Cardiorespiratory Fitness and the Flexible Modulation of Cognitive Control in Preadolescent Children

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Abstract

■ The influence of cardiorespiratory fitness on the modulation of cognitive control was assessed in preadolescent children separated into higher- and lower-fit groups. Participants completed compatible and incompatible stimulus–response conditions of a modified flanker task, consisting of congruent and incongruent arrays, while ERPs and task performance were concurrently measured. Findings revealed decreased response accuracy for lower- relative to higher-fit participants with a selectively larger deficit in response to the incompatible stimulus–response condition, requiring the greatest amount of cognitive control. In contrast, higher-fit participants maintained response accuracy across stimulus–response compatibility conditions. Neuroelectric measures indicated that higher-fit, relative to lower-fit, participants exhibited global increases in P3 amplitude and shorter P3 latency, as well as greater modulation of P3 amplitude between the compatible and incompatible stimulus–response conditions. Similarly, higher-fit participants exhibited smaller error-related negativity (ERN) amplitudes in the compatible condition, and greater modulation of the ERN between the compatible and incompatible conditions, relative to lower-fit participants who exhibited large ERN amplitudes across both conditions. These findings suggest that lower-fit children may have more difficulty than higher-fit children in the flexible modulation of cognitive control processes to meet task demands. ■

INTRODUCTION

With a growing tendency among industrialized societies for children to participate in sedentary activities, there has been a concomitant increase in the prevalence of certain physical diseases (e.g., cardiovascular disease, colon cancer, type-2 diabetes; Department of Health and Human Services & Department of Education, 2000). Thus, our evolutionary makeup, which has been shaped by an active lifestyle for much of human existence, may be maladapted to the sedentary lifestyle of today (Booth & Lees, 2006; Vaynman & Gomez-Pinilla, 2006). Accordingly, such sedentary behavior represents a physiological disjunction from healthy (physically active) behaviors and may have implication for poorer health not only in the physical domain but also in the cognitive domain, as evidenced by an increasing number of recent reports on the relation of physical activity to cognitive health (see Hillman, Erickson, & Kramer, 2008, for a review). In adult populations, this association appears to be disproportionately larger for tasks or task components that require extensive amounts of cognitive control (Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Colcombe & Kramer, 2003; Kramer et al., 1999). However, in school-aged children, the selective relation of fitness to cognitive health appears to be less well understood (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Buck, Hillman, & Castelli, 2008; Castelli, Hillman, Buck, & Erwin, 2007; Hillman, Castelli, & Buck, 2005; Sibley & Etnier, 2003; Tomporowski, 2003). Accordingly, further research is necessary to gain insight into the general versus selective nature of the relationship between fitness and cognition during development.

Cognitive control describes a subset of goal-directed, self-regulatory operations that are involved in, yet functionally distinct from, the selection, scheduling, and coordination of computational processes underlying perception, memory, and action (Rogers & Monsell, 1995). These processes allow for the optimization of behavioral interactions within the environment through the flexible modulation of attentional control (Botvinick, Braver, Barch, Carter, & Cohen, 2001; MacDonald, Cohen, Stenger, & Carter, 2000). The core cognitive processes, which collectively comprise what is termed "cognitive control," or "executive control," include inhibition, working memory, and cognitive flexibility (Diamond, 2006). In developing populations, inhibition is particularly important to the effective functioning of cognitive control (Brocki & Brohlin, 2004; Barkley, 1997), given that it relates to the ability to override a prepotent response in order to perform a less potent but correct response, block out task irrelevant information in the environment, and stop an ongoing response (Davidson, Amso, Anderson, & Diamond, 2006; Barkley, 1997). These abilities are central

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Journal of Cognitive Neuroscience 23:6, pp. 1332–1345

to sustaining attention and maintaining control over one's actions (Diamond, 2006).

Beyond the assessment of overt actions, ERPs provide an additional means of gaining insight into the relationship between fitness and cognitive control during development through the examination of distinct cognitive operations. ERPs refer to patterns of neuroelectric activation that occur in preparation for, or in response to, an event. One such ERP component that occurs following errors of commission is the error-related negativity (ERN; also known as the Ne). The ERN, which neuroimaging research (Miltner et al., 2003; van Veen & Carter, 2002; Carter et al., 1998; Dehaene, Posner, & Tucker, 1994) has indicated is generated in the dorsal portion of ACC, is thought to reflect activation of action-monitoring processes in response to erroneous behaviors in order to initiate top–down compensatory processes regardless of an individual's awareness of the error (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Gehring & Knight, 2000; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991).

A separate ERP complex, which occurs in response to a stimulus, includes the N2 and P3 (also known as the P300 or P3b) components. The amplitude of the fronto-central N2 is believed to reflect response inhibition (Schmitt, Münte, & Kutas, 2000) associated with conflict-monitoring processes during correct trials, such that larger N2 amplitude is associated with increased conflict, in a manner similar to that proposed for the ERN (Yeung, Cohen, & Botvinick, 2004; Ridderinkhof et al., 2002; van Veen & Carter, 2002). Recent evidence suggests that the latency of the fronto-central N2 reflects aspects of the response selection process (Gajewski, Stoerig, & Falkenstein, 2008). Distinct from the N2, the amplitude of the P3 component is thought to reflect neuronal activity associated with the revision of the mental representation of the previous event (Donchin, 1981), such that the P3 is sensitive to the allocation of attentional resources during stimulus engagement (Polich, 2007). P3 timing marked by its peak latency is thought to index stimulus classification and evaluation speed independent of response selection and action (Verleger, 1997; Duncan-Johnson, 1981).

Previous investigations using neuroelectric measures have begun to elucidate the beneficial relationship between fitness and cognitive health (see Hillman et al., 2008; Kramer & Hillman, 2006 for review). However, with few exceptions (Hillman et al., 2005, 2009), a paucity of research exists that examines the relationship between fitness and neurocognitive health in children. These initial investigations have provided emerging evidence to suggest that decreased cardiovascular fitness relates to poorer integrity of cognitive control. Specifically, lower-fit children exhibited smaller P3 amplitude (Hillman et al., 2005, 2009) and longer P3 latency (Hillman et al., 2005) relative to higher-fit children, indicating that lower-fit children are less effective in their allocation of attentional resources and process environmental information less efficiently relative to their higher-fit counterparts. Further, lower-fit children exhibited increased ERN and Pe amplitude, and a nonsignificant increase in N2 amplitude relative to higher-fit children, indicating less effective action monitoring following error production on a task requiring inhibitory control (Hillman et al., 2009). This increase in ERN amplitude with more sedentary behavior corroborates previous investigations in college-aged and older adults, which have observed larger ERN and increased ACC activation for sedentary participants, relative to their aerobically trained counterparts (Themanson, Pontifex, & Hillman, 2008; Themanson & Hillman, 2006; Themanson, Hillman, & Curtin, 2006; Colcombe et al., 2004). Taken together with behavioral findings of reduced response accuracy for lower- relative to higher-fit children, these neuroelectric findings suggest that reduced fitness may relate to a decreased ability to begin the cascade of processes required to signal the need for additional top–down control, allocate attention toward actions, and may experience greater response conflict relative to their higher-fit counterparts (Hillman et al., 2009).

