# Aerobic fitness and intra-individual variability of neurocognition in preadolescent children

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## ABSTRACT

This study examined behavioral and neuroelectric intra-individual variability (IIV) in preadolescent children during a task requiring variable amounts of cognitive control. The current study further examined whether IIV was moderated by aerobic fitness level. Participants performed a modified flanker task, comprised of congruent and incongruent arrays, within compatible and incompatible stimulus–response conditions. Results revealed that congruent, relative to incongruent, conditions were associated with less IIV of RT. Further, less IIV of RT, P3 amplitude, and P3 latency was observed for the compatible relative to the incompatible condition. Higher fitness was associated with shorter and less variable RT only for the incompatible condition, with no fitness-related differences observed for P3 variability. The findings suggest that conditions requiring greater cognitive control are associated with increased IIV, and that higher fitness may be associated with greater integrity of cognitive control systems during development.

## 1. Introduction

Physical activity, which is essential to maintain overall health and function, has been found to benefit weight control, bone mass, muscle strength, and reduce the risk of heart disease and certain cancers (USDHHS, 2008). Unfortunately, in today's industrial and technological society, children are becoming increasingly sedentary, exacerbating the prevalence of certain physical diseases including cardiovascular disease, colon cancer, and type-2 diabetes (Department of Health and Human Service and Department of Education, 2000). Beyond such physiological ramifications, physical activity has also been observed to relate to cognitive health across the life span (see Hillman, Erickson, & Kramer, 2008 for review). More specifically, in adult populations, aerobic exercise training is associated with modest improvements in attention, processing speed, cognitive control, and memory (Smith et al., 2010), with a disproportionate benefit observed during tasks requiring greater cognitive control (Colcombe & Kramer, 2003; Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Kramer et al., 1999). However, the specificity of the relation between fitness and cognitive health in developing populations continues to unfold (Buck, Hillman, & Castelli, 2008; Castelli et al., 2007; Hillman, Buck, Themanson,

Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Sibley & Etnier, 2003; Pontifex et al., 2011; Tomporowski, 2003) such that further inquiry is necessary to gain a greater understanding of the nature of the benefits of physical fitness on neurocognitive development.

Executive control refers to higher-order cognitive functions, which serve to coordinate the selection and execution of willed actions (Friedman, Nessler, Cycowicz, & Horton, 2009). Cognitive control refers to a subset of higher-order cognitive processes, which serve to regulate and optimize goal-directed behaviors through the selection, scheduling, coordination, and maintenance of processes underlying aspects of perception, memory, and action (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Meyer & Kieras, 1997; Norman & Shallice, 1986). The development of cognitive control progresses slowly in comparison to other cognitive processes, due to the protracted maturation of the prefrontal cortex (Anderson & Green, 2001; Blakemore & Choudhury, 2006; Diamond, 2002; Luna, Garver, Urban, Lazar, & Sweeney, 2004). With maturation, children exhibit better performance on cognitive control tasks, displaying shorter reaction times (RT) and greater response accuracy (Mezzacappa, 2004; Ridderinkhof, Van der Molen, Band, & Bashore, 1997; Rebok et al., 1997; Rueda et al., 2004). For instance, interference control (one aspect of cognitive control) begins to mature around 8 years of age, resulting in decreased RT and increased response accuracy across a variety of cognitive tasks (Ridderinkhof & van der Molen, 1995; Ridderinkhof et al., 1997; Rueda et al., 2004).

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One widely used task to examine interference control is the Eriksen flanker task (Eriksen & Eriksen, 1974). This task requires individuals to inhibit task-irrelevant information in order to correctly respond to a centrally presented target stimulus amid either congruent or incongruent flanking stimuli. The incongruent, relative to the congruent, condition requires greater amounts of interference control to inhibit flanking stimuli, as concurrent activation of both the correct response (elicited by the target) and the incorrect response (elicited by the flanking stimuli) occur before stimulus evaluation is complete (Spencer & Coles, 1999). Several studies using flanker tasks in adult populations have reported shorter RT (Hillman et al., 2006; Kramer et al., 1999) and increased response accuracy (Hillman et al., 2006) for more physically active adults, with the largest differences occurring during the incongruent condition. In preadolescent children, however, fitness-related differences in task performance remain less clear, as a more generalized fitness benefit has been observed during flanker performance (Hillman et al., 2009; Pontifex et al., 2011). Given the paucity of research on fitness and preadolescent cognition, additional research is necessary to better understand the relation of fitness and flanker performance in developing populations.

Most cognitive and neuropsychological research, however, has focused on mean differences in performance across individuals while leaving measures of within individual variability unevaluated (MacDonald, Li, & Bäckman, 2009), thus limiting interpretive power (Hockley, 1984; Ratcliff, 1993; Ratcliff & Murdock, 1976). Hence, the first aim of this study was to determine whether fitness was related to response variability. Measures of response variability provide a useful index of cognitive function beyond that of mean RT, with intra-individual variability (IIV) being widely used as a behavioral marker of neurological health (Macdonald, Nyberg, & Backman, 2006). IIV, as indexed by standard deviation (SD) of RT, describes the within-person fluctuations in behavioral performance. This fluctuation is separable from more enduring changes in learning and development (Macdonald et al., 2006), and affords an additional measure by which to understand behavioral development. For instance, increased SD of RT has been reliably found in children with attention-deficit/hyperactivity disorder (ADHD; see Kuntsi & Klein, 2011 for review). In healthy children, SD of RT during cognitive tasks decreases throughout childhood and adolescence (Li et al., 2004; Williams, Hultsch, Strauss, Hunter, & Tannock, 2005; Williams, Strauss, Hultsch, & Hunter, 2007), with reductions in SD of RT being linked to the maturation of white matter tracts and increased functional connectivity (Tamnes, Fjell, Westlye, Østby, & Walhovd, 2012). Across the lifespan, however, greater IIV is observed for tasks or task conditions requiring the up-regulation of cognitive control (Walhovd et al., 2011; Li & Lindenberger, 1999; Shammi, Bosman, & Stuss, 1998; West, Murphy, Armilio, Craik, & Stuss, 2002; Tamnes et al., 2012), and while numerous studies have examined SD of RT in clinical populations, little research has examined the relation between SD of RT and aerobic fitness. Previously, Wu et al. (2011) found that higher-fit children – those whose fitness was greater than the 70th percentile based on age and sex – exhibited decreased SD of RT and greater response accuracy across all conditions of a flanker task, relative to children whose fitness fell below the 30th percentile; while no group differences were observed for mean RT. To date, this is the only study that has evaluated IIV in relation to fitness and cognition. Thus, IIV represents an underutilized, yet potentially useful tool to further evaluate the relation between fitness and cognitive function. As such, the second purpose of the present study was to gain greater insight into IIV by evaluating preadolescent performance variability across the continuum of cardiovascular fitness.

