Developmental Psychology
2009, Vol. 45, No. 1, 114–129

0012-1649/09/$12.00 DOI: 10.1037/a0014437

Aerobic Fitness and Cognitive Development: Event-Related Brain Potential and Task Performance Indices of Executive Control in Preadolescent Children

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The relationship between aerobic fitness and executive control was assessed in 38 higher- and lower-fit children ($M_{\text{age}} = 9.4$ years), grouped according to their performance on a field test of aerobic capacity. Participants performed a flanker task requiring variable amounts of executive control while event-related brain potential responses and task performance were assessed. Results indicated that higher-fit children performed more accurately across conditions of the flanker task and following commission errors when compared to lower-fit children, whereas no group differences were observed for reaction time. Neuroelectric data indicated that P3 amplitude was larger for higher- compared to lower-fit children across conditions of the flanker task, and higher-fit children exhibited reduced error-related negativity amplitude and increased error positivity amplitude compared to lower-fit children. The data suggest that fitness is associated with better cognitive performance on an executive control task through increased cognitive control, resulting in greater allocation of attentional resources during stimulus encoding and a subsequent reduction in conflict during response selection. The findings differ from those observed in adult populations by indicating a general rather than a selective relationship between aerobic fitness and cognition.

Keywords: physical activity, exercise, cognitive control, P3, error-related negativity

A growing literature has emerged that describes the benefits of chronic physical activity on cognition across a variety of tasks and populations. To date, the vast majority of research has focused on adult populations, with reviews and meta-analyses concluding that physical activity has a small but significant relationship to cognitive function (see Etnier et al., 1997, for review). Other research on older adults has indicated that although the relationship is generally beneficial across different aspects of cognition, it is selectively larger for tasks or task components that require extensive amounts of executive control (Colcombe & Kramer, 2003; Hillman, Motl, et al., 2006). Relative to studies examining adult populations, there is a paucity of research focused on this relationship during childhood. Of the few studies that do exist in the literature (see Sibley & Etnier, 2003, for review), none have examined executive control, which according to Colcombe and Kramer (2003) is the very aspect of cognition that is disproportionately influenced by chronic participation in physical activity.

Executive control refers to a subset of goal-directed processes that encompass the selection, scheduling, and coordination of computational processes that are involved in perception, memory, and action (Meyer & Kieras, 1997; Norman & Shallice, 1986). In children, executive control function improves during the early stages of life; substantial improvements occur between 3 and 7 years of age, especially related to tasks involving inhibition and cognitive flexibility. During late childhood and adolescence, the development of the frontal lobes is associated with better performance on executive control tasks (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Travis, 1998). Younger children, whose frontal lobes are characterized by an earlier stage of maturation, have greater difficulty inhibiting irrelevant stimuli and focusing attention on relevant stimuli (Ridderinkhof & van der Molen, 1995). With maturation comes an increased ability to manage interference (Travis, 1998), and hold two or more pieces of information while inhibiting a prepotent response tendency (Diamond & Taylor, 1996), due to increases in the efficiency of the executive system and supporting structures.

The Eriksen flanker task (Eriksen & Eriksen, 1974) has frequently been used to examine interference control (i.e., one aspect of executive control), which is an individual's ability to inhibit task-irrelevant information in the stimulus environment. This task requires participants to discriminate between central (i.e., target) and peripheral (i.e., nontarget flanker) letters presented within an array. Congruent arrays (e.g., *HHHHH*) elicit faster and more accurate responses due to the smaller executive requirements that result from the low interference of flanking stimuli. Incongruent arrays (e.g., *SSHSS*) elicit slower and less accurate responses (Eriksen & Schultz, 1979), due to competing action schemas associated with the flanking stimuli (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Spencer & Coles, 1999). Several varia-

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tions of the flanker task have been used with preadolescent children (Ridderinkhof, van der Molen, Band, & Bashore, 1997; Rueda et al., 2004); the results indicate that children as young as 4 years of age can successfully complete this task, albeit with decreased accuracy and response speed when compared to older preadolescent children (Mezzacappa, 2004). Further, interference control increases until approximately 8 years of age, after which there is little difference in interference reaction time (RT) and response accuracy up through adulthood (Ridderinkhof & van der Molen, 1995; Ridderinkhof et al., 1997; Rueda et al., 2004; but see Ridderinkhof & van der Stelt, 2000, for review).

Several studies using flanker paradigms with adult populations have evidenced a relationship between physical activity and/or aerobic fitness and executive control. Specifically, cross-sectional (Hillman, Motl, et al., 2006) and randomized control (Kramer et al., 1999) designs have examined the relationship between physical activity and behavioral performance on flanker tasks. Results from these studies have observed faster (Hillman, Motl, et al., 2006; Kramer et al., 1999) and more accurate (Hillman, Motl, et al., 2006) responses for those participating in physical activity, with larger benefits for incongruent, relative to the congruent, trials. These findings suggest that although physical activity relates to general improvements in cognitive function (i.e., across congruent and incongruent trials of the flanker task), the relationship is selectively larger for tasks requiring more extensive amounts of executive control (i.e., incongruent trials). However, as mentioned previously, the extension of this research examining the relation of physical activity to executive control is lacking in preadolescent children. Accordingly, the main purpose of this investigation was to examine this relationship in preadolescent children to determine whether fitness is also beneficial to cognition during maturation.

In addition, we investigated the general versus selective nature of the relationship between aerobic fitness and cognitive function. Preliminary data from our laboratory have suggested that the relationship between fitness and cognition in preadolescent children may differ from that observed in adult populations in that it may be characterized by more general, rather than selective, benefits to task performance. Specifically, Buck, Hillman, and Castelli (2008) examined 7- to 12-year-old children to study the relation of aerobic fitness to Stroop task performance, a task that employs multiple conditions requiring variable amounts of executive control, including selective attention, response inhibition, interference control, and speeded responding (Adleman et al., 2002). Results indicated that regardless of age, greater amounts of aerobic fitness were related to better performance across all conditions of the Stroop task, indicating a general, rather than selective, relationship between fitness and cognition in this population.

Further, Hillman, Castelli, and Buck (2005) examined aerobic fitness and cognitive performance using an oddball paradigm, which requires discrimination between stimuli that are presented at variable probabilities. Neuroelectric and behavioral measures were compared in higher- and lower-fit preadolescent children (M_{age} = 9.6 years) and young adults (M_{age} = 19.5 years); results indicated differential neuroelectric function related to the increased allocation of attentional resources during working memory operations (i.e., P3 amplitude) and faster cognitive processing speed (i.e., P3 latency) for higher- compared to lower-fit children, regardless of task condition. Additionally, higher-fit children exhibited shorter RT than their lower-fit peers and response accuracies that did not differ from either adult group. Again, these data indicate a general relationship between fitness and cognition in preadolescent children, because benefits in neuroelectric and behavioral performance were observed during a task requiring minimal executive control.

Finally, with few exceptions (see Themanson, Hillman, & Curtin, 2006 for example), the vast majority of research examining neuroelectric indices of physical activity and cognition has examined the P3 component of the stimulus-locked event-related brain potential (ERP). ERPs provide information regarding a subset of processes involved between stimulus encoding and response execution. Stimulus-locked ERPs, such as the N2 and P3, are endogenous components related to upstream processes involved in response inhibition or conflict (N2 amplitude), attentional resource allocation (P3 amplitude), and cognitive processing speed (P3 latency). Although inferences regarding the P3 are fairly well established (see Polich & Kok, 1995, for review), much debate regarding the N2 remains, because multiple N2 components have been described in the literature that are modulated by various tasks and differ in topography. In tasks that generate conflict, such as a flanker task, a frontocentral N2 has been linked to response inhibition (Folstein & Van Petten, 2008), and dipole models have supported this “cognitive control” interpretation with the observed source localized to the medial frontal cortex (van Veen & Carter, 2002). Following these distinct components, sustained slow wave activity is often observed, which has been related to perceptual or conceptual aspects of stimulus processing (Ruchkin, Johnson, Mahaffey, & Sutton, 1988). Although the functional meaning of the sustained slow wave is often debated (see Dien, Spencer, & Donchin, 2004; Falkenstein, Hohnsbein, & Hoormann, 1994; García-Larrea & Cézanne-Bert, 1998), it is generally believed to reflect nonspecific activity elicited by any synchronized cognitive operations that occur after stimulus engagement (García-Larrea & Cézanne-Bert, 1998; Kok, 1997).