Accordingly, further insight into the relationship between fitness and cognition during development may be gained through the examination of the role of fitness in mediating the flexible allocation of cognitive control. That is, the majority of previous investigations (Hillman et al., 2009; Themanson et al., 2006, 2008) have assessed fitness-related differences in ERN in response to a modified flanker task with no overt instruction regarding response strategy (speed vs. accuracy) and have observed increased ERN amplitude for lower- relative to higher-fit participants. Interestingly, however, recent evidence from young adults also indicates that lower cardiorespiratory fitness is associated with a decreased ability to flexibly modulate cognitive control to meet task demands (Themanson et al., 2008). Specifically, Themanson et al. (2008) examined neuroelectric and behavioral indices of cognitive control in response to a modified flanker task during conditions emphasizing response accuracy or speed in a sample of 62 college-aged adults. Findings revealed that lower fitness levels were associated with decreased modulations of post-error accuracy and ERN amplitude across task instructions. In contrast, higher-fit young adults were able to up-regulate action-monitoring processes as a function of task instructions. Thus, lower fitness may relate to impairments in the ability to flexibly modulate and implement cognitive control operations in order to meet task demands (Themanson et al., 2008).

The present study sought to assess the extent to which fitness relates to the flexible modulation of cognitive control in preadolescent children. However, manipulation of response strategies via instruction may not be the most appropriate manipulation to assess cognitive control in developing populations. Davidson et al. (2006) suggested that preadolescent children respond more impulsively than adults with less modulation of their RT, indicating that response accuracy may be a more informative measure in this population. With this in mind, a modified flanker task that manipulated task difficulty through stimulus–response compatibility was used to modulate both inhibition and flexibility requirements (Friedman, Nessler, Cycowicz, & Horton, 2009). This approach allowed for the investigation of cognitive control processes across multiple levels of conflict. It was hypothesized that lower-fit children would exhibit poorer overall task performance, and an inability to maintain performance levels in response to increased task demands, relative to higher-fit children. It was also predicted that lower- relative to higher-fit children would demonstrate smaller P3 amplitude and longer P3 latency, suggesting a decreased ability to allocate attentional resources and delayed stimulus processing speed. With regard to action-monitoring processes, lower-fit children were predicted to exhibit larger ERN amplitude, reflecting a larger evaluative threshold necessary to signal for additional top–down control. Lastly, it was hypothesized that lower-fit children would have a decreased ability to modulate neuroelectric indices of cognitive control to meet task demands, as indexed by smaller changes in P3 and ERN component amplitudes across conditions differing in the need for cognitive control. Collectively, such a pattern of results would suggest that decreased cardiorespiratory fitness is associated with impairments in the modulation of cognitive control operations, resulting in deficits in the optimization of behavioral interactions with the environment.

METHODS

Participants

Demographic and fitness data for all participants are provided in Table 1. Sixty-five right-handed preadolescent children from the east-central Illinois region were recruited as participants. Participants were bifurcated based on aerobic fitness into higher-fit or lower-fit groups on the basis of whether their VO_2max fell above the 70th percentile or below the 30th percentile according to normative data provided by Shvartz and Reibold (1990). Participants with task performance below 50% accuracy in either condition were discarded from all analyses ($n = 7$; all from the lower-fit group). Further, participants with fewer than six errors of commission (Pontifex et al., 2010; Olvet & Hajcak, 2009) were discarded from all analyses ($n = 10$; 6 from the lower-fit group), leaving a total of 48 participants bifurcated based on aerobic fitness into higher-fit ($n = 24$) and lower-fit ($n = 24$) groups. These participants did not differ significantly from the initial sample in age, demographics, or fitness level [$t(63) \leq 1.6, p \geq .12$].

Table 1. Mean (*SD*) Values for Participant Demographics and Fitness Data

Measure	*Lower-fit*	*Higher-fit*
n	24 (13 girls)	24 (10 girls)
Age (years)	10.1 (0.6)	10.0 (0.6)
Tanner	1.7 (0.5)	1.7 (0.5)
K-BIT composite (IQ)	113.2 (14.9)	115.3 (8.6)
Socioeconomic Status (SES)	2.8 (0.6)	2.6 (0.7)
ADHD	6.3 (4.7)	6.9 (4.5)
VO_2max (ml/kg/min)*	35.7 (5.3)	52.6 (4.2)
VO_2max Percentile*	8.8 (5.3)	83.3 (4.1)

ADHD = scores on the Attention Deficit Hyperactivity Disorder Rating Scale IV; VO_2max = maximum oxygen consumption. Normative values for VO_2max may be found in Shvartz and Reibold (1990).

*$p \leq .05$.

All participants provided written assent and their legal guardians provided written informed consent in accordance with the Institutional Review Board of the University of Illinois at Urbana-Champaign. Prior to testing, legal guardians completed a health history and demographics questionnaire; reported that their child was free of neurological diseases, attentional disorders (as indexed by scores below 14 and 22 for girls and boys, respectively, on the ADHD Rating Scale IV; DuPaul, Power, Anastopoulos, & Reid, 1998), or physical disabilities; and indicated normal or corrected-to-normal vision based on the minimal 20/20 standard. Socioeconomic status (SES) was determined using a trichotomous index based on: (a) participation in free or reduced-price lunch program at school, (b) the highest level of education obtained by the mother and father, and (c) number of parents who worked full-time (Birnbaum et al., 2002). Participants, in collaboration with their legal guardian, completed the Tanner Staging System (Tanner, 1962), indicating that their pubertal status was at or below a score of 2 (i.e., prepubescent) on a 5-point scale. Additionally, children were administered the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990) by a trained experimenter to assess intelligence quotient, as well as the Edinburgh Handedness Inventory (Oldfield, 1971) to determine hand dominance.

Task

Participants completed a modified version of the Eriksen flanker task (Eriksen & Eriksen, 1974) in which they were instructed to respond as accurately as possible to the direction of a centrally presented arrow amid either congruous (e.g., <<<<< or >>>>>) or incongruous (e.g., <<><< or >><>>) flanking arrows (Pontifex & Hillman, 2007; Hillman et al., 2006). The incongruent, relative to the congruent, condition necessitates the concurrent activation of both the correct response (elicited by the target) and the incorrect response (elicited by the flanking stimuli) before stimulus evaluation is complete, thus requiring greater amounts of interference control to inhibit the flanking stimuli and execute the correct response (Spencer & Coles, 1999). Following completion of the compatible condition (described above), participants then completed an incompatible stimulus–response condition, wherein participants were instructed to respond as quickly and accurately as possible in the direction opposite to that of the centrally presented target arrow (Friedman et al., 2009). This condition manipulates task difficulty through multiple levels of conflict (i.e., perceptual and response conflict) such that the incongruent incompatible condition should necessitate the greatest amount of inhibitory control. For each compatibility condition, two blocks of 100 trials were presented with equiprobable congruency and directionality. The stimuli were 3 cm tall white arrows constituting a 16.5 cm wide array with a vertical visual angle of 1.32° and a horizontal visual angle of 7.26°, which were presented focally for 200 msec on a black background with a fixed interstimulus interval of 1700 msec. Multiple task performance indices were collected on reaction time and response accuracy. Specifically, response latency and accuracy were calculated for (1) correct trials, (2) error of commission trials, (3) match-correct trials (the subset of correct trials matched to specific error trials based on RT), (4) correct trials following an error trial, and (5) correct trials following a match-correct trial.

