Aerobic Fitness and Neurocognitive Function in Healthy Preadolescent Children

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ABSTRACT

HILLMAN, C. H., D. M. CASTELLI, and S. M. BUCK. Aerobic Fitness and Neurocognitive Function in Healthy Preadolescent Children. *Med. Sci. Sports Exerc.*, Vol. 37. No. 11, pp. 000–000, 2005. **Purpose:** We investigated the relationship between age, aerobic fitness, and cognitive function by comparing high- and low-fit preadolescent children and adults. **Method:** Twenty-four children (mean age = 9.6 yr) and 27 adults (mean age = 19.3 yr) were grouped according to their fitness (high, low) such that four approximately equal groups were compared. Fitness was assessed using the *Fitnessgram* test, and cognitive function was measured by neuroelectric and behavioral responses to a stimulus discrimination task. **Results:** Adults exhibited greater P3 amplitude at Cz and Pz sites, and decreased amplitude at the Oz site compared with children. High-fit children had greater P3 amplitude compared with low-fit children and high- and low-fit adults. Further, adults had faster P3 latency compared with children, and high-fit participants had faster P3 latency compared with low-fit participants at the Oz site. Adults exhibited faster reaction time than children; however, fitness interacted with age such that high-fit children had faster reaction time than low-fit children. **Conclusion:** These findings suggest that fitness was positively associated with neuroelectric indices of attention and working memory and response speed in children. Fitness was also associated with cognitive processing speed, but these findings were not age-specific. These data indicate that fitness may be related to better cognitive functioning in preadolescents and have implications for increasing cognitive health in children and adults. **Key Words:** EXERCISE, EVENT-RELATED POTENTIALS, EEG, P3, DEVELOPMENT, COGNITIVE FUNCTION

Physical activity has been associated with general and selective benefits in cognitive function, mainly in older adult populations (5). The relationship of aerobic fitness to underlying aspects of cognition in children is virtually unexplored. However, recent findings have indicated that fitness may be related to academic achievement. A California statewide study found that student achievement scores were positively associated with fitness in ninth grade students (California Department of Education (2002): State study proves physically fit kids perform better academically; at http://www.cde.ca.gov/re/nr/nr/yr02rel37.asp), and earlier research examining the influence of daily physical activity on math and reading performance found that despite the loss of academic time (i.e., the actual amount of time spent engaged in the subject matters of science, math, reading, language arts, and/or social studies) in order to provide additional time for physical activity, there was no decline in academic performance (12).

A meta-analysis conducted on 16 studies using true experimental designs found a positive relationship between physical activity and cognition or academic achievement in school-age children (34). Increased physical activity was related to cognitive performance along eight measurement categories (i.e., perceptual skills, intelligent quotient, academic achievement, verbal tests, math tests, memory, developmental level/academic readiness, and other), and results indicated a beneficial relationship for all categories, with the exception of memory (34). These findings suggest that fitness may be related to general improvements in cognitive function, but do not provide any understanding of the underlying mechanisms by which aerobic fitness may affect brain and cognition in children. Further, other factors such as socioeconomic status (SES) (10) may contribute to children's physical activity participation, rendering it difficult to determine the influence of fitness, as opposed to other factors, on cognitive function during the early stages of the human life span. Accordingly, the purpose of the present investigation was to expound this relationship by examining underlying brain function associated with cognition in high- and low-fit children. Specifically, measurement of the neuroelectric system may be more sensitive to fitness-related differences in cognition, compared with behavioral performance measures, because they provide information regarding how neural resources are being allocated, as well as topographical and temporal aspects of neural processing of the stimulus.

Research on the neuroelectric system has provided much insight into our understanding of cognitive processing (6,24,36). Specifically, event-related brain potentials (ERP), which reflect patterns of voltage change in ongoing neuroelectric activity that occur in response to, or in preparation for, a stimulus or response. The P3 is an endogenous component of the ERP occurring approximately 300–800 ms after a stimulus onset, which is elicited when participants

attend to and discriminate between stimuli (30). The P3 is theorized to index processes involved in the allocation of attention and working memory resources, which are engaged when the neural representation of the stimulus environment is updated (9). Findings have supported this theory as P3 amplitude (measured in microvolts) has been found to be proportional to the amount of attentional resources devoted to a stimulus, with increased amplitude related to increased attention toward a stimulus (29). Because the P3 occurs after a stimulus has been discriminated and categorized, the latency of this component (measured in milliseconds) is thought to reflect stimulus evaluation time (7), with shorter latency indicating faster cognitive processing speed.