Response-locked ERPs, such as the error-related negativity (ERN—Gehring, Goss, Coles, Meyer, & Donchin, 1993; or N_e—Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991) and error positivity (P_e; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990) reflect downstream aspects of response selection related to conflict detection (ERN; Yeung, Cohen, & Botvinick, 2004) and attentional resource allocation toward (Mathewson, Dywan, & Segalowitz, 2005) or evaluation of (Davies, Segalowitz, Dywan, & Pailing, 2001; Falkenstein et al., 1990) error commission (P_e). These latter components are further thought to reflect task-related learning involved in the modulation of cognitive control that underlies alterations in behavioral responses during subsequent environmental interaction (Holroyd & Coles, 2002; Yeung et al., 2004). Recently, the developmental literature has grown in its reports on the developmental trajectory of various aspects of cognition and the underlying ERP componentry involved in such operations (e.g., Kim, Iwaki, Imashioya, Uno, & Fujita, 2007; Ridderinkhof & van der Molen, 1995). Collectively, measurement of these various neuroelectric responses may lead to a greater understanding of the subset of processes influenced by fitness during development and provide unique information beyond that of behavioral responses.

Research examining physical activity’s influences on the neuroelectric system (Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; Hillman et al., 2005; Hillman, Kramer, Belopolsky, & Smith, 2006) has demonstrated larger P3 amplitude and faster P3 latency for physically active individuals, suggesting greater allocation of attentional resources and faster cognitive processing speed during stimulus encoding, respectively. Other research (Themanson & Hillman, 2006; Thémanson et al., 2006) has observed smaller ERN and larger P_e amplitudes with increased physical activity or aerobic fitness, indicating greater efficiency of neuroelectric processes involved in the cognitive control of action monitoring and the greater allocation of resources following error commission, respectively. It is important to note that these physical activity-related changes in the neuroelectric indices of action monitoring were related to greater slowing of RT following error commission, indicating that higher physical activity levels were related to greater cognitive control on subsequent trials through the modulation of task performance to ensure correct action (Gehring et al., 1993; Kerns et al., 2004). Taken together, previous findings indicating a reduction in ERN amplitude matched with an increase in P_e amplitude and greater post-error slowing might suggest a more effective conflict monitoring system for physically active individuals, whereby a lower threshold for detection and signaling of conflict (i.e., ERN) might enable an increase in the allocation of attentional resources toward, or the evaluation of, conflict (i.e., P_e) and a subsequent increase in the recruitment and implementation of cognitive control (i.e., greater RT slowing) following error commission.

Accordingly, the general versus selective nature of the relationship between aerobic fitness and cognition was examined in preadolescent children during a task requiring variable amounts of interference control, one component of executive control. On the basis of previous research (e.g., Hillman et al., 2004, 2005; Hillman, Kramer, et al., 2006; Themanson et al., 2006), neuroelectric and behavioral measures were examined to test several hypotheses. It was predicted that higher-fit children would exhibit greater task performance (i.e., shorter RT, increased accuracy) than their lower-fit peers. Further, higher-fit children were predicted to exhibit larger component amplitude than lower-fit children for stimulus-locked ERPs, reflecting response inhibition (N2) and attentional resource allocation (P3 amplitude), along with faster cognitive processing speed (P3 latency). Sustained slow-wave positivity was further predicted to increase with fitness, indicating greater activation of poststimulus engagement during cognitive operations. Fitness-related differences were also predicted for response-locked ERPs (i.e., smaller ERN, larger P_e amplitude), indicating that fitness is related to action-monitoring processes involved in cognitive control. The modulation of these response-locked ERP components were further predicted to relate to increased slowing and greater accuracy on subsequent trials, providing additional support for greater cognitive control with fitness (Themanson & Hillman, 2006). Supporting previous research (Buck et al., 2008; Hillman et al., 2005), these fitness-related differences were predicted across conditions requiring variable amounts of interference control, indicating a general rather than selective relationship between fitness and cognition in preadolescent children.

Method

Participants

Forty-eight preadolescent children were recruited and placed into higher ($n = 24$) or lower ($n = 24$) fitness groups based on aerobic capacity, as measured by the Progressive Aerobic Cardiovascular Endurance Run (PACER) test of the FITNESSGRAM (Welk, Morrow, & Falls, 2002). Children were recruited from a summer camp held at the University of Illinois and from the Champaign, Illinois, elementary school system. Four participants were left handed (3 higher-fit, 1 lower-fit) as measured via the Edinburgh Handedness Inventory (Oldfield, 1971). One lower-fit participant was excluded due to parent-disclosed diagnosis of attention-deficit/hyperactivity disorder (ADHD); 3 higher-fit participants were excluded due to excessive artifact in the neuroelectric data; and 6 participants (3 higher-fit, 3 lower-fit) were excluded due to an insufficient number of errors (< 5 errors), which did not allow for examination of neuroelectric (i.e., ERN, P_e) and behavioral (i.e., post-error RT and Accuracy) indices of action monitoring. Thus, analyses were conducted on 38 participants (19 higher-fit, 19 lower-fit) between the ages of 8 and 11. Table 1 lists demographic and fitness information for the final sample. None of the children received special education services related to cognitive disabilities (e.g., attention deficit disorder, etc.). All participants and their legal guardians provided written informed consent in accordance with the Institutional Review Board at the University of Illinois. Those children recruited through Champaign County schools also signed informed consent in accordance with the Champaign Unit #4 policies.

Participant Characteristics

Data were collected on several factors that have been found to affect either physical activity participation or cognitive function. Specifically, the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990) was administered by a trained experimenter to obtain a composite IQ score using measures of crystallized (vocabulary) and fluid (analogies) thinking. In addition, guardians completed the ADHD Rating Scale V (DuPaul, Power, Anastopoulos, & Reid, 1998) and provided information regarding participants' demographics and socioeconomic status (SES). SES was determined by creating a trichotomous index based on three variables: participation in free or reduced-price lunch program at school, the highest level of education

Table 1
Participant Mean (SD) Demographic and Fitness Data by Fitness Group

Variable	Higher-fit	Lower-fit
n	19 (9 girls)	19 (9 girls)
Age (years)	9.3 (0.9)^{a}	9.5 (1.0)^{a}
PACER (#laps)	31.2 (8.9)^{a}	12.6 (3.7)^{b}
BMI	16.6 (1.5)^{a}	21.0 (4.2)^{b}
K-BIT composite score (IQ)	111.0 (9.5)^{a}	115.7 (11.9)^{a}
K-BIT crystallized score (vocabulary)	107.2 (11.4)	111.1 (10.5)
K-BIT fluid score (matrices)	112.3 (10.3)	117.1 (12.0)
SES (median)	2.8 (0.5)^{a}	2.9 (0.3)^{a}
ADHD	7.4 (4.7)^{a}	10.1 (6.4)^{a}

Note. PACER and BMI = subscales of the FITNESSGRAM test; K-BIT = Kaufman Brief Intelligence Test; SES = socioeconomic status; ADHD = scores on the ADHD Rating Scale V. Normative values for the FITNESSGRAM may be found in G. J. Welk, J. R. Morrow, and H. B. Falls, *FITNESSGRAM Reference Guide*, Dallas, TX: Cooper Institute, 2002.
Values that share a common superscript are not significantly different at $p < .05$.

obtained by the mother and father, and number of parents who worked full-time (Birnbaum et al., 2002). All participants reported that they were free of adverse health conditions or neurological disorders, did not take any medications that influence central nervous system function, and had normal (or corrected to normal) vision based on the minimal 20/20 standard.

Fitness Testing

Participants' fitness was assessed using the FITNESSGRAM, which is a valid and reliable field assessment of physical fitness for ages 5 through adulthood (Welk et al., 2002). The FITNESSGRAM measures multiple aspects of physical fitness, including aerobic capacity (i.e., PACER), muscle fitness (i.e., push-ups and curl-ups, flexibility), and body composition through height and weight measures that are converted to a body mass index (BMI) score. With regard to aerobic capacity, the objective of the PACER test is to run as long as possible back and forth across a 20-m space at a specified pace, which increases in speed each minute. Mahar et al. (1997) found that 89% of 213 boys and girls age 10–11 were consistently classified into one of three categories using this measure: needs improvement, healthy fitness zone, or exceeding the healthy fitness zone. In this study, the participants were drawn from a larger sample of 592 children who completed the FITNESSGRAM in group settings (i.e., approximately 25 children per group) under the direction of the research team. The researchers used the criterion established by the FITNESSGRAM Scientific Advisory Committee (Welk et al., 2002) and ranked the children who scored in the bottom (i.e., needs improvement) and top (i.e., exceeding the healthy fitness zone) aerobic fitness categories (i.e., PACER score) to identify the participants with the highest and lowest aerobic capacity. Only the participants in the top 10% and bottom 10% of these categories were selected for study.