ERP Recording

EEG activity was recorded from 64 electrode sites (Fpz, Fz, FCz, Cz, CPz, Pz, POz, Oz, Fp1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/2/4/6/8, PO7/5/3/4/6/8, O1/2) arranged in an extended montage based on the International 10–10 System (Chatrian, Lettich, & Nelson, 1985) using a Neuroscan Quik-Cap (Compumedics, Charlotte, NC). Recordings were referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode, and impedance at less than 10 kΩ. Additional electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor EOG activity with a bipolar recording. Continuous data were digitized at a sampling rate of 500 Hz, amplified 500 times with a DC to 70 Hz filter, and a 60-Hz notch filter using a Neuroscan Synamps 2 amplifier. Continuous data were corrected off-line for EOG artifacts using a spatial filter (Compumedics, Neuroscan, 2003). Stimulus-locked epochs were created for correct trials from −100 to 1000 msec around the stimulus, baseline corrected using the −100 to 0 msec prestimulus period, and filtered using a zero-phase shift low-pass filter at 30 Hz (24 dB/oct). Trials with artifact exceeding ±75 μV were rejected. The N2 and P3 components were evaluated as the largest negative going peak within a 250 to 400 msec latency window and the largest positive going peak within a 350 to 600 msec latency window, respectively. Amplitude was measured as the difference between the mean prestimulus baseline and maximum peak amplitude; peak latency was defined as the time point corresponding to the maximum amplitude.[1]

Response-locked epochs were created from −600 to 1000 msec around the response, baseline corrected using the −400 to −200 msec preresponse period (Pontifex et al., 2010; Olvet & Hajcak, 2009), and filtered using a zero-phase shift 1 Hz (24 dB/oct) to 12 Hz (24 dB/oct) band-pass filter. Average ERP waveforms were created for error of commission trials and correct trials, which were individually matched (without replacement) to an error of commission trial with the closest possible RT latency (Coles, Scheffers, & Holroyd, 2001), in order to account for potential artifacts that may exist due to differences in response latency between correct and incorrect trials (Mathewson, Dywan, & Segalowitz, 2005; Falkenstein, Hoormann, & Hohnsbein, 2001). Trials with an error of omission or artifact exceeding ±75 μV were rejected. The ERN was evaluated as the average activity in a 0 to –150 msec window relative to the response.

Cardiorespiratory Fitness Assessment

Cardiorespiratory fitness data are listed in Table 1. Maximal oxygen consumption (VO_2max) was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400, Sandy, UT) with averages for oxygen uptake (VO_2) and respiratory exchange ratio (RER) assessed every 20 sec. A modified Balke protocol (ACSM, 2006) was employed using a motor-driven treadmill at a constant speed with increases in grade increments of 2.5% every 2 min until volitional exhaustion occurred. A Polar heart rate monitor (Polar WearLink+ 31; Polar Electro, Lake Success, NY) was used to measure HR throughout the test and ratings of perceived exertion (RPE) were assessed every 2 min using the children's OMNI scale (Utter, Roberson, Nieman, & Kang, 2002). Relative peak oxygen consumption was expressed in ml/kg/min and was based upon maximal effort as evidenced by (1) a peak heart rate ≥185 bpm (ACSM, 2006) and a heart rate plateau (Freedson & Goodman, 1993); (2) RER ≥1.0 (Bar-Or, 1983); and/or (3) ratings on the children's OMNI scale of perceived exertion ≥8 (Utter et al., 2002).

Procedure

Day 1: Cardiorespiratory Fitness Assessment

On the first visit to the laboratory, participants completed an informed assent, Edinburgh Handedness Inventory (Oldfield, 1971), as well as the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990). Concurrently, participants' legal guardians completed an informed consent, health history and demographics questionnaire, the ADHD Rating Scale IV (DuPaul et al., 1998), a modified Tanner Staging System questionnaire, and the Physical Activity Readiness Questionnaire (Thomas, Reading, & Shephard, 1992) to screen for any previous health issues that might be exacerbated by exercise. Participants were then fitted with a Polar HR monitor (Polar WearLink+ 31; Polar Electro) and had their height and weight measured using a stadiometer and a Tanita WB-300 Plus digital scale, respectively. Following completion of the cardiorespiratory fitness assessment, participants were given a cool-down period and waited for their HR to return to within 10 bpm of their resting HR prior to leaving. Participants were then invited to participate in the second day of testing if their VO_2max fell above the 70th percentile or below the 30th percentile according to normative data provided by Shvartz and Reibold (1990).

Day 2: Experimental Session

On the second visit, participants were fitted with a 64-channel Quik-Cap (Compumedics Neuroscan, 2003) and seated in a sound-attenuated room where the neuroelectric testing took place. Following the provision of task instructions, participants were afforded the opportunity to ask questions and 40 practice trials were administered prior to the start of testing. Upon completion of the last task condition, all electrodes were removed and participants were briefed on the purpose of the experiment.

Statistical Analysis

All statistical analyses were conducted using a significance level of $p = .05$, and analyses with three or more within-subjects levels used the Wilks' Lambda statistic with Bonferroni-corrected *t* tests for post hoc comparisons. Task performance (mean RT, response accuracy) was assessed separately using a 2 (Fitness: higher-fit, lower-fit) × 2 (Compatibility: compatible, incompatible) × 2 (Congruency: congruent, incongruent) multivariate repeated measures ANOVA. Secondary analyses examined task performance interference scores using a 2 (Fitness: higher-fit, lower-fit) × 2 (Compatibility: compatible, incompatible) multivariate repeated measures ANOVA. Post trial task performance was assessed using a 2 (Fitness: higher-fit, lower-fit) × 2 (Compatibility: compatible, incompatible) × 2 (Accuracy: post error, post match correct) multivariate repeated measures ANOVA.

The N2 and P3 components were assessed separately for amplitude and latency using a 2 (Fitness: higher-fit, lower-fit) × 2 (Compatibility: compatible, incompatible) × 2 (Congruency: congruent, incongruent) × 7 (Site: Fz, FCz, Cz, CPz, Pz, POz, Oz) multivariate repeated measures ANOVA. Lastly, the ERN component was assessed at the FCz electrode site (Miltner et al., 2003; Carter et al., 1998; Dehaene et al., 1994) using a 2 (Fitness: higher-fit, lower-fit) × 2 (Compatibility: compatible, incompatible) × 2 (Accuracy: error, match correct) multivariate repeated measures ANOVA.