Traditionally, the P3 has been elicited in stimulus discrimination paradigms that manipulate probability (29), such as the "oddball" task, in which rare target stimuli (i.e., oddballs) that require a specific cognitive response have to be detected within a train of frequent nontarget stimuli that do not require a response. In these tasks, the P3 has a maximum amplitude at electrodes placed over the centroparietal scalp region (i.e., Pz), with larger amplitude and longer latency for target, compared with nontarget, stimuli (29). However, the neural generators of the P3 to an oddball task are more varied with activation observed in the frontal lobes, temporoparietal junction, and the visual cortex (for visual paradigms), among other brain regions when measured with functional magnetic resonance imaging (fMRI) (20).

Both physical activity participation and aerobic fitness have been associated with the P3 and behavioral performance using cross-sectional (31) and randomized control designs (11,18) in adult populations. Adults that engage in habitual aerobic exercise exhibit greater P3 amplitude (31) and faster P3 latency (11,13) along midline scalp sites (Fz, Cz, Pz) in response to stimulus discrimination paradigms (e.g., oddball tasks), compared with their nonexercising peers. These findings suggest that that aerobic exercise may influence underlying neuroelectric concomitants of attention and working memory resource allocation, as well as cognitive processing speed. Additionally, faster and more accurate behavioral responses are observed for high-fit, compared with low-fit, participants (18). These findings suggest that aerobic exercise is associated with benefits in underlying processes involved in behavioral response aspects of cognitive function. To date, the relationship between fitness and neuroelectric indices of cognition has not been examined in preadolescent populations.

Preadolescent children, compared with young adults, exhibit lower performance on stimulus discrimination tasks, presumably due to the underdeveloped or immature brain structures that subserve various cognitive functions. These functions include maturation of processes involved in working memory and inhibitory function (8), continued myelination (40) and synaptogenesis (15) of specific brain regions, structural changes in the hippocampus and basal ganglia (4), and development of the frontal lobes leading to increased functioning of the executive system (37). Research examining the P3 has offered insight into the devel-

opment of the brain and subsequent cognitive processes of children (28). Specifically, preadolescent children exhibit significantly longer P3 latency than adults during oddball tasks, indicating slower cognitive processing speed (7). The findings regarding P3 amplitude are less clear, though with results indicating larger (1), smaller (16), or no difference (7) in amplitude when compared with adults. Accordingly, the relationship between development and P3 amplitude in response to cognitive tasks remains unclear and the equivocal findings may relate to differences in maturation, characteristics of the study sample, or the cognitive task employed. Despite this lack of consensus regarding P3 amplitude, robust behavioral differences have been observed, with preadolescents exhibiting longer reaction time (RT) latency and decreased response accuracy compared with adults (1,7,16).

Certain cognitive factors have also been found to influence neuroelectric function in preadolescent children. For example, faster P3 latency has been associated with children of gifted intelligence (i.e., IQ above 140 on the Wechsler Intelligence Scale for Children) (22,35), and greater equipotentiality of P3 amplitude across scalp-placed recording sites has been observed in children with attention deficit/hyperactivity disorder (25). However, the relationship between aerobic fitness and neuroelectric indices of cognition remains unexplored in children. Recent trends (38) have identified decreasing levels of physical activity and health status across the life span, with a growing number of children being unfit. Thus, the purpose of this study was to determine whether a high level of fitness was associated with better cognitive performance and a superior neuroelectric profile (as evidenced by increased P3 amplitude and decreased latency) on a visual discrimination task in preadolescent children. This discrimination task, known as an "oddball task," presents two stimuli with varying probability in a random series, such that one stimulus occurs relatively infrequently. The participant is required to distinguish between the stimuli and respond to the infrequent (i.e., target) stimulus via a button press and not respond to the frequent stimulus. It was predicted that high-fit children would exhibit larger P3 amplitude and faster P3 latency than their low-fit peers. It was further predicted that fitness would be positively associated with task performance with high-fit children responding faster and more accurately than low-fit children. Finally, as a point of comparison, high- and low-fit young adults were also examined to better determine the magnitude of change between high- and low-fit children.

METHOD

Participants. Table 1 lists participants' demographic and fitness information. Fifty-one participants were recruited for this study from a larger pool of potential participants and were placed into one of four groups: high-fit children, low-fit children, high-fit adults, and low-fit adults. Four participants were left handed (two high-fit children, two high-fit adults). Demographic data were incomplete for one high-fit child and three low-fit children due to the

TABLE 1. Group means (SD) of descriptive and fitness data for adult and child participants.

