4).

DISCUSSION

The provision of a 9-month randomized controlled PA intervention, directed toward increasing aerobic fitness, significantly improved brain and behavioral indices of executive control. More importantly, these effects were selective to aspects of cognition that required extensive inhibition and cognitive flexibility, with no changes observed for task components requiring lower-order (ie, nonexecutive) aspects of cognition. Further, the fitness-related benefits appear to follow a dose–response relationship, as higher attendance rate in the FITKids program was associated with larger changes in neural indices of attention (ie, P3 amplitude), processing speed (P3 latency), and improved performance during the executive control tasks. Given that no significant differences were observed for children assigned to the wait-list control, the key implication from this study is that participating in a daily, afterschool PA program enhances executive control.

Previous randomized controlled trials in this area have varied in outcomes studied, methodologies, and participant characteristics.[12–15] Among overweight children, Davis et al[12] demonstrated dose–response benefits of exercise on executive function and math achievement. Further, functional MRI results revealed

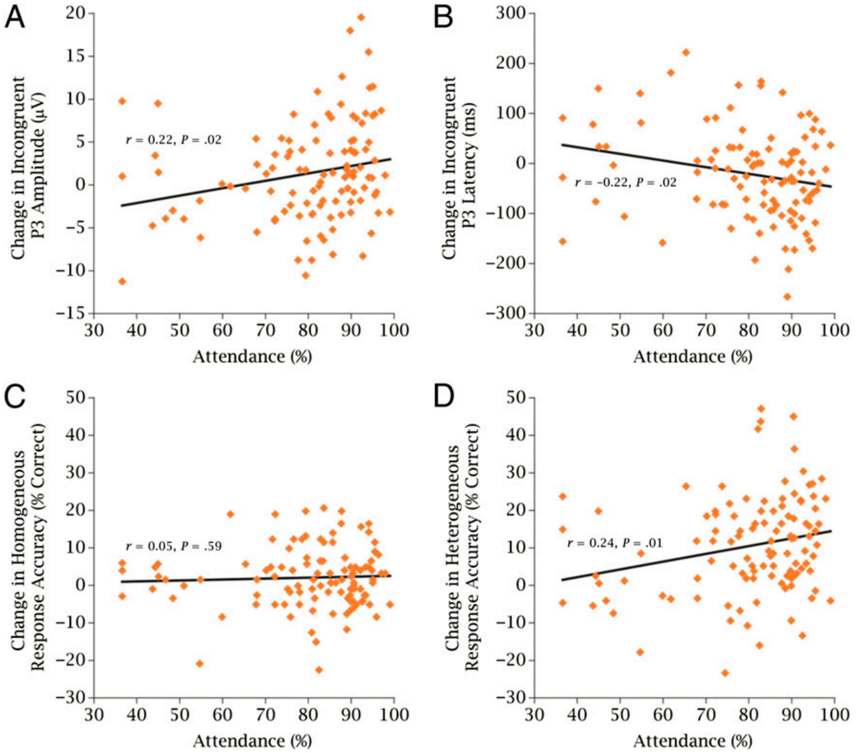

FIGURE 4

Scatterplots of the relationship between attendance at the FITKids afterschool PA program and pre- to posttest change in P3 amplitude to the incongruent condition of the flanker task (A), change in P3 latency to the incongruent condition of the flanker task (B), change in response accuracy for the homogenous condition of the switch task (C), and change in response accuracy for the heterogeneous condition of the switch task (D).

increased prefrontal and reduced posterior parietal cortex activity during an antisaccade task. In a similar sample, Krafft et al[15] found that an exercise intervention increased activation in regions involved in flanker accuracy including the anterior cingulate cortex and the superior frontal gyrus. Among a sample that varied in weight status, Chaddock-Heyman et al[14] observed that children receiving a PA intervention improved performance on a flanker task and showed anterior frontal brain patterns and incongruent task performance similar to that of college-aged adults after the intervention. This pattern of results was not observed in the preadolescent wait-list control group. In a similar sample, Kamijo et al[13] observed that daily PA improved working memory performance and increased frontal electrophysiological indices (ie, initial contingent negative variation) associated with improvements in the executive control of working memory after a 9-month PA intervention. The results from the current study are broadly consistent with the aforementioned studies revealing that daily PA not only improves aerobic fitness but also enhances brain function and behavioral sequelae during tasks that require extensive amounts of executive control among prepubertal children. In addition, the current study extends these findings to electrophysiological indices of cognitive flexibility, a novel contribution to the literature.

Furthermore, the dose–response relationship observed between attendance rate, brain function, and executive control demonstrates that brain and behavioral changes resulted as a function of the degree of participation in the PA program. These results are consistent with Krafft et al[25] who observed that attendance in an 8-month exercise program was positively associated with improved white matter integrity among a group of sedentary and overweight (BMI ≥ 85th percentile) 8- to 11-year-olds (94% African American). However, the findings from the current study provide further support for the importance of PA program attendance for cognitive benefit among a large heterogeneous sample of children with varying weight status. Given that health factors (physical inactivity, excess adiposity) have been related to absenteeism,[26] the findings herein indicate that increased time spent engaging in PA improves both physical and brain health, which has broad public health implications for effective functioning across the lifespan.

Although children in the FITKids intervention exhibited greater improvements in executive control relative to their wait-list control counterparts, there are some limitations of the current study. The use of a wait-list control renders it difficult to attribute the observed group differences entirely to the PA participation because other aspects of the program such as the educational component, social interaction with peers and intervention staff, and refining motor skills may have contributed to the results. However, it is unlikely that the educational component was the cause of group differences, given that it was brief and took place as part of the instruction for the PA intervention (see Supplemental Information). Another limitation of the study was that nonintervention PA was not measured. Therefore, we are unable to adjust for any influence of habitual PA on the findings. Future research would benefit from study designs that include active control groups and account for the potential influence of lifestyle factors such as habitual PA.

CONCLUSIONS

Participation in the FITKids intervention improved aerobic fitness, as well as brain and behavioral indices of executive control among prepubertal children. Importantly, these effects were selective to aspects of cognition that required extensive inhibition and cognitive flexibility. Given the rapid decline in PA opportunities for children at school, the dissemination of our findings is particularly important for educators and policy makers. Specifically, policies that reduce or replace PA opportunities during the school day (eg, recess), in an attempt to increase academic achievement, may have unintended effects.[27] Indeed, the current data not only provide causal evidence for the beneficial effects of PA on cognitive and brain health, but they warrant modification of contemporary educational policies and practices, and indicate that youth should receive more daily PA opportunities.[28] Finally, given that scholastic success in reading and mathematics is heavily reliant upon effective executive control,[29,30] our findings have broad relevance for public health, the educational environment, and the context of learning.

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Effects of the FITKids Randomized Controlled Trial on Executive Control and Brain Function

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