RESULTS

Table 2 provides mean (*SD*) values for neuroelectric and behavioral measures as a function of fitness and compatibility. All significant effects are characterized in Table 3 (for task performance) and Table 4 (for neuroelectric measures). Preliminary analyses were performed to test whether sex was related to any behavioral or neuroelectric variables. Findings revealed no significant main effects or interactions, thus all further analyses were collapsed across both sexes.

Task Performance

Reaction Time

Analyses revealed a main effect of Congruency with longer RT latency for incongruent (572 ± 18 msec) relative to congruent (524 ± 15 msec) trials. This effect was superseded by an interaction of Compatibility × Congruency. Decomposition of the Compatibility × Congruency interaction revealed longer RT latency for incongruent relative to congruent trials within each compatibility [$ts(47) \geq 3.7$,

Table 2. Mean (*SD*) Values for Neuroelectric and Behavioral Measures as a Function of Fitness and Compatibility

	Lower-fit		*Higher-fit*	
Measure	*Compatible*	*Incompatible*	*Compatible*	*Incompatible*
Reaction time (msec)	542 (96)	563 (146)	539 (106)	544 (143)
Response accuracy (%)	78.9 (8.9)	72.8 (12.8)	84.7 (7.1)	84.8 (10.0)
N2 amplitude (μV)	−2.0 (4.7)	−0.4 (4.2)	1.4 (4.7)	3.7 (4.9)
N2 latency (msec)	334 (16)	339 (21)	325 (17)	327 (19)
P3 amplitude (μV)	6.9 (5.0)	7.5 (4.4)	8.7 (3.2)	12.3 (4.8)
P3 latency (msec)	495 (33)	485 (38)	461 (29)	461 (34)
ERN amplitude (μV)	−1.8 (3.7)	−1.5 (3.5)	1.1 (3.7)	−1.6 (2.9)

All mean (*SD*) values within each compatibility condition are collapsed across congruency conditions. For stimulus-locked ERP data (N2 and P3), all mean (*SD*) values are collapsed across midline electrode sites; for response-locked ERP data (ERN), all mean (*SD*) values are from the FCz electrode site.

Table 3. Statistical Summary Table for Task Performance Effects

Measure	*Effect*	*df*	*F*	*p*	η^2
Reaction time	Congruency	1, 46	49.2	<.001	.52
	Compatibility × Congruency	1, 46	17.2	<.001	.27
Reaction time interference	Compatibility	1, 46	17.2	<.001	.27
Post trial reaction time	Accuracy	1, 46	49.4	<.001	.52
Response accuracy	Fitness	1, 46	12.1	.001	.21
	Compatibility	1, 46	5.1	.028	.1
	Fitness × Compatibility	1, 46	5.4	.025	.1
	Congruency	1, 46	78.8	<.001	.63
	Compatibility × Congruency	1, 46	14.1	<.001	.23
Response accuracy interference	Compatibility	1, 46	14.1	<.001	.23
Post trial response accuracy	Fitness	1, 46	4.4	.041	.08
	Accuracy	1, 46	8.1	.007	.15

Only significant ($p < .05$) effects are reported.

Table 4. Statistical Summary Table for Neuroelectric Measure Effects

Measure	*Effect*	*df*	*F*	*p*	η^2
N2 amplitude	Fitness	1, 46	9.3	.004	.17
	Compatibility	1, 46	12.0	.001	.2
	Congruency	1, 46	7.1	.01	.13
	Site	6, 41	6.8	<.001	.5
	Congruency × Site	6, 41	2.8	.02	.29
N2 latency	Fitness	1, 46	5.2	.027	.1
	Site	6, 41	26.1	<.001	.79
	Congruency × Site	6, 41	2.4	.042	.26
P3 amplitude	Fitness	1, 46	8.8	.005	.16
	Compatibility	1, 46	12.1	.001	.21
	Fitness × Compatibility	1, 46	5.9	.019	.11
	Site	6, 41	7.0	<.001	.51
P3 latency	Fitness	1, 46	12.5	.001	.21
	Congruency	1, 46	10.5	.002	.18
	Site	6, 41	8.6	<.001	.56
	Fitness × Site	6, 41	3.5	.007	.34
ERN	Accuracy	1, 46	95.6	<.001	.68
	Fitness × Compatibility × Accuracy	1, 46	5.7	.023	.11
ERN (error trials)	Compatibility	1, 46	4.5	.04	.09
	Fitness × Compatibility	1, 46	6.4	.015	.12

Only significant ($p < .05$) effects are reported.

$p \leq .001$], and longer RT latency for incompatible congruent trials relative to compatible incongruent trials [$t(47) = 3.7, p = .001$]. The secondary analyses comparing the interference effect (incongruent − congruent) within each compatibility condition yielded a main effect of Compatibility with a larger interference effect for the compatible (66 ± 7 msec) relative to the incompatible (31 ± 8 msec) condition.

Post Trial Reaction Time

Preliminary Bonferroni-corrected *t* tests were conducted for each compatibility condition comparing error RT to post-error RT. Results indicated longer RT latency for post-error trials relative to error trials across both compatibility conditions [$ts(47) \geq 10.2, p \leq .001$]. Analyses of post trial RT assessed Fitness × Compatibility × Accuracy and revealed a main effect of Accuracy indicating longer post error RT latency (555 ± 19 msec) relative to post match correct RT latency (494 ± 15 msec).

Response Accuracy

Analyses revealed main effects of Fitness with decreased response accuracy for lower-fit (75.9 ± 1.8%) relative to higher-fit (84.8 ± 1.8%) participants, and Compatibility with increased response accuracy for the compatible relative to incompatible condition. These effects were superseded by an interaction of Fitness × Compatibility. Decomposition of this interaction examined compatibility within each fitness group and revealed that the lower-fit group exhibited increased response accuracy for the compatible relative to the incompatible condition [$t(23) = 3.1, p = .005$], whereas the higher-fit group exhibited no difference in response accuracy between the compatible and the incompatible conditions [$t(23) = 0.05, p = .96$; see Figure 1]. Further, decomposition of the Fitness × Compatibility interaction by comparing fitness groups within each compatibility condition revealed a smaller reduction in task performance between lower- and higher-fit participants for the compatible (Cohen's $d = 0.7$) relative to the incompatible (Cohen's $d = 1.0$) condition. The secondary analyses comparing the interference effect (congruent − incongruent) within each compatibility condition yielded a main effect of compatibility with a larger interference effect for the compatible (11.0 ± 1.4%) relative to the incompatible (5.2 ± 1.0%) condition.

A main effect of congruency was also observed, which was superseded by an interaction of Compatibility × Congruency. Decomposition of the Compatibility × Congruency interaction revealed increased response accuracy for congruent relative to incongruent trials within each compatibility [$ts(47) \geq 5.5, p \leq .001$]. Increased response accuracy was also observed for the compatible congruent relative to the incompatible congruent and both incongruent conditions [$ts(47) \geq 3.7, p \leq .001$], and for the incompatible congruent relative to the compatible incongruent condition [$t(47) = 4.3, p < .001$].