Measure	High-Fit Adults	Low-Fit Adults	High-Fit Children	Low-Fit Children
No.	15 (6 males)	12 (7 males)	12 (7 males)	12 (6 males)
Age (yr)	19.1^a (1.2)	19.5^a (1.5)	9.3^b (1.2)	9.8^b (0.6)
Height (cm)	171.7^a (8.9)	172.1^a (9.2)	139.9^b (13.3)	144.9^b (9.2)
Weight (kg)	64.6^a (9.4)	75.1^a (18.4)	37.5^b (14.0)	47.8^b (20.0)
Education (yr)	14.7^a (1.0)	15.3^a (1.3)	5.0^b (0.9)	5.3^b (0.7)
K-BIT (IQ)	103.4^a (8.7)	104.5^a (6.8)	116.7^b (12.7)	108.7^b (11.0)
SES (median)	3.0^a	3.0^a	3.0^a	3.0^a
PACER (laps)	56.5^a (9.7)	32.1^b (12.7)	30.8^b (13.1)	12.6^c (5.3)
Push-ups	25.5^a (8.9)	$17.8^{a,b}$ (10.0)	14.2^b (6.6)	11.1^b (5.9)
Curl-ups	54.8^a (12.4)	33.3^b (14.5)	32.9^b (9.7)	15.0^c (8.1)
Sit and reach (L)	14.2^a (2.2)	13.4^a (2.7)	9.8^b (2.1)	8.7^b (3.7)
Sit and reach (R)	14.2^a (2.1)	13.9^a (2.3)	10.2^b (1.8)	8.9^b (3.6)
Body mass index	$21.8^{a,b}$ (1.8)	24.8^a (4.3)	18.7^b (4.1)	$22.2^{a,b}$ (6.8)

Education (yr), total number of years of education; K-BIT, composite score for IQ; SES, socioeconomic status. The PACER, push-ups, curl-ups, sit and reach, and BMI are subscales of the *Fitnessgram* test. Normative values for the *Fitnessgram* may be found in Welk et al. (40). Values that share a common superscript are not significantly different at $P \leq 0.05$.

addition of these measures after data collection began. Children were recruited from the Champaign, IL, elementary school system, and adults were recruited from courses in the Department of Kinesiology at the University of Illinois at Urbana-Champaign. None of the children in the sample received special education services related to cognitive disabilities (e.g., attention deficit disorder). All participants provided written informed consent, or written informed consent was provided by the participants' legal guardian, in accordance with the institutional review board at the University of Illinois. Children and their guardians also provided informed consent in accordance with the Champaign County school district.

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 (39). The reliability and validly of the aerobic capacity portion of the *Fitnessgram* have been found to be moderately high, with 85% of children and adults consistently classified (39). Further, greater than 70% of individuals were classified correctly by field test scores as judged by classifications based on directly measured $\dot{V}O_{2max}$ (39). Children completed the *Fitnessgram* during regularly scheduled physical education classes under the supervision of their physical education teachers, with the subtests administered by members of the research team. Children were familiarized with and allowed to practice the testing protocols during a separate physical education class that occurred before the two classes of data collection. Adults practiced and completed the *Fitnessgram* in a group setting that was administered by the research team. The *Fitnessgram* measures multiple aspects of physical fitness including aerobic capacity (i.e., the PACER (progressive aerobic cardiovascular endurance run)), muscle fitness (i.e., push-ups and curl-ups), flexibility fitness (i.e., sit and reach test), and body composition through height and weight measures that are converted to a body mass index (BMI) score. In total, 600 children completed the *Fitnessgram* testing. Children's scores on the test of aerobic capacity (i.e., PACER) were ranked with recruitment coming only from the top 10% and the bottom 10%. A similar procedure was used to identify high- and low-fit adults from a sample of 110 participants. A smaller sample of adults was tested because they were recruited from a previously screened participant pool. Scoring of the PACER test was based on criteria established by the *Fitnessgram* scientific advisory committee.

Participant characteristics. Data were collected on several factors that have been found to affect either physical activity participation or cognitive function. Specifically, the K-BIT (17) was administered by a trained experimenter to measure participants' intelligence quotient (IQ). Collection of the K-BIT took approximately 15–20 min. In addition, data were collected on participants' SES by creating a trichotomous index based on three variables: participation in free or reduced-price lunch program at school, the highest level of education obtained by the mother and father, and number of parents who worked full time (2). For children, these data were reported by their legal guardian.