To more accurately characterize the RT distribution during task performance, a growing number of reports have utilized the ex-Gaussian function (e.g., Heathcote, Popiel, & Mewhort, 1991;

McAuley, Yap, Christ, & White, 2006; Spieler, Balota, & Faust, 2000). Fitting the ex-Gaussian function to a RT distribution provides a more appropriate framework in which to evaluate IIV, as many RT distributions are non-normal (Whelan, 2010). The ex-Gaussian distribution represents the convolution of an exponential and Gaussian (normal) distribution. Parametrically, the ex-Gaussian distribution has three variables: mu ($\mu$) and sigma ($\sigma$), which respectively describe the mean and standard deviation of the normal component, and tau ($\tau$), which represents the mean and standard deviation of the exponentially distributed tail of the distribution that is positively skewed (Ratcliff, 1979). *Mu* and *sigma* of the ex-Gaussian distribution, should not be confused with the mean and SD of the Gaussian distribution, however, as the ex-Gaussian parameter $\mu$ = mean + *tau*, and the ex-Gaussian parameter $\sigma$ = SD + *tau*. As scores become more normally distributed (i.e. as tau diminishes), $\mu$ and $\sigma$ converge with the mean and SD, until *tau* reaches zero and the scores are normally distributed (Ratcliff, 1979). Ex-Gaussian analyses have been widely used to explore multiple aspects of cognition including inhibitory control (Heathcote et al., 1991; McAuley et al., 2006; Spieler et al., 2000) in aging populations (Myerson, Robertson, & Hale, 2007; West et al., 2002), as well as in children with ADHD (Leth-Steensen, Elbaz, & Douglas, 2000; Vaurio, Simmonds, & Mostofsky, 2009). However, few studies using ex-Gaussian analysis have examined the development of cognitive control (Leth-Steensen et al., 2000; McAuley et al., 2006; Vaurio et al., 2009). Using an inhibitory control paradigm, McAuley et al. (2006) observed that relative to young adults, children were more variable (as reflected by $\sigma$), rather than slower (as reflected by $\mu$) or more extreme (as reflected by $\tau$). To date, this is the only study examining the development of cognitive control via ex-Gaussian analyses in typical participants. As such, the current study sought to extend the extant literature by evaluating fitness and preadolescent cognition within an ex-Gaussian framework.

In addition to behavioral analyses, the present study sought to evaluate whether previously reported behavioral IIV findings (Wu et al., 2011) would extend to the neuroelectric domain. Beyond the measurement of overt responses, event-related brain potentials (ERPs) provide additional insight into the distinct cognitive operations that occur between stimulus engagement and response execution. Embedded in the stimulus-locked ERP is the P3 component, which is believed to reflect the allocation of attentional resources, as indexed by component amplitude (Polich, 2007), and stimulus classification and evaluation speed, as indexed by component latency (Duncan-Johnson, 1981; Verleger, 1997). Prior ERP reports indicate a beneficial relation between fitness and neurocognition in preadolescent children (Hillman et al., 2005, 2009; Pontifex et al., 2011), with higher-fit children exhibiting larger and more flexible modulation of P3 amplitude (Hillman et al., 2009; Pontifex et al., 2011) and shorter P3 latency (Pontifex et al., 2011) relative to their lower-fit counterparts during inhibitory control tasks. These findings suggest a fitness-related facilitation of attentional resources and stimulus evaluation and classification speed during environmental transactions requiring cognitive control. However, to date, no study has examined the relation between aerobic fitness and P3 variability, and few reports have examined IIV of P3 component values. One such study examining cognitive aging and IIV of P3 amplitude during a three-stimulus visual oddball task (Fjell & Walhovd, 2007) concluded that IIV at the level of the central nervous system coincides with IIV at the behavioral level. A similar investigation suggested that IIV of P3 latency was related to cognitive functions such as shifting and inhibition (Fjell, Rosquist, & Walhovd, 2009) with increasing IIV observed in association with aging and inhibitory demands. Results from these studies suggest that examining P3 variability may provide insight into cognitive variability associated with stimulus engagement. While greater IIV of task performance has been

observed for task conditions requiring greater amounts of cognitive control (Li & Lindenberger, 1999; Shammi et al., 1998; West et al., 2002), the locus of the fitness-related IIV differences in the information processing stream (i.e., at the level of stimulus evaluation versus response selection) remains unclear (Wu et al., 2011). As such, the last aim of the current study was to examine the role of neuroelectric IIV during cognitive control operations to determine whether fitness influenced this relationship.

Based on previous research it was hypothesized that regardless of fitness, lower response accuracy, increased IIV of RT, and increased IIV of P3 amplitude and latency would be observed for tasks requiring greater amounts of cognitive control. Further, higher amounts of fitness were expected to relate to greater response accuracy, thus replicating prior findings (Hillman et al., 2009; Pontifex et al., 2011). More importantly, however, higher fitness was expected to relate to decreased IIV of RT, and decreased IIV of P3 amplitude and latency. Such a pattern would suggest that fitness is associated not only with greater accuracy and shorter RT, but also more consistent cognitive performance at both the neuroelectric and behavioral level.

## 2. Methods

### 2.1. Participants

One hundred and fourteen preadolescent children (46 female; mean age: 8.8 ± 0.6 years) were recruited via flyers from the east-central Illinois region. Twelve participants were excluded due to parent disclosed diagnosis of attention-deficit/hyperactivity disorder (ADHD); 2 participants were excluded due to task performance below 50% accuracy; and 7 participants were excluded due to insufficient demographics data. Thus, analyses were conducted on the remaining 93 participants (39 females). All participants were between the ages of 8 and 10 years at time of testing. Table 1 lists demographic and fitness information for the final sample.

All participants provided written informed assent and their legal guardians provided written informed consent in accordance with the Institutional Review Board of the University of Illinois. Prior to testing, legal guardians completed a health history and demographics questionnaire, indicating that their children were free of neurological diseases or physical disabilities. Data were collected for certain factors that can influence physical activity participation or cognitive function. Specifically, the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990) was administered to each participant to create a composite intelligent quotient (IQ) score including measures of crystallized (vocabulary) and fluid (analogies) intelligence. The Attention-Deficit Hyperactivity Disorder Rating Scale IV (DuPaul, Power, Anastopoulos, & Reid, 1998) was completed by guardians to screen for the presence of attentional disorders (as indexed by scores above 14 and 22 for females

and males, respectively). Guardians also completed the Tanner Staging System (Taylor et al., 2001) to assess pubertal timing. All participants included were at or below a score of 2 (i.e. prepubescent) at time of testing. In addition, socioeconomic status (SES) was assessed by computing a trichotomous index based on three variables: (a) participation in a 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). Lastly, all included participants demonstrated right-handedness as measured by the Edinburgh Handedness Inventory (Oldfield, 1971).