Cognitive Task

Participants completed congruent and incongruent conditions of the Eriksen flanker task (Eriksen & Eriksen, 1974), which required them to respond as quickly as possible to an array of letters presented on a computer monitor from a distance of 1 m with visual angles of 1.7° and 3.7° in the vertical and horizontal directions, respectively. The stimuli were 7.62-cm-tall white letters presented focally on a black background in a random order for 200 ms with an interstimulus interval of 1,200 ms from stimulus offset to onset. Target stimuli (*H* and *S*) required a button press with the right and left thumbs, respectively. Congruent trials were those in which the target letter was flanked by the same letter (i.e., *HHHHH* or *SSSSS*). Incongruent trials were those in which the target letter was flanked by the opposing response letter (i.e., *HHSHH* or *SSHSS*). The two conditions were equiprobable and random within each block of trials. Six blocks of 52 trials were administered with a 2-min rest period between blocks. The participants were engaged in the task for 20 min from practice trials through the completion of the last task block. Task blocks were counterbalanced across participants. Stimulus presentation, timing, and task performance measures were controlled by Neuroscan Stim software (ver. 1.0; Neuro Inc., El Paso, TX).

Laboratory Procedure

After obtaining informed consent, a trained experimenter administered the K-BIT to the child participant while his or her guardian completed the ADHD Rating Scale V and the health and demographics questionnaire. The participant was then prepared for neuroelectric measurement in accordance with the guidelines of the Society for Psychophysiological Research (Picton et al., 2000). An experimenter read aloud the task instructions, and the participant performed 20 practice trials. Following the completion of the flanker task, all electrodes were removed, and the participant and guardian were briefed on the purpose of the experiment. The session lasted approximately 1.5 hr, and each participant received $20 for participating.

Electroencephalogram (EEG) Recording

EEG activity was measured from 28 midline and lateral Ag/AgCl electrodes in accordance with the 10-20 system (Jasper, 1958) using a Quik-Cap (Neuro, Inc., El Paso, TX). Ongoing EEG activity was referenced to the left mastoid (A1), with AFz serving as the ground electrode. Electro-oculographic activity was collected from electrodes placed above and below the right orbit and at the outer canthus of each eye to record bipolar eye movements. Impedances were kept below 10 kΩ. A Neuroscan SynAmps bioamplifier (Neuro Inc.) was used to continuously digitize (500 Hz sampling rate) and amplify (500×) the EEG signal with a 70-Hz low-pass filter and a 60-Hz notch filter. Continuous data were collected with Neuroscan Scan 4.3 (Neuro Inc.) software on a microcomputer.

Data Reduction

ERPs. All ERP reduction procedures included ocular artifact correction to continuous data using a spatial filter (Compumedics/Neuroscan, 2003), re-referencing to an average of the mastoid electrodes, and merging with behavioral data. Stimulus-locked and response-locked ERP components were reduced separately.[1] Stimulus-locked components of the ERPs included the creation of epochs from −100 to 1,000 ms around stimuli and baseline correction using the 100-ms prestimulus period. Data were filtered with a 30-Hz low-pass cutoff (24 dB/octave), and artifact detection excluded trials with amplitude excursions of ±100 μV. Artifact-free data that were accompanied by correct responses were averaged. The N2 and P3 components were defined as the largest negative-going peak within a 240–425-ms latency window and the largest positive-going peak within a 375–675-ms latency window, respectively. In addition, mean amplitudes were calculated for the sustained slow wave activity between 675 and 975 ms. To facilitate comparison, mean amplitudes for the P3 were also calculated between 375 and 675 ms. Amplitudes were measured as a change from the prestimulus baseline, and peak

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[1] By default, any trial in which an error occurred was removed from the stimulus-locked average (N2, P3), and any trial containing a correct response was not included in the response-locked (ERN, P_e) analyses. The only potential overlap occurred between the stimulus-locked and the correct-response-locked (CRN) averages, albeit with different measures extracted. In this case, an average of 83.3% of the trials co-occurred between the two averages. The other 16.7% of the trials that did not co-occur in the two averages were due to artifact rejection in one of the averages. Thus, an average of 6.1 trials did not co-occur. Regardless, CRN was not analyzed with regard to fitness.

latency was defined as the time point of the maximum peak amplitude. The average number of trials included in the stimulus-locked waveforms were 106 (range: 53–143) and 97 (range: 51–144) for congruent and incongruent trials, respectively.

Response-locked components of the ERPs included the creation of epochs from −500 ms preresponse to 1,500 ms postresponse and baseline correction using the 100-ms time window ranging from −200 ms to −100 ms prior to the response (Nieuwenhuis et al., 2002). Data were filtered using a 15 Hz (24 dB/octave) low-pass filter, and artifact detection excluded trials containing amplitude excursions of ±100 μV. Average ERP waveforms for correct trials were matched to error trial waveforms on response time and number of trials to protect against differential artifacts of the stimulus-related activity overlapping the response-locked ERP activity (Coles, Scheffers, & Holroyd, 2001). ERN was defined as the maximum negative deflection between 0–200 ms, and P_e was defined as the maximum positive deflection between 200–500 ms postresponse (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000). The average number of trials included in the response-locked waveform was 37 (range: 6–97). Matching involved selecting individual correct trials for each participant, without replacement, that matched the RT of each error trial for that individual. Because error trials are typically associated with shorter RT than correct trials (Falkenstein, Hoormann, & Hohnsbein, 2001; Mathewson et al., 2005; Yeung et al., 2004), this procedure removes artifacts that may exist in the timing of processing due to differences in response latency for correct and error trials and results in an equal number of matched-correct trials and error trials for each individual to compare differences across accuracy conditions.

Task performance. Behavioral data were collected on response latency (i.e., time in milliseconds from the presentation of the stimulus) and response accuracy (i.e., percentage of correct responses) for all trials across blocks within each task condition (i.e., congruent, incongruent). Errors of omission (nonresponses) were categorized as incorrect responses for calculations of response accuracy, though omission error trials were not included in the creation of response-locked ERP waveforms due to the lack of a behavioral response. Average response latencies were calculated for each participant for (a) correct trials, (b) commission error trials, (c) matched-correct trials (the subset of correct trials matched to specific error trials based on RT), (d) correct trials following an error trial, and (e) correct trials following a matched-correct trial. Each participant's average RT for correct trials following error trials was compared to his or her average RT for correct trials following matched-correct trials in statistical analyses to provide a measure of post-error response slowing, which is a behavioral indicator of increased recruitment and implementation of cognitive control (Gehring et al., 1993; Kerns et al., 2004). Due to the consistent finding that average RT on error trials is shorter than average RT on correct trials (Mathewson et al., 2005; Yeung et al., 2004), this comparison accounts for any effects of slowing that are present simply because responses on error trials generally tend to be faster than responses on correct trials.

Statistical Analysis

Statistical analyses were performed separately for each component of the stimulus- and response-locked ERP. N2 and P3 peak values (i.e., amplitude, latency), and mean amplitude values for the P3 and slow wave were submitted to a 2 (fitness: higher, lower) × 2 (condition: congruent, incongruent) × 3 (region: frontal, central, parietal) × 5 (site: 7, 3, *z*, 4, 8) mixed-model MANOVA with repeated measures. Region and site were included in these analyses to better examine the scalp distribution of this component. Response-locked ERN and P_e values were submitted to a 2 (fitness) × 2 (accuracy: error, matched–correct) repeated measures multivariate analysis of variance at the Cz site, because previous research has demonstrated that these components have their topographic maximum near this electrode site (Falkenstein et al., 2000).

Behavioral data (i.e., RT, response accuracy) were submitted to a 2 (Fitness) × 2 (Condition) repeated measures MANOVA to examine group differences in task performance. Following commission errors, behavioral data were submitted to a 2 (fitness) × 2 (accuracy) repeated measures MANOVA to examine performance changes associated with cognitive control (i.e., response slowing, increased accuracy). All analyses with three or more within-subjects levels used the Wilks's lambda statistic. Post hoc comparisons were conducted using Tukey's honestly significant difference tests. The alpha level for all tests was set at $p = .05$.

Results

Participant Characteristics

Participant demographic and fitness data are provided in Table 1. Fitness comparisons using between-subject *t* tests indicated that higher-fit participants ($M = 31.2 \pm 8.9$ laps) ran more laps during the PACER task than lower-fit participants ($M = 12.6 \pm 3.7$ laps), $t(36) = 8.4$, $p < .001$, confirming the aerobic fitness groupings. With the exception of BMI, the other demographic variables (e.g., age, IQ, SES, etc.) did not differ between fitness groups, $t(36) \leq 1.4$, $p > .18$. Fitness differences indicated lower BMI for higher-fit ($M = 16.6 \pm 1.5$) relative to lower-fit ($M = 21.0 \pm 4.2$) participants, $t(36) = 4.3$, $p < .001$; however, both groups fell within the healthy range for normative BMI values for this age group (Centers for Disease Control and Prevention, 2006). Regardless, Pearson product-moment correlations were conducted for BMI and all dependent variables (i.e., RT, response accuracy, stimulus- and response-locked ERP component amplitudes and latencies) across higher- and lower-fit participants. The correlations revealed no significant relationships between BMI and any of the dependent variables, with the exception of P_e during matched–corrected trials ($r = -.34$, $p < .05$). Thus, BMI was entered as a covariate during the subsequent P_e analyses.