Cognitive task. Participants engaged in a visual oddball paradigm, which required them to make a button press with their right thumb as quickly as possible to an infrequently presented target stimulus (i.e., 20% probability), whereas no response was required for the frequent, nontarget stimulus (i.e., 80% probability). For all participants, the target stimulus consisted of a black and white line drawing of a cat, and the nontarget stimulus was a black and white line drawing of a dog. The 10×10-cm stimuli were presented focally in a random order for 200 ms on a black background with an interstimulus interval of 1000 ms from stimulus offset to onset. Three 3-min blocks of 150 trials were administered with a 2-min rest period between blocks.

Laboratory procedure. Upon signing the informed consent, participants were prepared for neuroelectric measurement in accordance with the guidelines of the Society for Psychophysiological Research (26). An experimenter read the task instructions and had participants perform 10 practice trials. Following the completion of the cognitive task, all electrodes were removed and the participants were briefed on the purpose of the experiment. The task was administered during daylight hours, with approximately half the participants participating in the morning (i.e., 13 high-

fit, 10 low-fit) and afternoon (i.e., 14 high-fit, 14 low-fit). The entire procedure lasted approximately 1 h.

Electroencephalogram (EEG) recordings. EEG was measured from the following midline and lateral electrodes of the 10–20 system using a Quik Cap (Neuro, Inc., El Paso, TX): F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2, A2 (i.e., right mastoid) and referenced to the left mastoid (A1) with AFz as the ground electrode, and impedances kept below 10 kΩ. Electro-oculographic (EOG) 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. Neuroscan 64-channel Synamps bioamplifiers (Neuro Inc., El Paso, TX) were 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 4.2 software on a microcomputer. Stimuli were generated using Neuroscan Stim software on a microcomputer, which sent a trigger indicating the condition of each trial for offline sorting, reduction, and analysis of EEG and behavioral data.

Data reduction. Continuous data were merged offline with behavioral data, rereferenced to an average of the mastoid electrodes, and ocular artifacts were corrected using spatial filtering or the Semlitsch et al. (33) algorithm to minimize vertical and horizontal eye movement artifacts in EEG signals. Epochs of −100 to 800 ms around stimuli were created, and baseline correction occurred using the 100-ms prestimulus period. Data were filtered with a 30-Hz low-pass cutoff (24 dB/octave). Artifact detection excluded trials with amplitude excursions of ±100 μV, and artifact-free data that were accompanied by correct responses were averaged. The mean number of trials included for participant averages was 393.2 (±65.9). The P3 component of the ERP was defined as the largest positive-going peak within a 275- to 775-ms latency window after the N1-P2-N2 complex. Amplitude was measured as a change from the prestimulus baseline and peak latency was defined as the time point of the maximum amplitude. Amplitude analyses for age comparisons involving the site factor included the McCarthy and Wood (23) normalization procedure, which standardizes differences in the topographic distribution of the scalp activity across groups.

Statistical analysis. Statistical analyses were confined to the midline sites (8) with P3 amplitude and latency examined separately. P3 values for each participant were submitted to a 2 (age: adult, child) × 2 (fitness: high, low) × 2 (condition: target, nontarget) × 4 (site: Fz, Cz, Pz, Oz) mixed-model ANOVA with Greenhouse-Geisser corrections where appropriate. Response accuracy data were analyzed using a 2 (age) × 2 (fitness) × 2 (condition) ANOVA, and RT data (measured via the speed of the button press response) were analyzed using a 2 (age) × 2 (fitness) ANOVA, because responses were not required for the nontarget condition. *Post hoc* analyses were conducted using simple effects tests with the Bonferroni correction procedure. The alpha level for all tests was set at $P = 0.05$ before Bonferroni correction.

TABLE 2. Participant group means (SD) to target stimuli for reaction time (RT) and response accuracy.

Group	RT (ms) for Target Stimuli	Accuracy (%) for Target Stimuli
High-fit children	430.7 (53.4)	94.6 (10.2)
Low-fit children	509.1 (83.2)	88.1 (12.9)
High-fit young adults	352.8 (38.3)	98.4 (2.2)
Low-fit young adults	359.5 (36.0)	94.2 (10.2)

RESULTS

Behavioral measures. RT responses to target stimuli yielded significant effects of age ($F(1,47) = 53.0$, $P < 0.001$, $\eta(2) = 0.53$) and fitness ($F(1,47) = 7.9$, $P < 0.01$, $\eta(2) = 0.14$), indicating that adults (mean = 351.7 ms, SE = 9.0) and high-fit participants (mean = 391.1 ms, SE = 9.5) had faster RT than children (mean = 465.6 ms, SE = 9.0) and low-fit participants (mean = 426.2 ms, SE = 9.5), respectively. Further, an age × fitness interaction was observed ($F(1,47) = 5.7$, $P = 0.02$, $\eta(2) = 0.11$), with *post hoc* tests indicating that both adult groups were faster than both child groups ($t(1,22) \geq 3.7$, $p < 0.001$), but high-fit children were faster than low-fit children ($t(1,22) = 2.8$, $P = 0.01$) (Table 2). No RT differences were observed between high- and low-fit adults ($t(1,25) = 0.5$, $P = 0.65$).