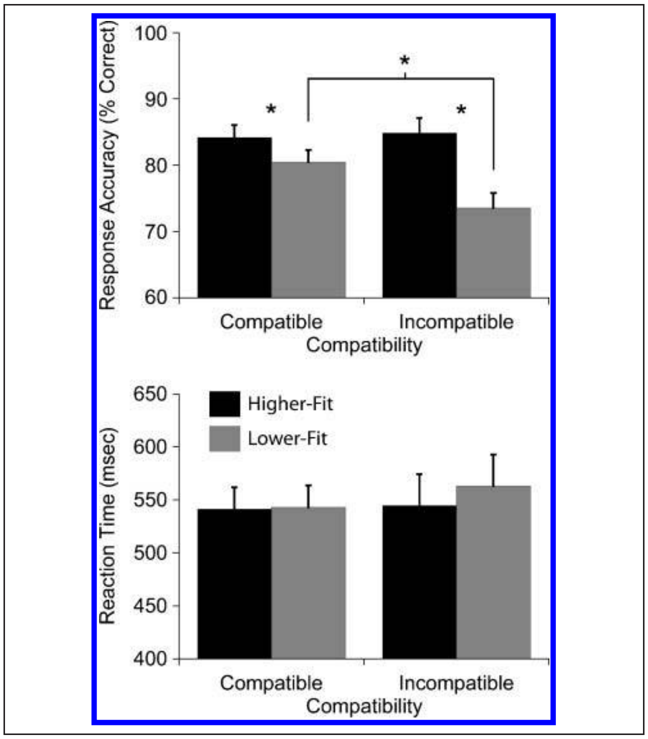


Figure 1. Mean (+1 *SE*) response accuracy and reaction time for each compatibility condition, collapsed across congruency, for higher- and lower-fit participants.

Post Trial Response Accuracy

Analyses revealed main effects of Fitness with decreased post trial response accuracy for lower-fit (72.0 ± 2.4%) relative to higher-fit (79.2 ± 2.4%) participants, and accuracy with increased post error response accuracy (78.6 ± 2.2%) relative to post match-correct response accuracy (72.6 ± 1.8%).

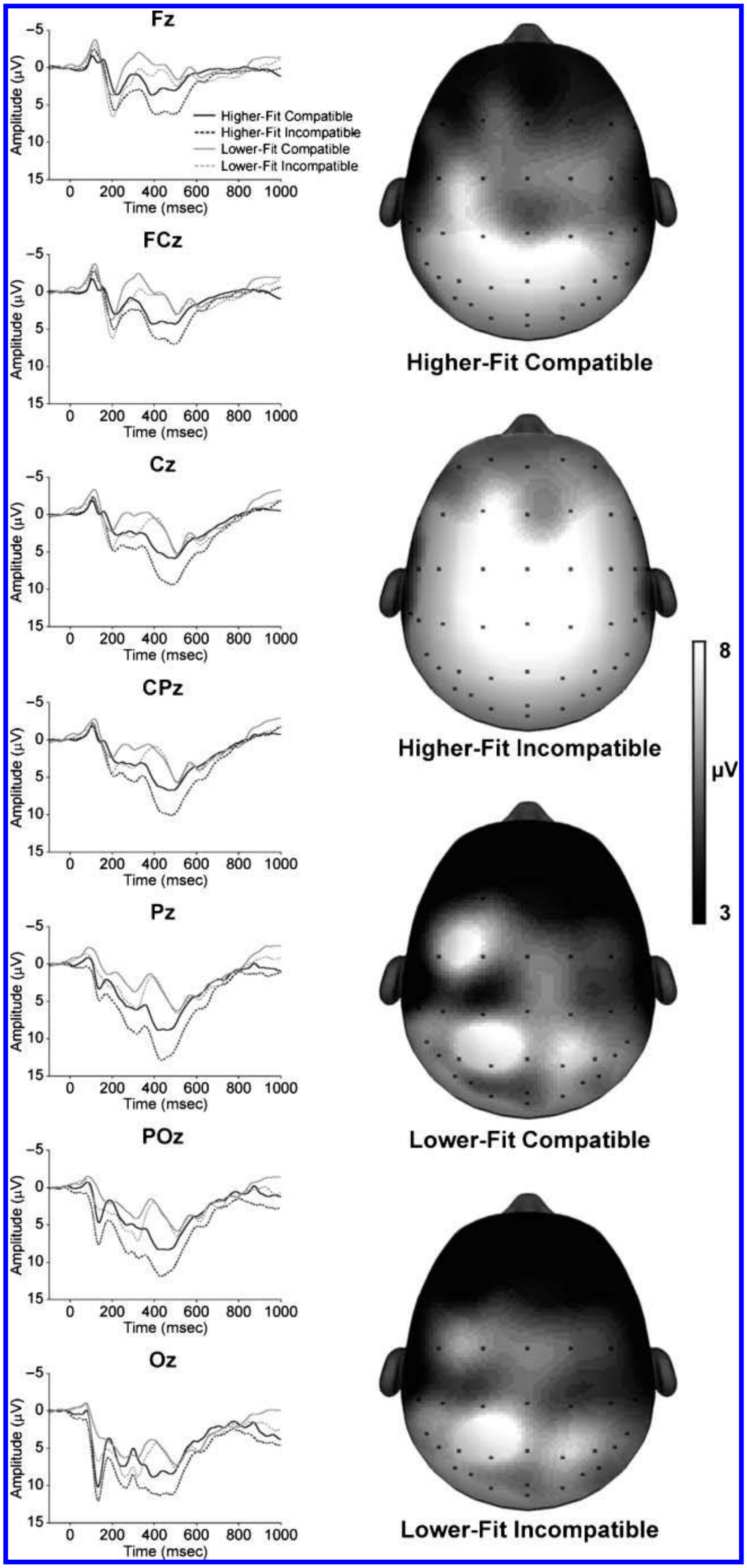
Neuroelectric Measures

Stimulus-locked ERPs

Preliminary analyses were conducted on the number of trials to ensure that between-group differences in stimulus-locked ERP components were not the result of different numbers of trials included in the stimulus-locked ERP averages. Analyses revealed no significant differences in the number of trials for either compatibility or congruency conditions [$ts(46) \leq 1.7, p \geq .11$].

N2 amplitude. Figure 2 illustrates the stimulus-locked grand average ERP waveforms at the midline electrode sites for each fitness group and compatibility condition. Analyses revealed main effects of Fitness with larger N2 amplitude for lower-fit (−1.2 ± 0.86 μV) relative to higher-fit (2.5 ± 0.86 μV) participants, and compatibility with larger

Figure 2. Stimulus-locked grand-average waveforms and topographic plots of P3 amplitude for each compatibility condition, collapsed across congruency, for higher- and lower-fit participants.



N2 amplitude for the compatible (−0.3 ± 0.7 μV) relative to the incompatible (1.6 ± 0.7 μV) condition. Main effects were also observed for Congruency and Site, which were superseded by an interaction of Congruency × Site. Decomposition of the Congruency × Site interaction included the examination of congruency within each site. Findings revealed larger N2 amplitude for incongruent relative to congruent trials only at the centro-parietal, parietal, and parieto-occipital electrode sites [$ts(47) \geq 3.1, p \leq .003$].