Task Performance

For the flanker task, incorrect responses and failure to respond were considered to be errors[2] in the overall task performance analysis. Table 2 provides means (*SD*) for RT and response accuracy data to congruent and incongruent conditions by fitness grouping. RT responses yielded a significant effect of condition, $F(1, 36) = 13.6$, $p < .001$, $\eta^2 = .27$, with all participants exhibiting longer responses on incongruent ($M = 561.8 \pm 95.6$ ms), relative to congruent ($M = 522.6 \pm 95.4$ ms), trials. Response

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[2] Commission errors accounted for 63.7% of the total number of errors committed. Higher- and lower-fit groups did not differ in the number or percentage of commission errors, *t*s $(36) \leq 1.2$, $p > .23$.

Table 2
Task Performance by Fitness Group for Congruent and Incongruent Conditions of the Flanker Task

Measure	Higher-fit children	Lower-fit children
Mean RT (ms)		
Congruent trials	514.6 ± 77.0	530.6 ± 112.5
Incongruent trials	565.1 ± 93.0	558.6 ± 100.5
Median RT (ms)		
Congruent trials	510.5 ± 73.7	513.4 ± 93.8
Incongruent trials	548.1 ± 97.6	552.7 ± 103.6
Response accuracy (%)		
Congruent trials	85.3 ± 10.1	77.8 ± 10.2
Incongruent trials	78.8 ± 11.1	72.3 ± 9.1

Note. RT = reaction time.

accuracy also yielded a significant effect of condition, $F(1, 36) = 32.2$, $p < .001$, $\eta^2 = .47$, with participants responding more accurately on congruent ($M = 81.5 \pm 10.7\%$) relative to incongruent ($M = 75.6 \pm 10.5\%$) trials. In addition, a fitness effect was observed for response accuracy, $F(1, 36) = 5.0$, $p = .03$, $\eta^2 = .12$, with higher-fit participants ($M = 82.1 \pm 10.2\%$) responding more accurately than lower-fit participants ($M = 75.2 \pm 9.9\%$).

For post-error analyses, only commission errors were included because an incorrect response is required to assess the ERN. Analyses of error and matched-correct RT revealed a significant effect, $F(1, 36) = 17.2$, $p < .001$, $\eta^2 = .32$, with shorter RT on error trials ($M = 421.0 \pm 79.5$ ms) compared to matched correct trials ($M = 429.6 \pm 79.6$ ms), regardless of fitness. Further, RTs on correct trials following error trials were significantly longer ($M = 565.6 \pm 111.3$ ms) compared to RTs on error trials ($M = 421.0 \pm 79.5$ ms), $F(1, 36) = 149.3$, $p < .001$, $\eta^2 = .81$, indicating that response slowing occurred following an incorrect response, regardless of fitness. Analysis of posttrial RT for both error and matched-correct trials also revealed a significant effect, $F(1, 36) = 66.8$, $p < .001$, $\eta^2 = .65$, with longer RTs on trials following an error trial ($M = 656.6 \pm 111.3$ ms) relative to trials following a matched-correct trial ($M = 505.1 \pm 98.1$ ms). Response accuracy data for posttrial responses indicated main effects of fitness, $F(1, 36) = 4.2$, $p < .05$, $\eta^2 = .10$, and accuracy, $F(1, 36) = 4.0$, $p = .05$, $\eta^2 = .10$, indicating that higher-fit participants ($M = 81.9 \pm 10.5\%$) were more accurate following both error and matched-correct trials than lower-fit participants ($M = 74.7 \pm 11.3\%$), and that all participants were more accurate following error trials ($M = 80.0 \pm 13.1$ %) relative to matched-correct trials ($M = 76.6 \pm 11.9\%$).

Stimulus-Locked ERP Analysis

Figure 1 illustrates stimulus-locked grand averaged ERP waveforms for each fitness group at the three midline electrode sites (Fz, Cz, Pz) to congruent and incongruent stimuli.

N2. The omnibus analysis for N2 amplitude revealed a main effect of condition, $F(1, 36) = 5.5$, $p < .03$, $\eta^2 = .13$, with larger N2 amplitude for incongruent ($M = -3.5 \pm 2.6$ μV) relative to congruent ($M = -3.1 \pm 2.6$ μV) trials. Further, a site effect was observed, $F(4, 33) = 8.5$, $p < .001$, $\eta^2 = .51$, which was modified by a Region × Site interaction, $F(8, 29) = 6.8$, $p < .001$, $\eta^2 = .65$. Decomposition of this interaction yielded significant site effects in all three regions, $F\text{s}(4, 34) > 9.0$, $p < .001$, $\eta^2 > .52$. Pair samples t test revealed that F7, F3, and Fz exhibited larger amplitude than F4 and F8, $t\text{s}(37) > 3.2$, $p < .003$. At central sites, T7 exhibited larger amplitude than C3 and C4, and Cz exhibited larger amplitude than C3 and C4, $t\text{s}(37) > 3.6$, $p < .001$. Parietal region analyses yielded larger amplitude at P7 and P8 relative to P3 and P4, and at all lateral sites relative to Pz, $t\text{s}(37) \geq 3.6$, $p \leq .001$.

The omnibus analysis for N2 latency revealed effects of condition, $F(1, 36) = 19.1$, $p < .001$, $\eta^2 = .35$; region, $F(2, 35) = 11.1$, $p < .001$, $\eta^2 = .39$; and site, $F(4, 33) = 7.3$, $p < .001$, $\eta^2 = .47$; and two-way interactions of Condition × Region, $F(2, 35) = 3.4$, $p < .05$, $\eta^2 = .16$, and Region × Site, $F(8, 29) = 8.9$, $p < .001$, $\eta^2 = .71$, that were modified by a three-way interaction of Condition × Region × Site, $F(8, 29) = 2.6$, $p = .03$, $\eta^2 = .42$. Decomposition of this interaction revealed similar effects at frontal and central regions. Specifically, a condition effect was observed, $F(1, 37) > 7.8$, $p < .01$, $\eta^2 = .17$, with congruent trials eliciting shorter N2 latency than incongruent trials. In addition, a site effect was observed with F7 and F8 exhibiting longer N2 latency relative to F3, Fz, and F4, and T7 exhibiting longer latency relative to the other four sites, $t\text{s}(37) > 2.9$, $p \leq .007$. Lastly, a Condition × Site interaction was observed over the parietal region, $F(4, 34) > 2.7$, $p = .05$, $\eta^2 = .24$. Follow up analyses indicated longer latency for incongruent relative to congruent trials only at the Pz electrode site, $t(37) = 2.6$, $p = .01$.

P3. The omnibus analysis revealed three main effects of fitness, $F(1, 36) = 4.7$, $p < .04$, $\eta^2 = .12$, with larger P3 amplitude for higher- ($M = 9.4 \pm 2.4$ μV) compared to lower-fit participants ($M = 7.6 \pm 2.7$ μV), region, $F(2, 35) = 138.5$, $p < .001$, $\eta^2 = .89$, and site, $F(4, 33) = 46.1$, $p < .001$, $\eta^2 = .85$. However, these main effects were modified by two two-way interactions of Fitness × Region, $F(2, 35) = 5.4$, $p < .01$, $\eta^2 = .23$, and Region × Site, $F(8, 29) = 23.7$, $p < .001$, $\eta^2 = .87$. Decomposition of the Fitness × Region interaction indicated that higher-fit participants exhibited larger P3 amplitude over central and parietal regions, relative to lower-fit participants, $t\text{s}(36) \geq 2.4$, $p < .025$. No such effect was observed over the frontal region, $t(36) = .7$, $p = .5$ (see Figure 2). Decomposition of the Region × Site interaction yielded significant differences between the sites in each of the three regions, $F\text{s}(4, 34) \geq 10.5$, $p < .001$, $\eta^2 \geq .6$. Simple effects tests indicated that P3 amplitude achieved its maxima over midline sites in the central and parietal regions, and over right lateral sites in the frontal region.

P3 latency analyses revealed main effects of condition, $F(1, 36) = 21.6$, $p < .001$, $\eta^2 = .38$, with longer latency for incongruent ($M = 529.4 \pm 38.6$ ms) relative to congruent ($M = 506.6 \pm 35.5$ ms), trials, and region, $F(2, 35) = 35.1$, $p < .001$, $\eta^2 = .67$. This latter effect was superseded by a Region × Site interaction, $F(8, 29) = 8.2$, $p < .001$, $\eta^2 = .69$, and follow-up analyses indicated significant site effects over frontal and parietal regions, $F\text{s}\ (4, 34) \geq 7.3$, $p < .001$, $\eta^2 \geq .46$. Simple effects tests indicated shorter P3 latency over left lateral and midline sites relative to right midline sites. No effects of fitness were observed.