Response accuracy yielded significant effects of age ($F(1,47) = 4.9$, $P = 0.03$, $\eta(2) = 0.09$) and condition ($F(1,47) = 17.3$, $P < 0.001$, $\eta(2) = 0.27$, $\varepsilon = 1.0$), with adults (mean = 98.0%, SE = 1.0) exhibiting greater accuracy than children (mean = 94.8%, SE = 1.1), and all participants exhibiting greater accuracy for nontarget (mean = 99.0%, SE = 0.2) compared with target (mean = 93.8%, SE = 1.3) stimuli. In addition, a fitness × condition interaction was observed, $F(1,47) = 6.3$, $P < 0.02$, $\eta(2) = 0.12$. *Post hoc* tests indicated that high-fit participants (mean = 96.5%, SE = 1.8) were more accurate than low-fit participants (mean = 91.3%, SE = 1.9) to target stimuli, but this effect was not significant after Bonferroni correction ($t(1,49) = 2.1$, $P = 0.04$) (Table 2). High (mean = 98.6%, SE = 0.3)- and low (mean = 99.5%, SE = 0.3)-fit participants did not differ in their responses to nontarget stimuli, $t(1,49) = 1.5$, $P = 0.14$.

ERP analysis. Figure 1 illustrates the ERP waveforms for each participant group at the four midline electrode sites (Fz, Cz, Pz, Oz) to target and nontarget stimuli.

P3 amplitude. A condition effect was observed ($F(1,47) = 82.7$, $P < 0.001$, $\eta(2) = 0.64$, $\varepsilon = 1.0$), with increased amplitude for target (mean = 15.2 μV, SE = 0.8) compared with nontarget (mean = 9.0 μV, SE = 0.5) stimuli. A site effect was also observed, $F(2.6,121.6) = 126.0$, $P < 0.001$, $\eta(2) = 0.73$, $\varepsilon = 0.86$), with *post hoc* tests indicating the largest amplitude at Pz and Oz, the smallest amplitude at Fz, with Cz falling in between ($t(1,50) \geq 5.8$, $P < 0.001$). However, these main effects were superseded by a condition × site interaction ($F(2.6,120.4) = 36.9$, $P < 0.001$, $\eta(2) = 0.44$, $\varepsilon = 0.85$), as increased amplitude was observed at Cz, Pz, and Oz for target compared with nontarget stimuli ($t(1,50) \geq 6.4$, $P < 0.001$).
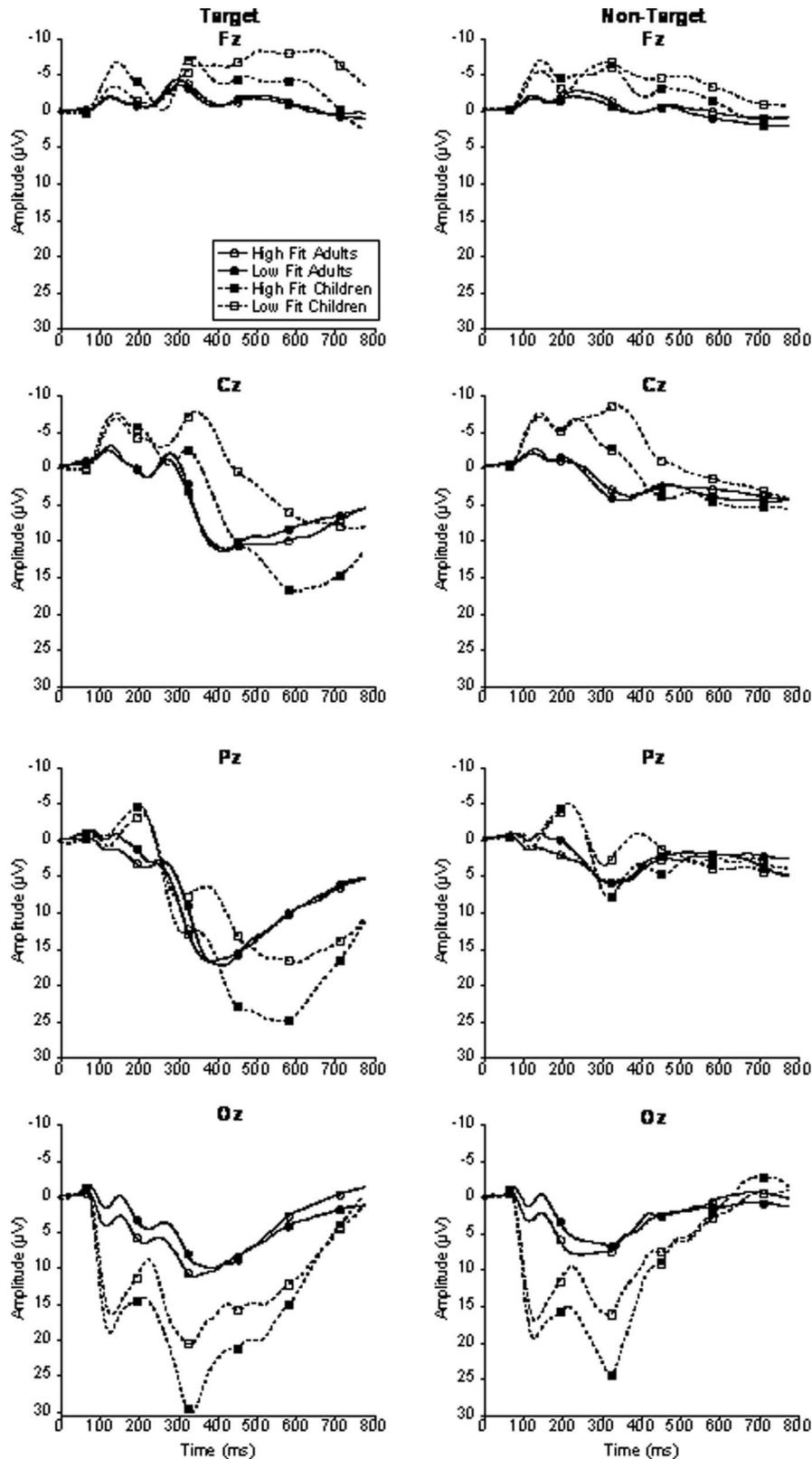
T2