### 2.2. Cardiorespiratory fitness assessment

Maximal aerobic capacity ($VO_{2max}$), was measured on a motor-driven treadmill. A modified Balke protocol was followed, which is recommended for graded exercise testing with children (ACSM, 2006). Prior to testing, all participants had their height and weight measured and were fitted with a Polar heart rate (HR) monitor (Polar WearLink® + 31, Polar Electro, Finland) to measure HR throughout the fitness assessment. Following a warm-up period, the motor-driven treadmill was set to a constant speed during the test, while grade increments of 2.5% occurred every 2 min until volitional exhaustion. Oxygen consumption was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400) with averages for oxygen uptake ($VO_2$) and respiratory exchange ratio (RER) assessed every 20 s. Concurrently, ratings of perceived exertion (RPE) were measured every 2 min using the children's OMNI scale (Utter, Roberson, Nieman, & Kang, 2002). $VO_{2max}$ was defined as the highest oxygen consumption corresponding to a minimum of 2 of the following 4 criteria: (1) a plateau in oxygen uptake corresponding to an increase of less than 2 ml/kg/min despite an increase in exercise workload; (2) a peak heart rate $\geqslant 185$ bpm (ACSM, 2006) and a heart rate plateau (Freedson & Goodman, 1993); (3) RER $\geqslant 1.0$ (Bar-Or, 1983); (4) ratings on the children's OMNI scale of perceived exertion $\geqslant 8$ (Utter et al., 2002); The relative peak oxygen consumption was expressed in milliliters/kilogram of body weight/min.

### 2.3. Cognitive task

Cognitive control was assessed by performance during a modified flanker task (Eriksen & Eriksen, 1974; Hillman et al., 2006; Pontifex & Hillman, 2007). During the task participants attended to a centrally presented target stimulus (cartoon fish) amid an array of laterally presented flanking stimuli (cartoon fish). During the compatible version of the task, participants were required to make a left-hand thumb press on a response pad (Neuroscan STIM system; Compumedics, Charlotte, North Carolina) when the target stimulus pointed left and a right-hand thumb press when the target stimulus pointed right. During the incompatible condition, participants were required to manually respond in the opposite direction of the target fish (i.e. Left thumb press to a right pointing target). The manipulation of stimulus–response compatibility alters both the inhibitory and flexibility requirements for successful task performance, allowing for the investigation of cognitive control processes across multiple levels of conflict (Friedman et al., 2009). Five yellow fish stimuli, measuring 3 cm tall and separated by 1 cm were presented focally for 200 ms on a blue–green background. A fixed inter-stimulus interval of 1700 ms was used, and both the number of trials within each condition and the frequency of target direction were equiprobable, with randomly presented trials within each task block. Participants were administered two blocks of 75 trials for each compatibility condition and given a brief break and encouragement between each block. For all analyses, individual trials with RT's outside the 200–1650 ms post-stimulus

**Table 1**
Mean (SD) demographic information for all participants and categorized by sex.

| Variable | All participants | Females | Males |
|---|---|---|---|
| Sample size ($n$) | 93 | 39 | 54 |
| Age (years) | 8.8 (0.6) | 8.9 (0.6) | 8.7 (0.6) |
| Tanner scales | 1.6 (0.5) | 1.6 (0.5) | 1.6 (0.5) |
| K-BIT (IQ) | 109.7 (11.5) | 109.8 (12.0) | 109.6 (11.3) |
| ADHD | 7.7 (5.6) | 5.3 (3.9) | 9.3 (6.1) |
| SES | 2.0 (0.9) | 2.1 (0.9) | 2.0 (0.9) |
| $VO_{2max}$ (ml/kg/min) | 38.2 (7.3) | 35.0 (6.7) | 40.5 (6.9) |
| $VO_{2max}$ percentile | 20.0 (21.6) | 19.4 (23.9) | 20.4 (20.0) |

*Note*: Tanner scales refer to pubertal timing; K-BIT is a composite score for IQ. ADHD was assessed with the ADHD Rating Scale IV. SES = socioeconomic status. $VO_{2max}$ = maximum oxygen consumption. Normative values for $VO_{2max}$ may be found in Shvartz and Reibold (1990).

onset window were excluded from analyses (Dikman & Allen, 2000; Gooties, Bruggeling, Magnee, & Van Strien, 2007; Pailing & Segalowitz, 2004; Soto, Montoro, & Humphreys, 2009; Wu et al., 2011).

## 2.4. Laboratory procedure

### 2.4.1. Day 1

Participants and their guardians completed an informed assent and informed consent, respectively. Next, participants completed the Edinburgh Handedness Inventory followed the K-BIT, which was administered by a trained experimenter. Concurrently, participants' legal guardians completed the health history and demographics questionnaire, the ADHD Rating Scale IV, the modified Tanner Staging System, and the Physical Activity Readiness Questionnaire. After completing all questionnaires, participant information was screened to prevent any participants who did not qualify from unnecessarily completing subsequent testing. All participants included in the current study met inclusion criteria set by the behavioral and demographic assessments. Participants who qualified then had their height and weight measured and completed the cardiorespiratory fitness assessment. Upon completion of the fitness assessment, participants were given a cool down period and remained in the laboratory until their HR returned to within 10 bpm of their resting HR.

### 2.4.2. Day 2

Participants returned to the laboratory and were outfitted with an EEG cap and seated in a sound attenuated testing chamber. After being provided instructions for the flanker task, participants were given the opportunity to ask questions. Participants then performed a practice block of 40 trials prior to each compatibility condition. The experimenter observed participants during the practice trials and checked their performance to ensure that they understood the task. If a participant's task performance was below 60%, another practice block was administered. All participants performed adequately following the second set of practice trials. Upon the completion of the task, participants were briefed on the purpose of the experiment, and paid $10/h for their participation.

## 2.5. Electroencephalogram (EEG) recording

Electroencephalographic (EEG) activity was measured from 64 Ag/AgCl electrodes arranged according to the International 10–10 system (Chatrian, Lettich, & Nelson, 1985). Ongoing EEG activity was referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode. Impedances were kept below 10 kΩ. To monitor artifacts caused by eye movements, vertical electrooculogram (EOG) was recorded using additional electrodes placed above and below the left orbit; horizontal EOG was recorded from the outer left and right canthi. 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 (Neuro, Inc., Charlotte, NC).