Mean P3 amplitude. As expected, the omnibus analysis corroborated the P3 peak amplitude findings with three main effects of fitness, $F(1, 36) = 4.9$, $p < .04$, $\eta^2 = .12$, with larger positivity for higher- ($M = 5.1 \pm 3.5$ μV) compared to lower-fit participants ($M = 3.3 \pm 3.5$ μV); region, $F(2, 35) = 116.2$, $p < .001$, $\eta^2 =$

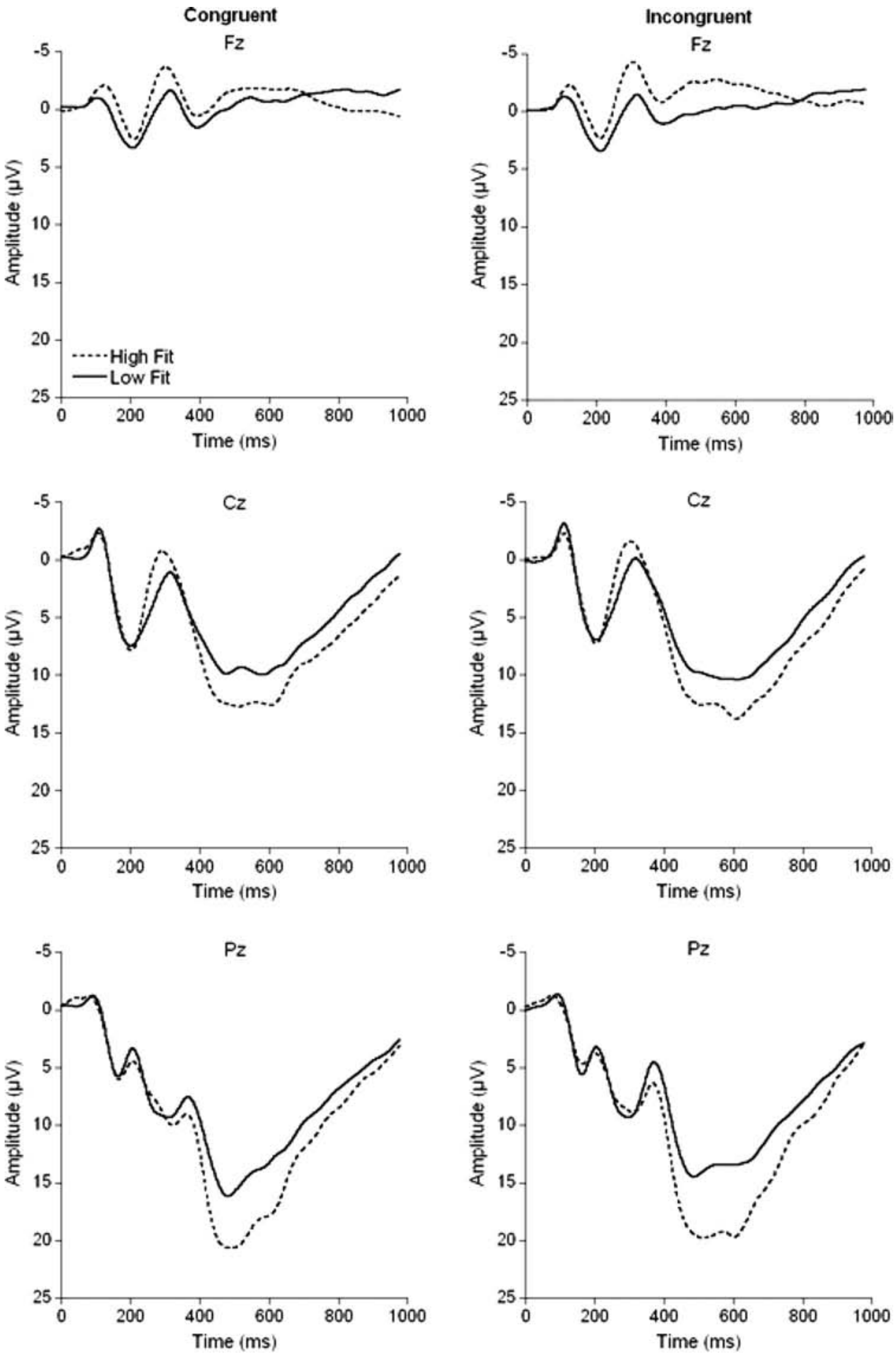

Figure 1. Grand averaged stimulus-locked ERP waveforms for each fitness group at the three midline electrode sites to congruent and incongruent trials of the flanker task.

.87; and site, $F(4, 33) = 43.8$, $p < .001$, $\eta^2 = .84$. However, these main effects were modified by three 2-way interactions of Fitness × Region, $F(2, 35) = 5.6$, $p < .01$, $\eta^2 = .24$; Congruency × Region, $F(2, 35) = 3.9$, $p = .03$, $\eta^2 = .18$; and Region × Site, $F(8, 29) = 20.4$, $p < .001$, $\eta^2 = .85$. Decomposition of the Fitness × Region interaction indicated that higher-fit participants exhibited larger positivity over central and parietal regions relative to lower-fit participants, $ts(36) \geq 2.3$, $p < .025$. No such effect was

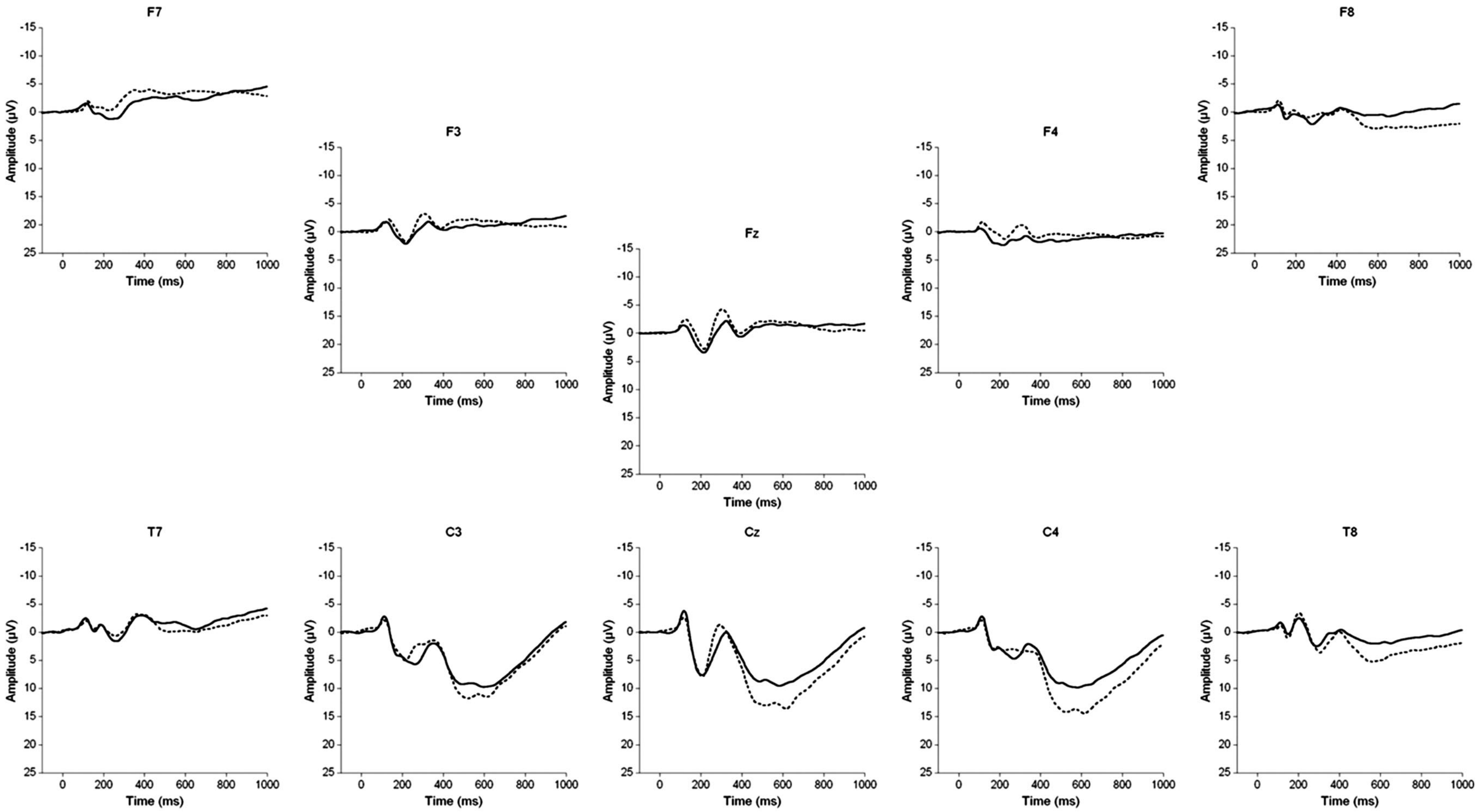

Figure 2. Grand averaged stimulus-locked event-related potential waveforms for each fitness group at the frontal, central, and parietal regions across conditions of the flanker task.