F1

FIGURE 1—Grand average waveforms for each group at the four midline electrode sites to the target and nontarget stimuli of the oddball task. Note the larger P3 amplitude for the high-fit preadolescent children.

Further, an age effect was observed for P3 ($F(1,47) =$ 18.8, $P < 0.001$, $\eta(2) = 0.29$), with increased amplitude for children (mean = 14.6 μV, SE = 0.8) compared with adults (mean = 9.6 μV, SE = 0.8). This effect was superseded by an age $\times$ site interaction ($F(2.6,121.6) = 31.5$, $P < 0.001$, $\eta(2) = 0.40$), with follow-up tests (which were conducted using standardized means from the McCarthy and Wood (24) procedure) indicating that adults exhibited larger P3
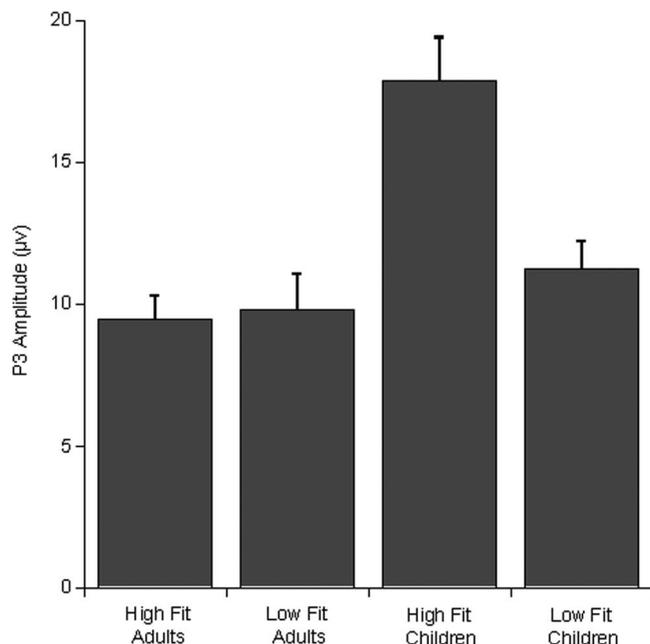
FIGURE 2—Age × fitness interaction for P3 amplitude. Note the significant increase in amplitude for high-fit children compared with the other three groups.

amplitude at Cz and Pz and smaller P3 amplitude at Oz ($t(1,49) \geq 2.8$, $P < 0.008$) when compared with children.