## 2.6. Data reduction

### 2.6.1. Task performance

Behavioral data were collected in terms of RT (i.e., time in milliseconds from stimulus presentation until participant response) for correct trials, and response accuracy (i.e., percentage of correct responses) for each task (i.e., congruent and incongruent) and response compatibility (i.e., compatible and incompatible) condition. For standard analyses, the primary variables of interest were mean RT and SD of RT, measured as the intra-individual standard deviation (Stuss, Murphy, Binns, & Alexander, 2003). However, given the

**Table 2**
Number of correct trials by congruency and response compatibility for the flanker task.

| Number of trials | Response compatible condition | | Response incompatible condition | |
|---|---|---|---|---|
| | Congruent | Incongruent | Congruent | Incongruent |
| Mean | 58.4 | 53.8 | 53.9 | 51.9 |
| Standard deviation | 9.7 | 10.0 | 11.6 | 12.3 |
| Maximum | 74 | 71 | 73 | 72 |
| Minimum | 41 | 38 | 37 | 35 |

non-normal, positively skewed distribution of participant RTs, ex-Gaussian analyses were performed using MATLAB software developed by Lacouture and Cousineau (2008), which utilized a maximum likelihood algorithm to fit normal and exponential components to the RT distribution. The mean number of correct trials used for fitting each condition was 54.5 ± 10.9 (see Table 2 for a summary of compatibility and congruency condition). One set of parameters ($\mu$, $\sigma$, and $\tau$) were obtained for each condition and each participant.

### 2.6.2. ERPs

Prior to averaging, an off-line EOG reduction procedure was applied to individual trials via a spatial filter (Compumedics Neuroscan, 2003), which performed a principle component analysis (PCA) to determine the major components that characterize the EOG artifact between all channels. This procedure then reconstructed all of the original channels without the artifact components. Data were filtered with a 1 Hz high-pass and a 30-Hz low-pass cutoff (24 dB/octave rolloff). Stimulus-locked components of ERPs included the creation of epochs from −100 to 1000 ms around stimuli and baseline correction using the 100-ms pre-stimulus period.

The P3 component and EEG artifacts were identified using a P3-screening procedure in which the midpoint of a 2 Hz half-sign wave template was shifted across a 400–700 ms window of individual trial epochs to identify when a P3 was absent (Ford, White, Lim, & Pfefferbaum, 1994) or if an amplitude excursion of ±75 µV occurred. Screening was carried out at the parietal electrode site (Pz). If the correlation was larger than .33, the trial was accepted, otherwise the trial was rejected (mean number of trials rejected due to screening = 21.5). Artifact-free data that were accompanied by correct responses were retained for single trial analysis and averaging. The P3 component in single trials was defined as the largest positive-going component peak within a 400–700-ms window. Amplitude was measured as a change score from the pre-stimulus baseline and peak latency was defined as the time point of the maximum amplitude. The mean number of trials included in the stimulus-locked waveforms was 54.5 ± 10.9. Similar to analyses in behavioral data, primary variables of interest were the mean of P3 amplitude and latency measured from single trials, and the SD of P3 amplitude and latency measured from single trials. Ex-Gaussian analyses were not pursued for neuroelectric data due to the normal distribution of P3 component values.

## 2.7. Statistical analysis

### 2.7.1. IIV of task performance and IIV of the P3 component

Pearson product–moment correlations were conducted on intra-individual SD of RT and intra-individual SD of P3 amplitude and latency for congruent and incongruent trials within compatible and incompatible conditions.

### 2.7.2. Task condition and IIV

Behavioral IIV data were characterized by computing Gaussian (SD) and ex-Gaussian parameters (mu, sigma, tau) for RT. SD of P3 component amplitude and latency were computed to assess P3 variability. Outcome measures for task performance (RT, accuracy) including (1) mean; (2) intra-individual SD (3) mu; (4) sigma; and (5) tau, as well as P3 component values (mean amplitude, mean latency, SD of amplitude, SD of latency) were submitted to separate 2 (congruency: congruent, incongruent) × 2 (compatibility: compatible, incompatible) repeated measures MANOVAs. Post hoc comparisons were conducted using Bonferroni corrected $t$ tests. The family-wise alpha level for all tests was set at $p = .05$ prior to Bonferroni corrections. Cohen's $d$ is reported to indicate effect size.

### 2.7.3. Aerobic fitness and intra-individual variability

Initial Pearson product–moment correlations were conducted on scores for dependent variables from the flanker task (P3 amplitude, P3 latency, response accuracy and RT scores for congruent and incongruent trials within compatible and incompatible conditions), fitness testing ($VO_{2max}$ percentile), and all demographic variables (e.g., age, IQ, sex). Any variable exhibiting a significant correlation with the dependent variable was included as a covariate in the first step of a multiple linear regression analyses (Themanson, Pontifex, & Hillman, 2008). Sex was included in the first step of all regression analyses due to its established relationship with fitness (ACSM, 2006), and transformed into a dummy code (0 = female, 1 = male). Next, separate multiple hierarchical linear regression analyses were conducted for each dependent measure. Sex and any demographic factors found to be significantly correlated with the dependent measure were entered in the first step, and fitness was added into the second step of the analysis. Goodness-of-fit of the models were considered in terms of the variance explained by the variables in the equation, expressed as $R^2$. The increase in variance explained by the models was tested for significance after each step to establish whether fitness accounted for a significant proportion of the variance in the dependent measure.

## 3. Results

### 3.1. Bivariate correlation analyses for IIV of task performance and IIV of P3 components

Pearson product–moment correlation analyses demonstrated a significant relationship between RT variability and P3 variability. That is, replicating previous results (Saville et al., 2011), SD of RT was positively correlated with SD of P3 latency for the incongruent–compatible ($r = .33$, $p = .001$) and incongruent–incompatible ($r = .26$, $p = .01$) conditions of the task. Further, SD of RT was positively correlated with SD of P3 amplitude for the incompatible ($r = .26$, $p < .001$), but not the compatible condition of the flanker task ($r = .13$, $p > .21$).

### 3.2. Cardiorespiratory performance

Cardiorespiratory fitness data are listed in Table 1. The mean (±SD) $VO_{2max}$ score for males was 40.5 ± 6.9 ml/kg/min, indicating that the participants were lower fit, averaging around the 19th percentile relative to age- and sex-specific normative values of $VO_{2max}$ (Shvartz & Reibold, 1990). For females, the mean (±SD) $VO_{2max}$ score was 35.0 ± 6.7 ml/kg/min, representing the 20th percentile and also indicating that the participants were lower fit relative to age- and sex-specific normative values (Shvartz & Reibold, 1990). It should be noted, that physical activity and fitness levels of children have steadily declined since the publication of these normative values (Eisenmann & Malina, 2002; Matton et al., 2006; Tomkinson & Olds, 2007), and therefore changes in lifestyle behaviors may account for the relatively low percentiles presently witnessed.