(*Figure continues*)

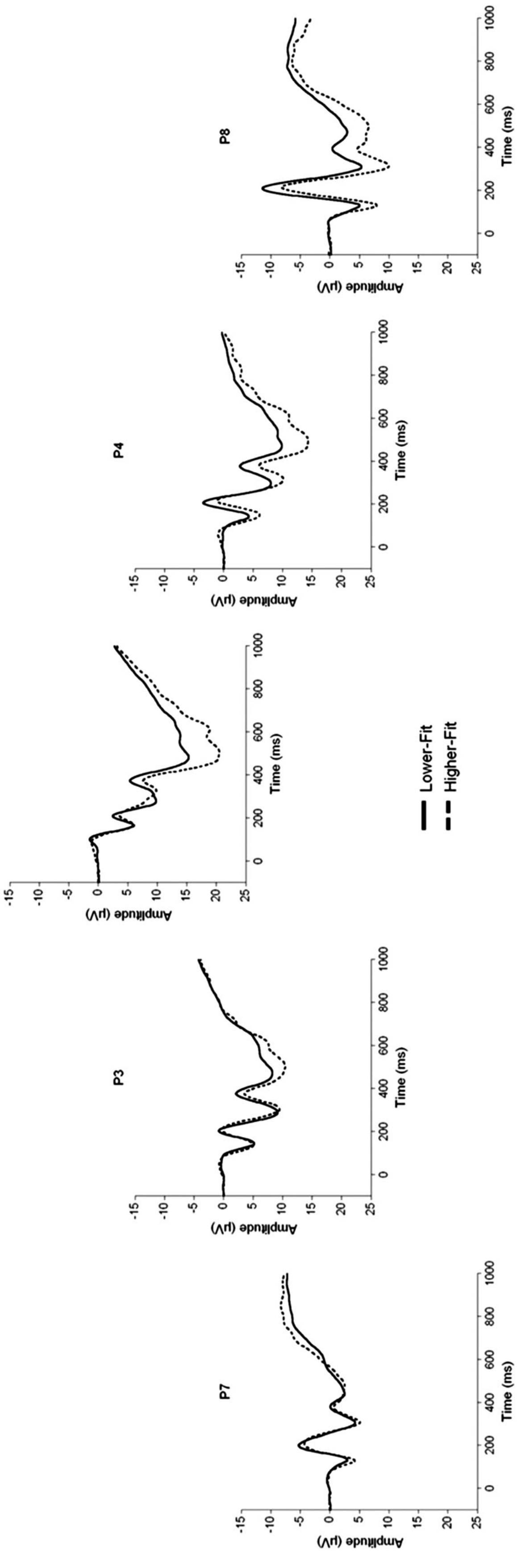

Figure 2. (*continued*)

observed over the frontal region, $t(36) = 0.5$, $p = .6$ (see Figure 2). Decomposition of the Congruency × Region interaction indicated larger positivity (i.e., less negativity) for congruent (-0.42 ± 2.8 μV) relative to incongruent (-0.88 ± 2.6 μV) trials in the frontal region, $t(37) = 2.7$, $p = .01$, and no effect in the central or parietal regions, ts$(36) \leq 1.5$, $p > .13$. Decomposition of the Region × Site interaction yielded significant differences among the sites in each of the three regions, Fs$(4, 34) \geq 9.6$, $p < .001$, $\eta^2 \geq .5$. Simple effects tests indicated that the early positivity achieved its maxima over midline sites in the central and parietal regions and over right lateral sites in the frontal region.

Slow wave. The omnibus analysis indicated main effects of region, $F(2, 35) = 56.3$, $p < .001$, $\eta^2 = .76$, and site, $F(4, 33) = 32.0$, $p < .001$, $\eta^2 = .8$, which were modified by two 2-way interactions of Congruency × Region, $F(2, 35) = 6.3$, $p = .005$, $\eta^2 = .27$, and Region × Site, $F(8, 29) = 39.2$, $p < .001$, $\eta^2 = .92$. Decomposition of the Congruency × Region interaction indicated larger positivity (i.e., less negativity) for incongruent (-0.12 ± 5.2 μV) relative to congruent (-1.1 ± 4.8 μV) trials in the parietal region, $t(37) = 2.7$, $p = .01$, and no effect in the frontal or central regions, ts$(37) \leq 1.9$, $p > .06$. Decomposition of the Region × Site interaction yielded significant differences among the sites in each of the three regions, Fs$(4, 34) \geq 4.5$, $p < .005$, $\eta^2 \geq .4$. Simple effects tests indicated that the early positivity achieved its maxima over midline sites in the central and parietal regions, and over right lateral sites in the frontal region. No effects of fitness were observed.

Response-Locked ERP Analysis

Figure 3 illustrates response-locked grand averaged ERP waveforms for each fitness group at the three midline electrode sites (Fz, Cz, Pz) to congruent and incongruent stimuli.

ERN. Initial analyses were conducted on three midline electrodes (Fz, Cz, Pz) to determine the topography of the ERN component. A 2-way interaction of Accuracy (error, matched-correct) × Site was observed, $F(2, 36) = 9.7$, $p < .001$, $\eta^2 = .35$, with post hoc t tests indicating greater ERN amplitude for error relative to matched-correct trials at the Cz site, $t(37) = 2.4$, $p = .02$. Marginally smaller effects (ps $< .06$) were observed at the Fz and Pz electrode sites, indicating that the ERN component had maximal amplitude over the central scalp region. Accordingly, further analyses were conducted using the Cz electrode site. Subsequent analyses comparing fitness groups revealed a 2-way interaction of Fitness × Accuracy, $F(1, 36) = 6.3$, $p < .02$, $\eta^2 = .15$. Decomposition of this interaction revealed smaller ERN amplitude for higher-fit relative to lower-fit participants for error trials,[3] $t(36) = 2.5$, $p < .02$, whereas no such effect was observed for matched-correct trials, $t(36) = 0.3$, $p = .77$ (see Figure 4).

P_e. Similar to the ERN, initial analyses were conducted on the three midline electrodes (Fz, Cz, Pz) to determine the topography of the P_e component. A two-way interaction of Accuracy × Site was observed, $F(2, 36) = 42.2$, $p < .001$, $\eta^2 = .7$, with post hoc t tests indicating greater P_e amplitude for error relative to matched-correct trials at the Cz and Pz sites, $t(37) \geq 7.1$, $p < .001$ (see Figure 3). Accordingly, further analyses were conducted using the Cz electrode site,[4] and these analyses also included BMI as a covariate. Subsequent analyses comparing fitness groups revealed a two-way interaction of Fitness × Accuracy, $F(1, 35) = 9.7$, $p <$

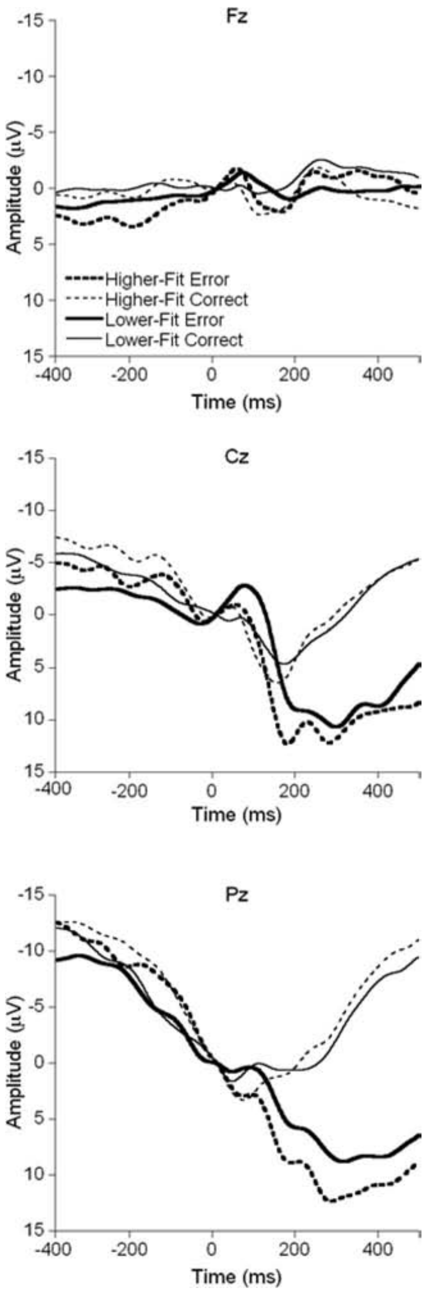

Figure 3. Grand averaged response-locked event-related potential waveforms for each fitness group at the four midline electrode sites for error and matched-correct trials of the flanker task.