N2 latency. Figure 2 illustrates the stimulus-locked grand average ERP waveforms for each fitness group and compatibility condition. Analyses revealed a main effect of fitness with longer N2 latency for lower-fit (336 ± 3 msec) relative to higher-fit (325 ± 3 msec) participants. A main effect of site was also observed, which was superseded by an interaction of Congruency × Site. Decomposition of the Congruency × Site interaction examined congruency within each site and revealed no significant differences in congruency across sites [$ts(47) \leq 2.0, p \geq .057$].

P3 amplitude. Figure 2 illustrates the stimulus-locked grand-average ERP waveforms and topographic plots of P3 amplitude for each fitness group and compatibility condition. Analyses revealed main effects of Fitness with smaller P3 amplitude for lower-fit (7.2 ± 0.8 μV) relative to higher-fit (10.5 ± 0.8 μV) participants, and compatibility with smaller P3 amplitude for the compatible (7.8 ± 0.6 μV) relative to the incompatible (9.9 ± 0.7 μV) condition. These effects were superseded by an interaction of Fitness × Compatibility. Decomposition of the Fitness × Compatibility interaction examined fitness within each compatibility condition and revealed smaller P3 amplitude for lower-fit relative to higher-fit across both compatibility conditions [$t(46) \geq 3, p \leq .01$]. Further decomposition of the Fitness × Compatibility interaction examined compatibility within each fitness group and revealed that the lower-fit group exhibited no difference in P3 amplitude between the compatible and incompatible conditions [$t(23) = 0.7, p = .47$], whereas the higher-fit group exhibited smaller P3 amplitude in the compatible relative to the incompatible condition [$t(23) = 4.3, p < .001$; see Figure 2]. A main effect of site was also observed with P3 amplitude being significantly different at Cz relative to the Fz electrode site [$t(47) = 4.5, p < .001$]; at CPz relative to the Fz and FCz electrode sites [$ts(47) \geq 3.3, p \leq .002$]; at Pz and POz relative to the Fz, FCz, Cz, and CPz electrode sites [$ts(47) \geq 3.5, p \leq .001$]; and at Oz relative to the Fz, FCz, and Cz electrode sites [$ts(47) \geq 3.2, p \leq .002$].

P3 latency. Figure 2 illustrates the stimulus-locked grand-average ERP for each fitness group and compatibility condition. Analyses revealed main effects of Fitness with longer P3 latency for lower-fit (490 ± 5 msec) relative to higher-fit (460 ± 6 msec) participants, and site. These effects were superseded by an interaction of Fitness × Site. Decomposition of the Fitness × Site interaction examined fitness within each site and revealed longer P3 latency for lower-fit, relative to higher-fit, participants at the central, centro-parietal, parietal, and parieto-occipital sites [$ts(46) \geq 2.9, p \leq .006$]. A main effect of Congruency was also observed with longer P3 latency for the incongruent (482 ± 5 msec) relative to the congruent (469 ± 5 msec) condition.

Response-locked ERP

Preliminary analyses were conducted on the number of error/correct trials to ensure that between-group differences were not the result of a different number of trials included in the response-locked ERP averages. Analyses revealed no significant differences between groups for the number of trials in either compatibility condition [$ts(46) \leq 1.7, p \geq .1$].

Error-related negativity. Figure 3 illustrates the response-locked grand-average ERP waveforms for each fitness group and compatibility condition within each accuracy condition. Analyses revealed a main effect of Accuracy, which was superseded by an interaction of Fitness × Compatibility × Accuracy. Decomposition of this interaction examined Fitness × Compatibility within each accuracy condition and revealed no significant effects for match-correct trials. However, error-trial analyses revealed a main effect of Compatibility, which was superseded by an interaction of Fitness × Compatibility. Decomposition of this interaction examined fitness within each compatibility condition and revealed larger ERN amplitude for lower-fit relative to higher-fit participants in the compatible condition [$t(46) = 2.7, p = .01$]. No such fitness effect was observed for the incompatible condition [$t(46) = 0.1, p = .91$]. Further, decomposition of the Fitness × Compatibility interaction for error trials examined compatibility within each fitness group and revealed no significant differences for the lower-fit group across compatibility conditions [$t(23) = 0.3, p = .75$], whereas the higher-fit group exhibited smaller ERN amplitude in the compatible relative to the incompatible condition [$t(23) = 2.9, p = .007$; see Figure 3].

DISCUSSION

The current findings indicated that lower-fit children exhibited decreased overall response accuracy compared to their higher-fit counterparts with a larger reduction in task performance for the incompatible stimulus–response condition. By contrast, higher-fit participants were able to maintain a high level of response accuracy across stimulus–response compatibility conditions, suggesting greater capability to flexibly modulate cognitive control processes. Neuroelectric findings revealed increased N2 amplitude, decreased P3 amplitude, and longer N2 and P3 latency for lower- relative to higher-fit children, suggesting that lower-fit children experience greater response conflict, a reduced capacity to allocate attentional resources, and