### 3.3. Task performance

#### 3.3.1. Response accuracy

Omnibus analysis revealed a Congruency effect, $F(1,92) = 77.5$, $p < .001$, $\eta^2 = .46$, with greater accuracy observed for congruent (76.3 ± 1.3%) relative to incongruent (72.1 ± 1.3%) trials across both compatibility conditions (see Fig. 1a).

#### 3.3.2. Mean and mu of RT

Omnibus analysis indicated an effect of congruency, with longer mean RT observed for incongruent (577.3 ± 10.7 ms) relative to congruent (556.4 ± 10.5 ms) trials, $F(1,92) = 65.6$, $p < .001$, $\eta^2 = .42$ (see Fig. 1b). As expected, a congruency effect was also observed for mu of RT (incongruent = 439.0 ± 10.6; congruent = 416.5 ± 9.4), $F(1,92) = 15.6$, $p < .001$, $\eta^2 = .15$ (see Fig. 1d). In addition, a compatibility effect was observed, with longer mean RT for the incompatible (593.4 ± 11.7 ms) relative to the compatible (540.2 ± 11.5 ms) condition, $F(1,92) = 30.9$, $p < .001$, $\eta^2 = .25$ (see Fig. 1b). This effect was further mirrored for mu of RT (incompatible = 452.4 ± 10.2; compatible = 403.1 ± 11.5), $F(1,92) = 22.9$, $p < .001$, $\eta^2 = .20$ (see Fig. 1d). No significant interactions were observed for either mean or mu of RT, $p$'s > .21.

#### 3.3.3. SD and sigma of RT

Omnibus analysis for SD of RT revealed a congruency effect, $F(1,92) = 18.5$, $p < .001$, $\eta^2 = .17$, with RTs for incongruent trials (181.2 ± 5.9 ms) being more variable than congruent trials (170.3 ± 5.5 ms; see Fig. 1c). A similar effect was observed for sigma of RT (incongruent = 92.7 ± 4.5; congruent = 82.8 ± 3.7), $F(1,92) = 8.3$, $p = .005$, $\eta^2 = .08$ (see Fig. 1e). Further, compatibility effects were observed, with increased SD of RT for the incompatible (182.0 ± 7.0 ms) relative to the compatible (169.5 ± 5.3 ms) condition, $F(1,92) = 5.2$, $p < .03$, $\eta^2 = .05$ (see Fig. 1c), and increased sigma of RT for the incompatible (93.7 ± 4.9) relative to the compatible (81.8 ± 4.5) condition, $F(1,92) = 4.4$, $p = .04$, $\eta^2 = .05$ (see Fig. 1e). No significant interaction was found for either SD or sigma of RT, $p$'s > .14.

#### 3.3.4. Tau of RT

No significant congruency or compatibility effects were observed for tau of RT, $F$'s$(1,92) < 1.5$, $p$'s > .25, $\eta^2 < .02$ (see Fig. 1f).

### 3.4. Stimulus-locked ERP analysis

Exploratory examination of ERP intra-individual variability was conducted using the midline parietal (Pz) site, because it exhibited the topographic maximum for the P3 component. P3 component values for IIV of amplitude and latency were derived from single-trial ERP data (see Fig. 2 for grand average waveforms). It is noted that Fig. 3 shows the grand average waveform obtained through a commonly used method (i.e., averaging waveforms) in order make waveforms observable across task conditions. However, no statistical analyses were conducted from these ensemble waveform data since the main purpose of the current study was to investigate the relation of fitness to neurocognitive variability, which requires the use of single trial data.