A fitness effect was also found for P3 ($F(1,47) = 7.6$, $P = 0.008$, $\eta(2) = 0.14$), with increased amplitude for high-fit (mean = 13.7 μV, SE = 0.8) relative to low-fit (mean = 10.5 μV, SE = 0.8) participants. However, this effect was superseded by an age × fitness interaction ($F(1,47) = 9.4$, $P = 0.004$, $\eta(2) = 0.17$). *Post hoc* analyses indicated that high-fit children exhibited larger P3 amplitude than the other three groups ($t(1,22) \geq 3.7$, $P < 0.001$) (Fig. 2).

P3 latency. A site effect was observed ($F(2.2,105.0) = 38.6$, $P < 0.001$, $\eta(2) = 0.45$, $\varepsilon = 0.74$) that was superseded by two two-way interactions of age × site ($F(2.2,105.0) = 5.5$, $P = 0.005$, $\eta(2) = 0.11$) and condition × site ($F(2.8,132.4) = 5.4$, $P = 0.002$, $\eta(2) = 0.10$, $\varepsilon = 0.94$). *Post hoc* analyses indicated that adults, compared with children, had faster latency at the Cz and Pz electrode sites ($t(1,49) \geq 3.0$, $P < 0.004$), and nontarget stimuli elicited faster latency than target stimuli at the Pz site ($t(1,50) = 3.7$, $P = 0.001$).

In addition, a fitness × condition interaction was observed ($F(1,47) = 9.8$, $P = 0.003$, $\eta(2) = 0.17$), which was superseded by a significant three-way interaction of fitness × condition × site ($F(2.8,132.4) = 4.2$, $P < 0.01$, $\eta(2) = 0.08$). Decomposition of this interaction was conducted by examining fitness × condition at each site. A significant fitness × condition interaction was observed at Fz ($F(1,49) = 14.1$, $P < 0.001$, $\eta(2) = 0.22$), but *post hoc* Bonferroni corrected *t*-tests failed to find significant fitness effects for either task condition ($t(1,49) \leq 2.0$, $P > 0.05$). A condition effect was observed at Pz ($F(1,49) = 13.3$, $P = 0.001$, $\eta(2) = 0.21$, $\varepsilon = 1.0$), indicating faster P3 latency for nontarget (mean = 414.2 ms, SE = 23.9) compared with target (mean = 484.6 ms, SE = 15.5) stimuli, and a fitness effect was

observed at Oz ($F(1,49) = 4.6$, $P < 0.05$, $\eta(2) = 0.09$), indicating faster latency for high-fit (mean = 331.3 ms, SE = 8.8) compared with low-fit (mean = 359.0 ms, SE = 9.4) participants.

DISCUSSION

Our findings indicate that high-fit preadolescent children had greater P3 amplitude when compared with low-fit children and both adult groups, indicating that a larger population of neurons is being recruited for the task. Additionally, high-fit children and adults had faster P3 latency at the occipital recording site than their low-fit counterparts, indicating faster neurocognitive processing. Behaviorally, high-fit children responded faster to target stimuli compared with low-fit children, but remained slower than both adult groups, suggesting that fitness may be related to modest improvements in task performance during preadolescents.

Based on classic interpretations of P3, the observed increase in amplitude for higher fit children suggests greater allocation of attention and working memory resources related to stimulus processing, thus supporting previous research on physical activity and cognitive function (13). That is, comparison of older and younger adults has demonstrated increased P3 amplitude for physically active compared with sedentary individuals (13). Of interest is determining the functional relationship between fitness and the observed increased activation in individuals who are in the process of cognitive maturation or degradation associated with early and late phases of the human life span, respectively.

Differences in the amount and location of neural activation among older and younger adults in response to cognitive tasks have been observed using fMRI. These findings may provide some insight into the observed increases in neuroelectric activation for high-fit children found in the current study. For example, increased activation in older adults was associated with better task performance, whereas better performance was associated with decreased activation in younger adults (32). Further, Bunge et al. (3) compared 8- to 12-yr-old children with young adults and found that children activated left ventrolateral prefrontal cortex (PFC) rather than the expected right ventrolateral PFC exhibited in adults. The children's activation of the left ventrolateral PFC was similar in magnitude to that of the adult's activation of the right ventrolateral PFC, suggesting that throughout development, children may recruit different neural resources than adults to achieve similar goals, albeit with less efficiency. Other research has found that children recruited the same general network of cortical structures as adults, but to a greater degree, with additional recruitment of cortical networks not activated in adults (21). Collectively, these findings indicate that greater cortical activation is beneficial to task performance during the early and late stages of the human lifespan; but that performance in younger adults may benefit from cognitive efficiency (i.e., less cortical activation). The data reported here indicate a similar pattern for higher fit preadolescent children and suggest that fitness may be associated with increasing neuroelectric activation

related to the allocation of attention and working memory resources, which perhaps may influence the speed of behavioral performance.