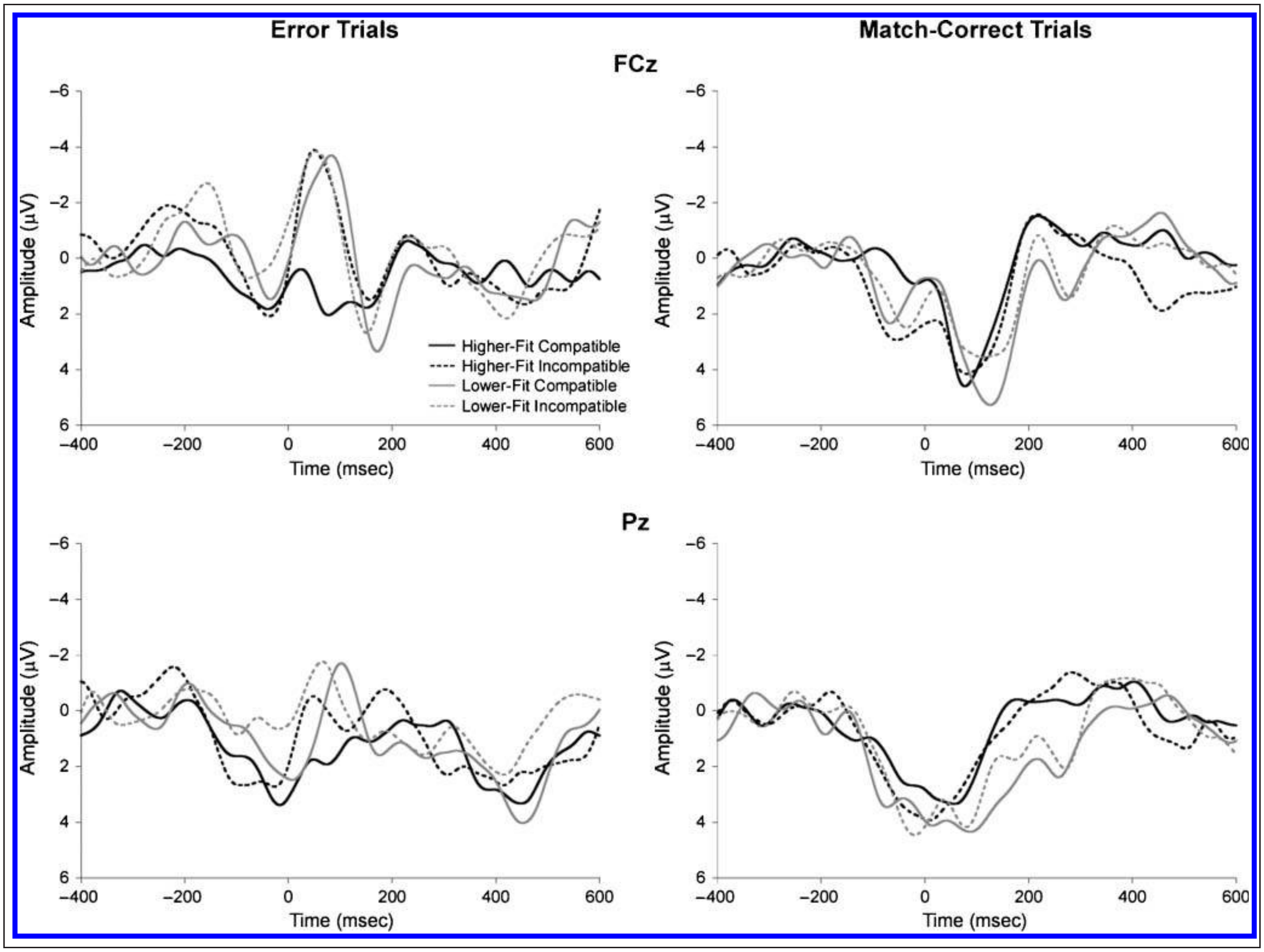


Figure 3. Response-locked grand-average waveforms for each compatibility condition, collapsed across congruency, for higher- and lower-fit participants.

delayed stimulus classification and processing speed relative to their higher-fit counterparts. Alternatively, higher-fit children were able to flexibly modulate cognitive control operations by exhibiting larger ERN and P3 amplitude in response to the incompatible, relative to the compatible, condition. Thus, the overall pattern of findings suggests that lower levels of cardiorespiratory fitness relate to deficits in the flexible allocation of cognitive control to meet task demands.

Replicating previous investigations, deficits in task performance were observed for lower-fit relative to higher-fit children (Hillman et al., 2005, 2009), with no differences observed in reaction time, suggesting that these findings are not the result of a shift in response strategy (i.e., a speed–accuracy tradeoff). Collectively, these findings suggest that reduced fitness may relate to general impairments in performance on cognitive control tasks. Novel to this investigation, however, was the inclusion of the stimulus–response manipulation during the flanker task. Findings revealed decreased response accuracy for the incompatible stimulus–response mapping relative to the compatible stimulus–response mapping, replicating the findings of Friedman et al. (2009) and providing evidence that the stimulus–response manipulation engendered greater cognitive control requirements. With regard to fitness, the finding of a selectively larger decrement in task performance for lower-fit participants in response to the task condition requiring the greatest amount of cognitive control replicates previous findings in adult populations (Hillman et al., 2006). That is, in adult populations, the association between fitness and cognition appears to be general yet disproportionately larger for tasks or task components requiring extensive amounts of cognitive control (Kramer et al., 1999, 2005; Colcombe & Kramer, 2003). The present findings suggest that the prototypical perceptually induced response conflict manipulation (i.e., congruent vs. incongruent) utilized in previous investigations (Hillman et al., 2009) may not be sufficient to fully engender fitness-related differences in cognitive control requirements in children; however, the increased cognitive control requirements of the incompatible stimulus–response mapping allows for this general yet selective relationship to be observed.

Also novel to the present investigation is the observation of longer N2 latency and larger N2 amplitude for lower- relative to higher-fit participants, suggesting that lower-fit participants exhibit delayed response selection and experience greater response inhibition associated with conflict-monitoring processes relative to their higher-fit counterparts (Gajewski et al., 2008; Schmitt et al., 2000). Contrary to a priori predictions, larger N2 amplitude was observed in response to the compatible, relative to the incompatible condition, suggesting that participants experienced decreased response inhibition to the incompatible condition, which should elicit the greatest amount of conflict (Friedman et al., 2009). Given that smaller N2 amplitude was observed for congruent relative to incongruent trials, it may be that compatibility and congruency engender different aspects of conflict or that the incompatible condition created increased response uncertainty, resulting in reduced N2 amplitude. That is, unlike congruency effects in the flanker task, where the incongruent stimuli concurrently activate the correct and incorrect response before stimulus evaluation is complete, necessitating the inhibition of the incorrect response (Spencer & Coles, 1999), the incompatible condition—which layers multiple levels of conflict (i.e., perceptual and response conflict)—may create a situation in which neither response is activated until stimulus processing is complete, thus requiring lower levels of response inhibition. It is clear, however, that further research is necessary to better understand the relationship between N2 amplitude, congruency, and compatibility. With regard to the P3 component, the present findings corroborate previous investigations observing smaller P3 amplitude and longer P3 latency for lower-fit children (Hillman et al., 2005, 2009), suggesting a decreased ability to allocate attentional resources and efficiently process environmental information relative to their higher-fit counterparts (Polich, 2007; Duncan-Johnson, 1981). Novel to this investigation is the finding that higher-fit children exhibited larger P3 amplitude in response to the incompatible stimulus–response condition relative to the compatible stimulus–response condition, an effect that was not observed in lower-fit participants. Taken together, the current dataset replicates and extends this area of research by demonstrating a selectively greater deficit in the allocation of attentional resources in response to task conditions requiring greater cognitive control demands associated with decreased fitness levels and further suggests that poorer fitness might relate to a decreased ability to modulate cognitive control operations to meet task demands.

Analysis of the ERN component provides further support for this view. That is, the current data replicate previous reports indicating a relationship between physical activity (Themanson et al., 2006) and aerobic fitness in both children (Hillman et al., 2009) and young adults (Themanson & Hillman, 2006), with increased ERN amplitude for lower- relative to higher-fit participants. These findings suggest that lower-fit participants exhibit greater activation of action-monitoring processes in response to erroneous behaviors, which may relate to an increased evaluative threshold necessary to initiate top–down compensatory processes (Gehring et al., 1993). Interestingly, lower-fit children exhibited no differences in ERN amplitude across stimulus–response compatibility conditions, whereas higher-fit children exhibited an increase in ERN amplitude in response to the incompatible stimulus–response condition. Accordingly, the current dataset suggests that lower cardiorespiratory fitness may be associated with a decreased ability to modulate action-monitoring processes in order to optimize behavioral interactions within the environment.