#### 3.4.1. Mean P3 amplitude

Omnibus analysis revealed a main effect of compatibility, $F(1,92) = 6.6$, $p = .012$, $\eta^2 = .07$, with larger P3 amplitude for the
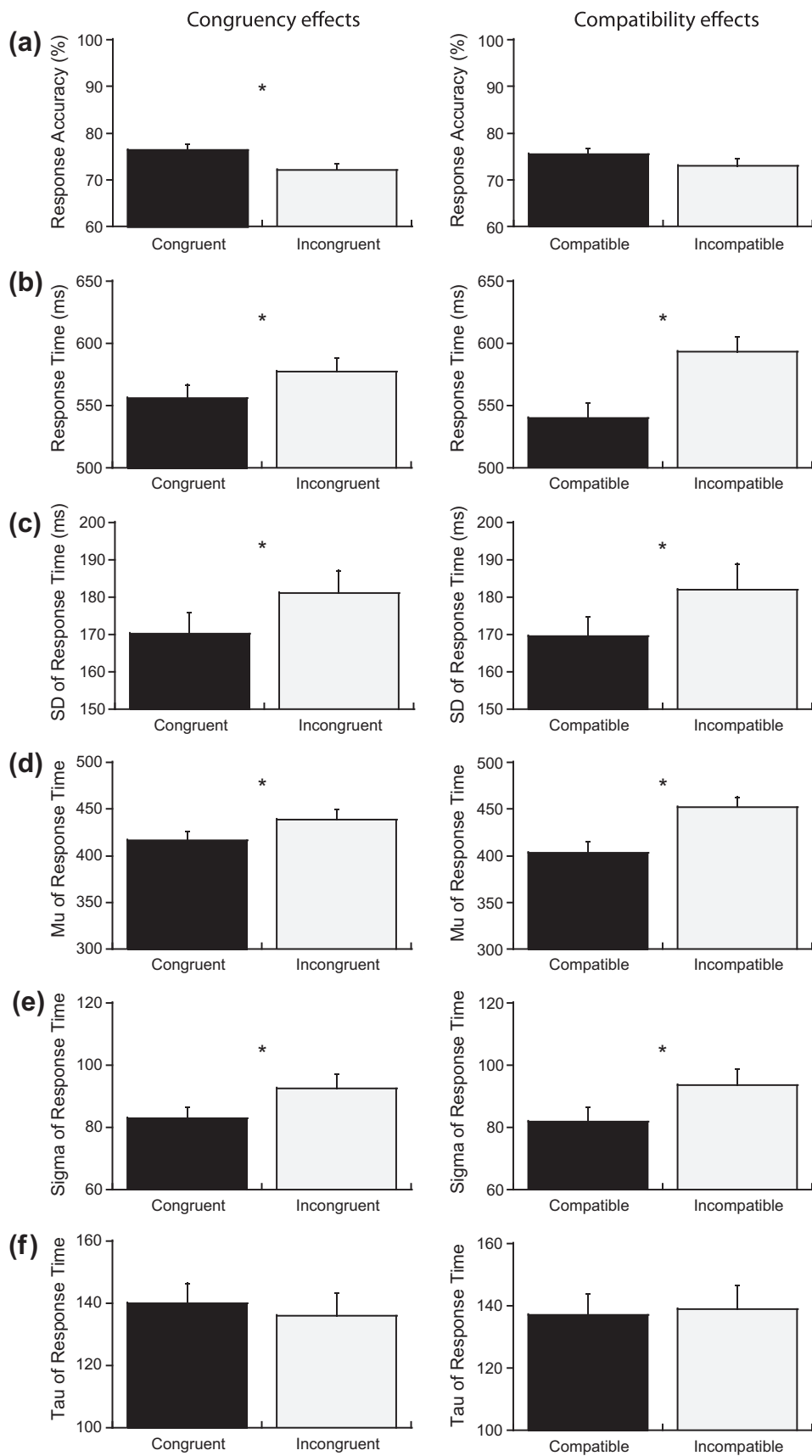
**Fig. 1.** Congruency and compatibility effects of task performance for Gaussian and ex-Gaussian variables. *p < .05.
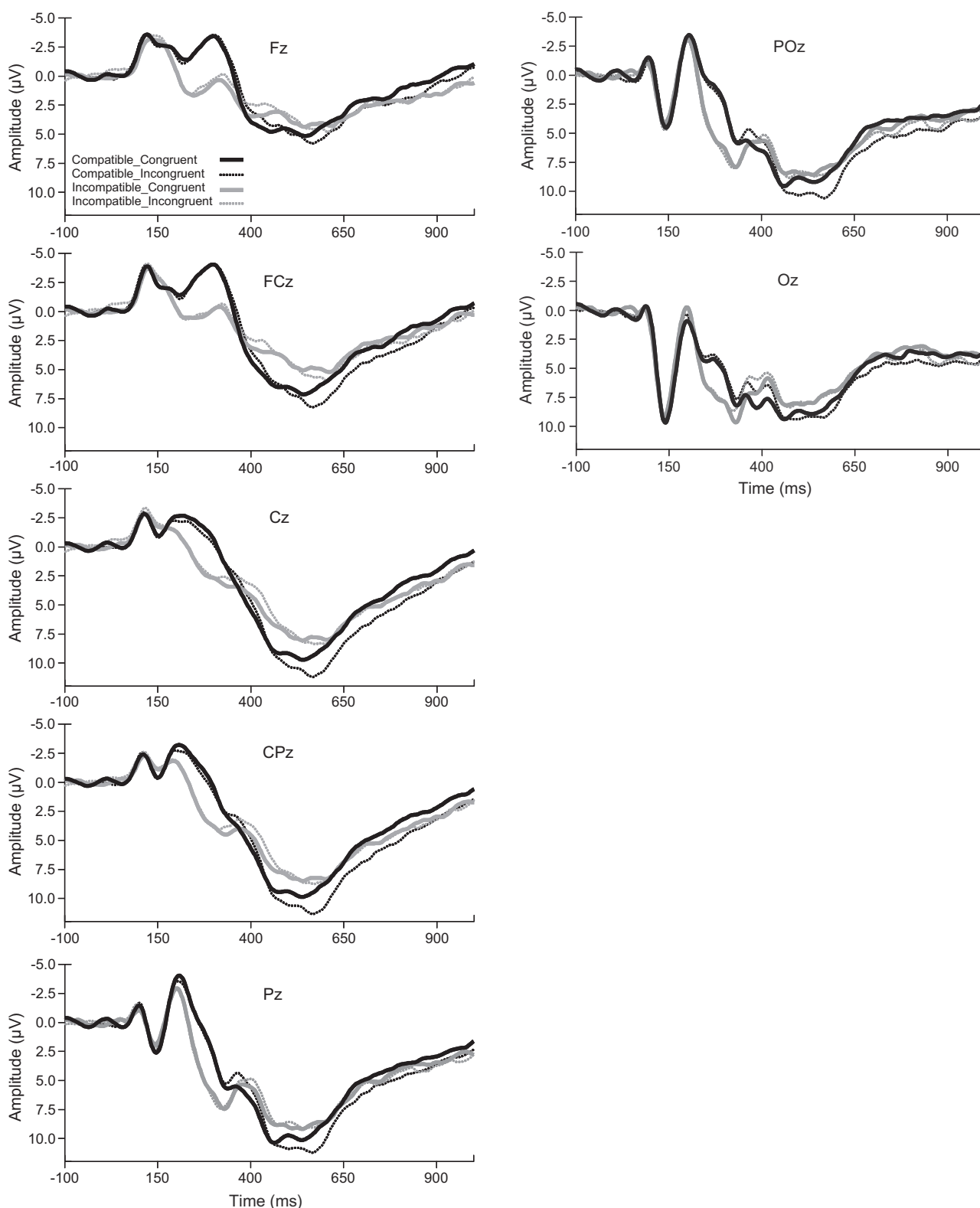
**Fig. 2.** Grand average waveforms for each of the midline electrode sites across all condition of the flanker task.

compatible (26.2 ± 0.7 µV) relative to the incompatible (25.4 ± 0.7 µV) condition (see Fig. 3a). No congruency or interaction effects were observed for mean of P3 amplitude, *p*'s > .10.

### 3.4.2. SD of P3 amplitude

Omnibus analysis for SD of P3 amplitude revealed a compatibility effect, $F(1,92) = 4.0$, $p < .05$, $\eta^2 = .04$, indicating greater SD of P3

amplitude for the incompatible (16.1 ± 0.4 µV) relative to compatible (15.4 ± 0.4 µV) condition (see Fig. 3b). No congruency or interaction effects were observed for SD of P3 amplitude, *p*'s > .47.