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[3] Secondary ERN analyses were conducted with the removal of 4 participants (2 high fit, 2 low fit) who exhibited less than 15 errors to ensure that those participants were not driving the fitness effect. Analyses revealed similar fitness differences for ERN amplitude, $t(33) = 2.5$, $p = .02$.

[4] P_e analyses conducted on the Pz electrode site revealed effects similar to those reported for the Cz electrode site.

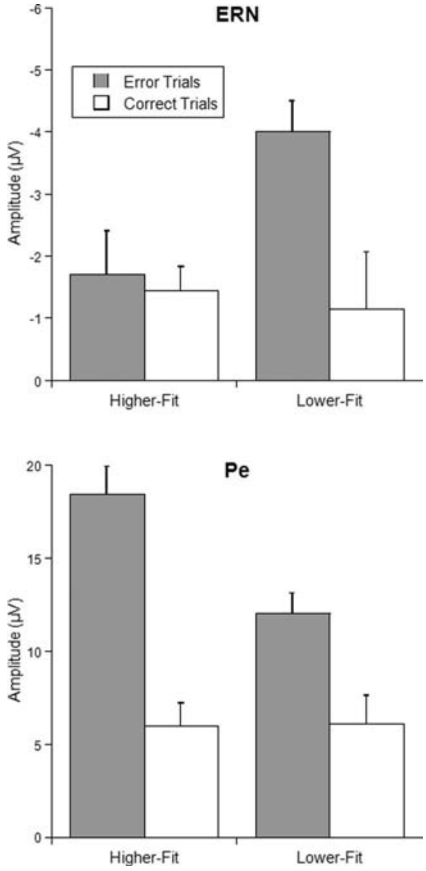

Figure 4. Error-related negativity (ERN) and P_e amplitudes for each fitness group at the Cz electrode site.

.005, $\eta^2 = .22$. Decomposition of this interaction revealed larger P_e amplitude for higher-fit relative to lower-fit participants for error trials, $t(36) = 2.8$, $p < .01$, whereas no such effect was observed for matched-correct trials, $t(36) = 0.06$, $p = .95$ (see Figure 4).

Correlations. Pearson product-moment correlations were conducted to assess the relationship between the behavioral and neuroelectric measures. Analyses revealed a significant positive correlation between post-error response accuracy and the P_e component at the Cz electrode site, $r = .5$, $p = .001$, indicating that larger amplitude following a commission error was associated with greater accuracy on the subsequent trial. An examination of this relationship separately for each fitness group indicated that higher-fit participants exhibited a significant correlation between post-error response accuracy and P_e amplitude, $r = .51$, $p < .03$, whereas no such relationship was observed for lower-fit participants, $r = .33$, $p = .16$. No other correlations were observed.

Discussion

Aerobic fitness was related to better cognitive function in preadolescent children using a task that required variable amounts of interference control, one aspect of executive control. Higher- and lower-fit children exhibited the expected increase in RT and decrease in response accuracy to incongruent compared to congruent trials. However, higher-fit children also exhibited greater response accuracy compared to lower-fit children, regardless of task condition. The neuroelectric data supported fitness-related differences in task performance, with higher-fit children exhibiting differential ERPs relative to lower-fit children on upstream stimulus encoding processes and downstream action monitoring processes. These findings suggest that fitness may be related to general improvements in cognition during development and extend the fitness–cognition database to include executive function in preadolescent children.

Task Performance

Replicating previous research (Mezzacappa, 2004; Ridderinkhof & van der Molen, 1995), preadolescent children, regardless of fitness level, performed better on congruent compared to incongruent trials of the Eriksen flanker task, indicating that tasks requiring greater amounts of interference control are associated with decrements in task performance. The present data also suggest that aerobic fitness was beneficial to components of task performance in preadolescent children. Specifically, higher-fit children exhibited increased response accuracy compared to lower-fit children across task conditions, suggesting that fitness may be related to general improvements on tasks requiring variable amounts of interference control. However, significant differences were not observed for RT, indicating that fitness was not associated with response speed. The latter finding diminishes the possibility that higher- and lower-fit children employed differential cognitive strategies, such as a speed-accuracy trade-off (i.e., one group performing as accurately as possible and the other performing as quickly as possible) during task performance.

The observation of fitness-related differences in response accuracy corroborates the extant literature regarding physical activity and interference control in adult populations (Hillman, Motl, et al., 2006). Hillman, Motl, et al. (2006) examined the relationship between self-reported physical activity and interference control using a modified flanker task in 241 community-dwelling individuals between 15 and 71 years of age. The findings revealed that increases in physical activity were related to decreases in response speed across congruent and incongruent conditions of the flanker task, suggesting a general relationship between physical activity and response speed. Further, physical activity was associated with increased accuracy for both congruent and incongruent trials in older adults, whereas no relationship was found for younger adults. However, this relationship was disproportionately larger for incongruent trials in the older adults, indicating that physical activity has both a general and selective relationship to task performance (Hillman, Motl, et al., 2006). Taken together, the data suggest a beneficial relationship between physical activity and behavioral indices of cognitive performance in children and adults. However, the exact nature of this relationship remains elusive, as the findings differ across studies despite similarities in the tasks employed. As such, the general versus selective nature observed across studies may change across the lifespan as a result of alteration in the brain structures supporting performance on executive tasks.

To date, only one previous study has examined the relationship between aerobic fitness and neurocognitive function in preadolescent children. Specifically, Hillman et al. (2005) compared higher- and lower-fit children using an oddball task, which requires stimulus discrimination and manipulates presentation probability. Findings revealed shorter RT and a trend toward greater accuracy in higher-fit children. The current findings also corroborate, in part, Hillman et al. (2005) and suggest general, rather than selective, benefits in task performance may be associated with aerobic fitness during preadolescent childhood, because differences were observed across task conditions. Although some differences may be noted between the findings of Hillman et al. (2005) and the present data, this may be due to differences in the tasks performed, which varied substantially in the amount of executive control required. That is, the observed lack of fitness-related differences for RT in the present dataset may be due to the greater demand for executive control, which is largely mediated by the frontal lobes (Robbins et al., 1998), an area of the brain that has been found to be immature in preadolescent children (Bunge et al., 2002). Alternatively, given the relatively small executive control requirement necessitated by a simple stimulus discrimination task, the fitness-related difference for RT in Hillman et al. (2005) may be related to improved health and function of other brain regions, which mature earlier in the human lifespan. Clearly, future research is needed to better understand the complex relationship between fitness and the underlying mechanisms responsible for changes in task performance in children.

Neuroelectric Indices of Stimulus Engagement

Hillman et al. (2005) also observed larger P3 amplitude for higher- compared to lower-fit children in response to a stimulus discrimination task. The current dataset replicated this finding because larger P3 amplitude was again found for higher-fit children, and extends the physical activity database in children to tasks involving variable amounts of interference control. Based on contemporary theories of P3, the increased amplitude observed with fitness may reflect an increase in the allocation of attentional resources during stimulus encoding (Polich & Kok, 1995). One mechanism by which aerobic fitness may facilitate cognitive performance is through the recruitment of additional resources toward the processing of incoming information in the stimulus environment (Polich & Herbst, 2000; Polich & Kok, 1995). Therefore, increases in P3 amplitude associated with fitness may reflect an increase in the quality with which information is processed (Polich & Herbst, 2000). This finding has now been observed across multiple studies examining physical activity and various aspects of executive control (e.g., Hillman, Kramer, et al., 2006) and other aspects of cognition (see Kramer & Hillman, 2006, for a review) in adult populations, suggesting that this relationship is robust. The current dataset extends this area of research to include tasks involving variable amounts of interference control in preadolescent children and further indicates that aerobic fitness may relate to improved cognitive health during development through the increased quality of information processing during stimulus encoding.