Although speculative, the observed differences in cognitive control operations as a function of cardiorespiratory fitness may be related to differences in the utilization of two cognitive control strategies, referred to as "proactive" and "reactive" (Braver, Gray, & Burgess, 2007). That is, these strategies are distinguished by the time course in which behavior modifications occur, with proactive control modifying interactions in the environment prior to stimulus engagement (i.e., early selection) and reactive control occurring in direct response to the demands of an event (i.e., late correction; Jacoby, Kelley, & McElree, 1999). Proactive cognitive control, which neuroimaging research suggests is likely rooted in dorsolateral prefrontal cortex (Braver et al., 2007; MacDonald et al., 2000), works to continually exert top–down control in preparation for and during ongoing information processing to provide flexible, on-line adjustments of attention (Braver et al., 2007; Botvinick et al., 2001). These adjustments in attention serve to facilitate optimal completion of a task by providing improved maintenance of task demands and stimulus representations (Botvinick et al., 2001). However, such active maintenance requires extended activation of neural networks (e.g., lateral PFC), resulting in greater metabolic demands (Braver et al., 2007). Alternatively, reactive cognitive control, which neuroimaging research suggests is likely rooted in ACC (Botvinick et al., 2001), is transiently engaged following the occurrence of some imperative event and serves to initiate the activation of compensatory adjustments in top–down control in an effort to resolve conflict, increase response strength, or correct an impending error (Braver et al., 2007; Botvinick et al., 2001). Reactive control, however, represents a suboptimal control strategy that may be more susceptible to stimulus-based interference and may be insufficient when stimulus processing is constrained (Braver et al., 2007). Taken together, these "proactive" and "reactive" cognitive control strategies interact to optimize behavioral interactions within the environment (MacDonald et al., 2000).

Accordingly, speculation on the current findings suggests that higher- and lower-fit children may engage in differential cognitive control strategies. That is, lower-fit preadolescents exhibited increased ERN amplitude relative to their higher-fit peers in response to the compatible stimulus–response condition. Given that the ERN is thought to be generated within ACC, an area of the brain that initiates compensatory, on-line adjustments in top–down control, the ERN may serve as a neuroelectric index of reactive control strategies. Based on the findings presented herein, lower-fit children may adopt a reactive control strategy in response to the compatible stimulus–response condition, and thus, have difficulty up-regulating these processes to meet the increased task demands of the incompatible stimulus–response condition. In contrast, given the smaller ERN amplitude exhibited by higher-fit children, it appears that they might not rely as heavily on reactive control strategies in response to the compatible condition, thus are better able to up-regulate reactive control to maintain high levels of task performance under more strenuous conditions (i.e., incompatible stimulus–response condition).

Less straightforward than the ERN–reactive control relationship is the relationship between the stimulus-driven P3 potential and proactive control strategy. That is, the generation of the P3 is representative of the summation of neuroelectric activity from frontal and temporal/parietal networks (Kirino, Belger, Goldman-Rakic, & McCarthy, 2000; Ebmeier et al., 1995). However, dorsolateral prefrontal cortex is also thought to contribute to the underlying generation of the P3 (Salisbury, Krljes, & McCarley, 2003). Thus, the P3, which is believed to index the allocation of attentional resources toward a given stimulus or task (Polich, 2007), may further serve to reflect alterations in proactive cognitive control strategies to facilitate optimal completion of a goal via adjustments in attentional engagement. Given the increased metabolic demands required for prolonged activation of proactive cognitive control processes (Braver et al., 2007), lower-fit participants may be unable to generate the necessary neuroelectric resources to engage, as well as modulate, proactive control mechanisms, thus exhibiting a smaller overall P3 and relying more heavily on reactive control mechanisms. Hence, it appears that higher-fit compared to lower-fit participants may be able to selectively up-regulate and effectively alter proactive control strategies, as indexed by a larger overall P3 across conditions and greater modulation of P3 between stimulus–response conditions, as well as engage reactive control mechanisms on an "as-needed" basis to maintain high levels of task performance.

Collectively, the findings reported herein replicate and extend previous findings in children and young adults to suggest that there is a general, yet selective, influence of cardiorespiratory fitness on cognitive control. Specifically, lower-fit children exhibited reduced overall task performance, with a disproportionately greater reduction in performance in response to the incompatible stimulus–response condition, relative to higher-fit children. These data further replicate and extend the findings of Themanson et al. (2008), who observed that lower-fit participants exhibit a decreased ability to flexibly modulate cognitive control processes. Thus, cardiorespiratory fitness appears to relate to the ability to successfully engage cognitive control strategies to optimize task performance across the lifespan. It should be noted, however, that given the cross-sectional nature of this investigation, individual differences in personality, genetic predisposition, or other factors may be associated with the self selection of participants into specific fitness groups. Future research employing randomized control trials are necessary to fully elucidate these effects.

Taken together, however, these findings confirm previous research demonstrating a positive association between physical activity and school-based academic performance (Chomitz et al., 2009; Trudeau & Shephard, 2008; Castelli et al., 2007; Coe, Pivarnik, Womack, Reeves, & Malina, 2006). That is, a number of recent reports have observed that participation in vigorous physical activity and increased aerobic fitness relate to increased academic performance in core topics such as mathematics and reading (Castelli et al., 2007; Coe et al., 2006). Despite these findings, and those of an ever-growing body of research indicating a positive association between physical activity and cognitive health, an increasing number of schools are eliminating time spent on nonacademic subject matters (e.g., physical education, arts, and music) in response to recent federal mandates aimed at increasing academic competency. Accordingly, these data speak to the importance of physical activity for the maturation of neural networks underlying aspects of cognitive control and have implications for maximizing cognitive health and function in real-world settings during development.

Acknowledgments

Support for our research and the preparation of this manuscript was provided by grants from the National Institute on Aging to Arthur Kramer (RO1 AG25667 and RO1 AG25302), the National Institute of Child Health and Human Development (NICHD) to Charles Hillman (RO1 HD055352), and a fellowship awarded to Matthew Pontifex through the NICHD Developmental Psychobiology and Neurobiology Training Grant at the University of Illinois (2 T32 HD007333).

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Note

1. Further analyses were conducted using the mean amplitude for N2 within a 250- to 350-msec latency window and P3 within a 350- to 600-msec latency window. Omnibus analyses of mean N2 amplitude revealed main effects of Fitness $[F(1, 46) = 4.3, p = .045, \eta^2 = .09]$, Compatibility $[F(1, 46) = 19.1, p < .001, \eta^2 = .29]$, Congruency $[F(1, 46) = 5.6, p = .023, \eta^2 = .11]$, and Site $[F(6, 41) = 7.8, p < .001, \eta^2 = .53]$, replicating the findings from analysis of peak N2 amplitude. In contrast to the peak N2 amplitude analysis, no interaction of Congruency × Site was observed for mean N2 amplitude. Analysis of mean P3 amplitude revealed main effects of fitness $[F(1, 46) = 15.6, p < .001, \eta^2 = .25]$, compatibility $[F(1, 46) = 7.6, p = .008, \eta^2 = .14]$, site $[F(6, 41) = 8.3, p < .001, \eta^2 = .55]$, and an interaction of Fitness × Compatibility $[F(1, 46) = 4.4, p = .04, \eta^2 = .09]$, replicating all findings from the analysis of P3 peak amplitude.

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