### 3.4.3. Mean of P3 latency

Omnibus analysis of mean of P3 latency revealed a compatibility effect, with longer P3 latency observed for the incompatible
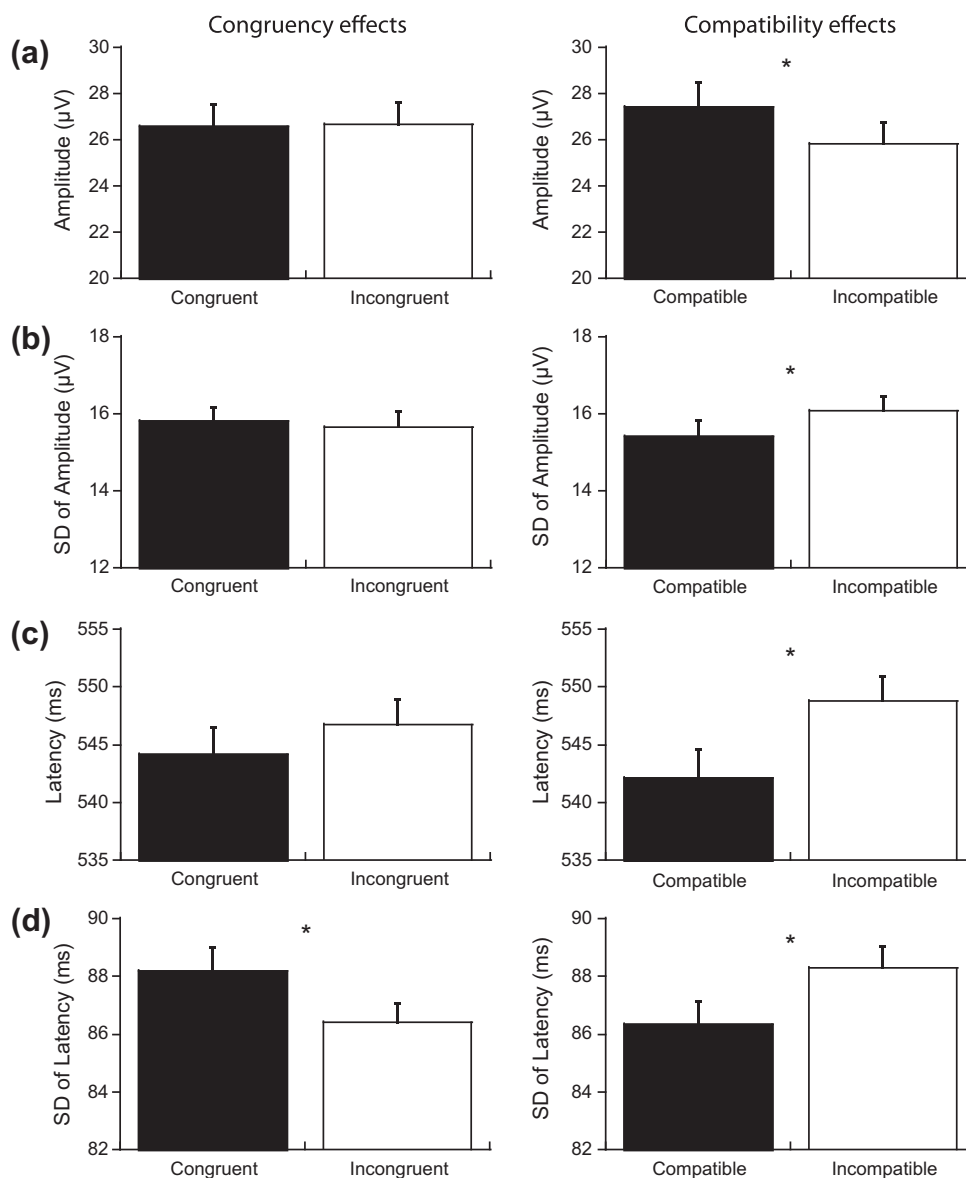
**Fig. 3.** Congruency and compatibility effects for P3 amplitude and latency. $^*p < .05$.

(548.8 ± 2.1 ms) relative to the compatible (542.1 ± 2.5 ms) condition, $F(1,92) = 9.8$, $p = .002$, $\eta^2 = .10$ (see Fig. 3c). No congruency or interaction effects were observed for mean P3 latency, $p$'s > .28.

### 3.4.4. SD of P3 latency

Omnibus analysis of SD of P3 latency revealed a congruency effect, $F(1,92) = 5.9$, $p < .02$, $\eta^2 = .06$, with greater SD of P3 latency for congruent (88.2 ± 0.8 ms) relative to incongruent (86.4 ± 0.6 ms) trials (see Fig. 3d). Further, a compatibility effect was observed, $F(1,92) = 4.4$, $p < .04$, $\eta^2 = .05$, with greater SD of P3 latency observed for the incompatible (88.3 ± 0.3 ms) relative to compatible (86.3 ± 0.8 ms) condition (see Fig. 3d). No significant interaction was observed for SD of P3 latency, $p$'s > .47.

### 3.5. Bivariate correlation analyses

Tables 3 and 4 provide correlations among fitness, demographics, and dependent measures for each compatibility condition, respectively. Results of the correlation analyses indicated that fitness was correlated with Sex. Relative to task performance, fitness

was negatively correlated with mean, SD, mu, and sigma of RT for the incompatible (see Table 4), but not the compatible, condition of the flanker task (see Table 3).

### 3.6. Multiple regression analyses

Given the purpose of this study and the number of variables included in the study design, only those findings that involve fitness are reported in the multiple hierarchical regression section. Please refer to Fig. 4 for graphical representations of the regression results.

### 3.6.1. Task performance
#### 3.6.1.1. Response accuracy.
Analysis revealed that fitness did not significantly add to the prediction of response accuracy for either the compatible, $\Delta F$'s $(1,88) \leqslant 0.5$, $p$'s $\geqslant .47$, or the incompatible, $\Delta F$'s $(1,89) \leqslant 0.8$, $p$'s $\geqslant .38$, condition, regardless of congruency.

#### 3.6.1.2. Mean and mu of RT.
Analysis revealed that fitness did not significantly add to the prediction of mean RT for the compatible