An alternate explanation for the fitness-related differences in P3 also exists. Polich and Lardon (31) have theorized that aerobic exercise effects on ERP may be based in fundamental changes observed in resting neuroelectric activity. Lardon and Polich (19) observed increased EEG spectral power in the theta (4–8 Hz), alpha I (7.5–9.5 Hz), alpha II (9.5–12.5 Hz), beta I (12–20 Hz), and beta II (12–70 Hz) bands and increased mean frequency in the delta (0.25–4 Hz), theta, and beta I and II bands for chronic exercisers compared with low-active control participants, suggesting that exercise may serve to increase neuronal synchrony. Further, Polich (27) found that interparticipant variations in alpha power are related to individual variability in the P3 component, indicating that changes in resting EEG may directly influence ERP. Thus, aerobic exercise may increase synchrony in the firing of neuronal generators, which in turn may increase P3 amplitude and decrease P3 latency. However, the functional significance of greater neuronal synchrony still remains unclear.

The current data may also shed light on the inconsistent P3 amplitude findings between children and young adults. That is, previous research has reported that children exhibit P3 amplitudes that are larger (1), smaller (16), or no different (7) than young adults. Given the differential P3 amplitude observed for high- and low-fit children, it is possible that specific health or other individual differences that are not typically accounted for in neuropsychological research may act on the neuroelectric system and result in the inconsistencies observed across studies. Indeed, fitness may account for a portion of this variance, because widespread differences in physical activity habits of preadolescent children have been reported (34,38).

P3 latency replicated previous research, as preadolescent children exhibited longer latencies compared with young adults over the centroparietal region of the scalp. Fitness was also associated with P3 latency, because high-fit participants exhibited faster latency compared with low-fit participants at the Oz site. These data replicate previous P3 research on physical activity and cognition in adults (11,13,14) and indicate that fitness is positively associated with cognitive processing speed during stimulus discrimination tasks. However, these data should be interpreted cautiously as fitness effects were only observed over the occipital scalp region rather than over the predicted centroparietal scalp region. Given that a visual oddball task was employed and neural generators for the P3 have been observed in the occipital cortex (in addition to other brain regions) using fMRI (20), it is plausible that faster cognitive processing associated with fitness may be observed over this scalp location. Nonetheless, future research should replicate this finding to better determine the robustness of this effect.

Most notably, fitness was positively associated with behavioral performance in preadolescents, as high-fit children exhibited faster RT speed compared with low-fit children. Despite this interesting finding, the RT for high-fit children was still slower than both adult groups, suggesting that small, but significant, improvements in response speed may be associated with aerobic fitness. With regard to response accuracy, a trend was observed such that high-fit children and adults performed more accurately than their low-fit peers to target stimuli. Importantly, this finding suggests that the fitness-related improvements associated with RT are not due to a speed–accuracy tradeoff, because task performance did not differ statistically between high- and low-fit participants.

There are several limitations associated with the present study. First, the study is cross-sectional, and therefore a selection bias may account for the findings that were attributed to different levels of fitness. It is plausible that high- and low-fit participants differ on many other factors (e.g., genetics, skull thickness, personality characteristics) that could lead to differences in fitness as well as neuroelectric and behavioral performance. However, the probability of this happening was partially reduced by matching the high- and low-fit participants on the variables listed in Table 1. Randomized clinical trials should be conducted in future research to account for possible selection bias. A second limitation of the present study is that the sample size may have been insufficient to detect the interaction of age and fitness for all measures. Thus, future research should examine fitness effects on cognition using a larger sample size to ensure adequate power. Last, a field test of aerobic fitness was favored over an objective measure of fitness (e.g., $\dot{V}O_{2max}$). However, as stated in the method, 70% of individuals were accurately classified for the PACER test of the *Fitnessgram* based on directly measured $\dot{V}O_{2max}$ (39).

In summary, we found that aerobic fitness was positively associated with neuroelectric function and behavioral performance in preadolescent children engaged in a stimulus discrimination task. Specifically, larger P3 amplitude and faster RT were observed for high-fit, relative to low-fit, children. Fitness was also associated with P3 latency such that faster cognitive processing speed was observed for high-fit participants. These findings provide additional support for the beneficial affects of fitness on cognition across the human lifespan.

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