It is interesting that the observed fitness-related findings did not extend to the sustained slow wave activity. That is, the increased amplitude (both peak and mean) observed for higher- relative to lower-fit participants' P3 did not continue into the slow wave period, indicating that the beneficial influence of fitness during stimulus engagement may be limited to encoding processes. Given that the functional significance of the sustained slow wave is thought to be task dependent, it is somewhat difficult to determine the specific processes occurring after stimulus engagement that are impervious to fitness (e.g., response selection, conceptual processing, memory storage). Regardless of the functional significance of the sustained slow wave, fitness-related differences appear to be selective to encoding processes during stimulus engagement. However, slow wave activity differentiated flanker congruency, with incongruent trials eliciting a larger positivity over the parietal regions relative to congruent trials. This finding corroborates previous research indicating that the late positive slow wave may reflect perceptual difficulty (Ruchkin et al., 1988) engendered by conflict processing (West, 2003). Accordingly, although the sustained slow wave was not influenced by aerobic fitness, it was sensitive to the increased conflict inherent in the more perceptually demanding incongruent trials.

Neuroelectric Indices of Action Monitoring

With regard to the relation of fitness to alterations in cognitive control, the observed results corroborate previous findings in adult populations, as reduced ERN amplitude and increased P_e amplitude were observed for higher- compared to lower-fit children during error trials, but not during correct trials. It is interesting that P_e amplitude was correlated with post-error accuracy in higher-fit children, whereas no such relationship was observed for lower-fit children. Collectively, this pattern of findings across both neuroelectric and behavioral measures suggests that fitness may relate to increased effectiveness of the action monitoring system. Specifically, a reduction in ERN amplitude with fitness may indicate a reduction in the evaluative threshold to signal the need for increased top-down control, prompting an increase in the integrity of attentional allocation or evaluation toward the error indicated by an increase in the P_e component and greater regulation of cognitive control processes on subsequent trials, as denoted by increased response accuracy.

The current data also extend two previous reports relating fitness to action-monitoring processes in adult populations (Themanson & Hillman, 2006; Themanson et al., 2006). These reports have indicated a beneficial relationship between both physical activity (Themanson et al., 2006) and aerobic fitness (Themanson & Hillman, 2006) in younger and older adults on neuroelectric and behavioral indices of action monitoring. Specifically, both studies revealed a reduction in the evaluative signal (i.e., decreased ERN amplitude) necessary to trigger top-down control of action monitoring processes. The ERN has been related to either the detection of errors during task performance (Gehring et al., 1993; Holroyd & Coles, 2002; Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996) or more generally to the detection of response conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Yeung et al., 2004), which can be elicited by commission errors. Thus, although debate remains as to the specific functional significance of the ERN, current theories hold that the ERN is a critical early index of action-monitoring processes used to signal for adjustments in control to improve task performance. Thus, fitness may be one factor that can improve the effectiveness with which this detection system operates and ultimately lead to improvements in task execution.

Further, both studies (Themanson & Hillman, 2006; Themanson et al., 2006) evidenced an increase in P_e amplitude, which has been related to the allocation of attentional resources following conflict monitoring (Mathewson et al., 2005) and the postresponse evaluation of an error (Davies et al., 2001; Falkenstein et al., 1990), relating greater effectiveness in detection to an increased evaluation of behavioral shortcomings. It is important that these previous reports have indicated an additional relationship between neuroelectric indices of action monitoring and alterations in post-error responding, indicating that physical activity participation and aerobic fitness may have a positive influence on the cognitive control of behavior (Themanson & Hillman, 2006; Themanson et al., 2006). Accordingly, the current data extend the fitness and cognition database and suggest that the relationship between fitness and downstream action-monitoring processes involved in cognitive control appears during preadolescent maturation and is stable across the lifespan.

The current findings also corroborate neuroimaging research by Colcombe et al. (2004), who examined the relationship between aerobic fitness and executive function using a flanker task. They found increased activation of task-related prefrontal and parietal brain regions involved with inhibitory functioning in high-fit, compared to low-fit, older adults and in older adults who completed a 6-month aerobic exercise intervention compared to those who received a nonaerobic flexibility intervention (Colcombe et al., 2004). They concluded that increased recruitment of relevant brain regions for higher-fit individuals may reflect an increase in the ability of the frontal attentional networks to bias task-related activation in the parietal cortex (Colcombe et al., 2004), which may underlie the observed fitness-related changes in the various ERP component amplitudes found herein. In addition, they observed reduced activation in the rostral anterior cingulate cortex (ACC) in high-fit and aerobically trained older adults compared to their sedentary and untrained counterparts, respectively, indicating that decreased behavioral conflict is related to increases in aerobic fitness (Colcombe et al., 2004). However, it should be noted that rostral ACC activation has typically been observed during affective responding (Bush, Luu, & Posner, 2000), but some reports have observed activation in this region of the ACC during conflict monitoring (Luu, Tucker, & Makeig, 2004). Accordingly, whereas fitness-related reductions in ERN amplitude are similar to the reduced ACC activation reported by Colcombe et al. (2004), future research will need to disentangle the contributions of the rostral and dorsal regions of the ACC to determine influences fitness may have on conflict monitoring.

Further, Colcombe et al. (2006) observed increased brain volume, including increases in both gray and white matter, following a 6-month aerobic exercise intervention in older adults, which was not observed for those who participated in a 6-month stretching and flexibility training group. Accordingly, there appears to be convergent evidence from the neuroelectric and functional magnetic resonance imaging findings indicating that aerobic fitness is related to the health of specific brain structures and the cognitive functions supported by them. The data herein extend these findings with older adults and suggest that these brain structures may be amenable to fitness during a period of the lifespan characterized by neural growth and organization. A wealth of evidence supports specific physical-activity-related effects on brain and cognition at the molecular, cellular, systems, and behavioral level. However, an in-depth discussion of the various mechanisms is beyond the scope of this article. The interested reader may refer to several recent reviews (e.g., Hillman, Erickson, & Kramer, 2008; Kramer & Erickson, 2007; Vaynman & Gomez-Pinilla, 2006).

Lastly, no relationship was found for aerobic fitness and the N2 component. Given that the N2 is believed to reflect response inhibition (Schmitt, Münte, & Kutas, 2000) associated with conflict monitoring processes during correct trials in a manner similar to that proposed for the ERN (Ridderinkhof et al., 2002), it is not readily apparent why differences were not observed. However, previous research with young adults (Themanson & Hillman, 2006) also did not find a relationship between fitness and N2 amplitude. Thus, despite the fact that N2 has been localized to the same area of the ACC as the ERN (van Veen and Carter, 2002), it appears that the relation of fitness to the modulation of cognitive control during environmental interactions is specific to instances generating increased conflict, processes related to error commission, or post-error adjustments in control (Themanson & Hillman, 2006).

Limitations

Several limitations of this research should be noted. First, the cross-sectional design leaves open the possibility that the observed differences, which were related to fitness, may be due to another factor or combination of factors. This possibility was minimized by the collection of several other variables (e.g., IQ, SES, BMI) that have been found to relate to fitness or cognition but does not eliminate the possibility that a selection bias may have occurred. Randomized control interventions are needed to better establish a direct relationship between fitness and interference control in children. Second, group differences in BMI were observed. Although this was controlled statistically when appropriate, future research should exert greater matching between samples. This may prove challenging, given the robust relationship between physical inactivity and increases in BMI (Departments of Health and Human Services and Education, 2000). Third, participants in both fitness groups exhibited mean IQ scores approximately 1 *SD* above the mean. As such, the current data may not generalize to those children with average or below-average IQ. Finally, a field test of aerobic capacity was chosen over an objective measure of cardiorespiratory fitness (e.g., VO_2 max). However, earlier research has established that fitness level was accurately classified using the PACER in 70% of individuals based on directly measured VO_2 max (Welk et al., 2002).

Summary

In conclusion, the findings suggest that aerobic fitness may shape cognitive processes and their neural underpinnings. Specifically, fitness was associated with alterations in both upstream neuroelectric processes related to stimulus engagement and downstream processes related to action monitoring. Further, fitness was associated with better response accuracy, whereas no differences were observed for response speed. These findings indicate that fitness may relate to general improvements in cognitive function in tasks requiring variable amounts of executive control during preadolescent development.

The findings herein challenge traditional thinking with regard to the influence of aerobic fitness on cognition, which until recently has been examined with regard to cognitive aging. That is, the vast majority of research has examined fitness as a means of protecting against age-related loss of cognitive health and function (Kramer & Hillman, 2006), with the assumption that decrements in cognitive aging may be ameliorated by this factor. However, the current data examining preadolescent children suggest that fitness may also benefit cognition during earlier periods of the lifespan characterized by development and neural organization, rather than reserved as a means of prolonging cognitive health during aging. Accordingly, the current data provide support for the notion of early physical activity intervention to promote aerobic fitness as a means of improving not only physical health but cognitive health as well. Given recent reports (Castelli, Hillman, Buck, & Erwin, 2007) indicating that aerobic fitness is related to better performance on school-based achievement tests of mathematics and reading, the current data provide an initial understanding of mechanisms that may underlie fitness effects on cognitive health during development.

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Received May 1, 2007
Revision received October 9, 2008
Accepted October 14, 2008 ■