**Table 3**
Intercorrelations between variables for all participants during the compatible flanker condition.

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | VO$_{2max}$ | – | | | | | | | | | | | | | | | | | |
| 2. | Sex | .37** | – | | | | | | | | | | | | | | | | |
| 3. | Age | .03 | −.15 | – | | | | | | | | | | | | | | | |
| 4. | Tanner | −.14 | −.04 | .17 | – | | | | | | | | | | | | | | |
| 5. | K-BIT | .07 | −.06 | .09 | −.14 | – | | | | | | | | | | | | | |
| 6. | SES | .11 | −.03 | .11 | −.05 | .49** | – | | | | | | | | | | | | |
| 7. | mAcc.Con | −.06 | −.20 | .21* | −.17 | .25* | .15 | – | | | | | | | | | | | |
| 8. | mAcc.Inc | .004 | −.24* | .22* | −.13 | .24* | .17 | .87** | – | | | | | | | | | | |
| 9. | mRT.Con | −.13 | −.24* | −.24* | .02 | .07 | −.05 | .16 | .30** | – | | | | | | | | | |
| 10. | mRT.Inc | −.13 | −.26* | −.22* | −.001 | .07 | −.05 | .24* | .36** | .96** | – | | | | | | | | |
| 11. | SD.Con | −.19 | −.09 | −.30** | .07 | −.10 | −.15 | −.33** | −.23* | .58** | .52** | – | | | | | | | |
| 12. | SD.Inc | −.14 | −.15 | −.18 | −.05 | −.15 | −.09 | −.24* | −.13 | .57** | .60** | .80** | – | | | | | | |
| 13. | Mu.Con | .01 | −.18 | −.11 | −.08 | .15 | .01 | .32* | .42** | .83** | .81** | .10 | .18 | – | | | | | |
| 14. | Mu.Inc | −.05 | −.17 | −.13 | .01 | .18 | −.03 | .43* | .46** | .74** | .76** | .12 | .02 | .83** | – | | | | |
| 15. | Sigma.Con | −.07 | −.05 | −.03 | −.13 | .08 | .03 | .13 | .14 | .58** | .56** | .15 | .23* | .78** | .60** | – | | | |
| 16. | Sigma.Inc | −.08 | −.11 | −.03 | .04 | .12 | −.03 | .32** | .33** | .61** | .58** | .26* | .15 | .60** | .83** | .58** | – | | |
| 17. | Tau.Con | −.23* | −.10 | −.22* | .18 | −.13 | −.10 | −.29** | −.21* | .28** | .25* | .80** | .66** | −.31** | −.16 | −.35** | −.01 | – | |
| 18. | Tau.Inc | −.11 | −.11 | −.11 | −.02 | −.18 | −.02 | −.30** | −.18 | .23* | .27** | .53** | .79** | −.11 | −.43** | −.11 | −.41** | .58** | – |

*Note*: VO$_{2max}$ = maximum oxygen consumption. Tanner refers to pubertal timing; K-BIT is a composite score for IQ. SES = socioeconomic status. mAcc = mean performance accuracy; mRT = mean response time; Con = congruent trials; Inc = incongruent trials.
* $p < .05$.
** $p < .01$.

**Table 4**
Intercorrelations between variables for all participants during the incompatible flanker condition.

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | VO$_{2max}$ | – | | | | | | | | | | | | | | | | | |
| 2. | Sex | .37** | – | | | | | | | | | | | | | | | | |
| 3. | Age | .03 | −.15 | – | | | | | | | | | | | | | | | |
| 4. | Tanner | −.14 | −.04 | .17 | – | | | | | | | | | | | | | | |
| 5. | K-BIT | .07 | −.01 | .09 | .14 | – | | | | | | | | | | | | | |
| 6. | SES | .11 | −.03 | .11 | −.05 | .49** | – | | | | | | | | | | | | |
| 7. | mAcc.Con | .07 | −.07 | .09 | −.04 | .28** | .14 | – | | | | | | | | | | | |
| 8. | mAcc.Inc | .05 | −.08 | .12 | −.04 | .33** | .06 | .91** | – | | | | | | | | | | |
| 9. | mRT.Con | −.33** | −.23* | −.25* | .02 | −.15 | −.20 | −.12 | −.002 | – | | | | | | | | | |
| 10. | mRT.Inc | −.34** | −.19 | −.23* | .02 | −.13 | −.21* | −.17 | −.05 | .94** | – | | | | | | | | |
| 11. | SD.Con | −.33** | −.15 | −.15 | .10 | −.30** | −.27** | −.45** | −.45** | .71** | .65** | – | | | | | | | |
| 12. | SD.Inc | −.26* | −.10 | −.19 | .17 | −.39** | −.28** | −.62** | −.54** | .55** | .60** | .80** | – | | | | | | |
| 13. | Mu.Con | −.22* | −.19 | −.19 | .20 | −.03 | −.08 | .26* | .36** | .74** | .72** | .11 | .11 | – | | | | | |
| 14. | Mu.Inc | −.17 | −.09 | −.18 | −.06 | .09 | −.04 | .18 | .22* | .64** | .68** | .20 | −.03 | .71** | – | | | | |
| 15. | Sigma.Con | −.31** | −.11 | −.14 | .01 | −.29* | −.18 | −.17 | −.08 | .59** | .61** | .37** | .44** | .69** | .44** | – | | | |
| 16. | Sigma.Inc | −.21* | −.08 | −.11 | −.07 | −.14 | −.16 | −.21* | −.12 | .52** | .54** | .45** | .32** | .42** | .69** | .62** | – | | |
| 17. | Tau.Con | −.21* | −.09 | −.11 | .11 | −.18 | −.19 | −.50** | −.46** | .51** | .44** | .88** | .67** | −.20 | .03 | −.03 | .22* | – | |
| 18. | Tau.Inc | −.20 | −.14 | −.11 | .25* | −.33** | −.24* | −.47** | −.37** | .35** | .40** | .53** | .78** | −.15 | −.36** | .24* | −.15 | .45** | – |

*Note*: VO$_{2max}$ = maximum oxygen consumption. Tanner refers to pubertal timing; K-BIT is a composite score for IQ. SES = socioeconomic status. mAcc = mean performance accuracy; mRT = mean response time; Con = congruent trials; Inc = incongruent trials.
* $p < .05$.
** $p < .01$.

condition across congruent and incongruent trials, $\Delta F$'s$(1, 89) < 0.1$, $p$'s $> .88$. However, analysis of RT for congruent trials during the incompatible condition indicated that older participants and those with higher fitness had shorter mean RT (see Table 5). Analysis of incongruent trials during the incompatible condition also indicated that older participants and higher-fit participants displayed shorter mean RT (see Table 5). Analyses of mu of RT revealed that fitness did not significantly add to the prediction of mu of RT during either the compatible or incompatible condition, $p$'s $> .14$.

*3.6.1.3. SD and sigma of RT.* Analysis revealed that fitness did not significantly add to the prediction of either SD or sigma of RT across congruent and incongruent trials during the compatible condition of the task, $p$'s $> .18$. However, analysis of SD of RT for congruent trials during the incompatible condition indicated that smaller SD of RT was associated with higher fitness (see Table 5). Analysis of incongruent trials revealed a similar effect in that smaller SD of RT was associated with higher IQ and fitness (see Table 5). Further, sigma of RT revealed a similar pattern of results to those

previously described for SD of RT, with a significant effect observed for congruent trials during the incompatible condition, and smaller sigma of RT being associated with higher IQ and fitness (see Table 5)[1]. No effect was observed for incongruent trials during the incompatible condition, $p > .13$.

*3.6.1.4. Tau of RT.* Analysis revealed that fitness did not significantly add to the prediction of tau of RT across all conditions, $\Delta F$'s$(1, 89) < 3.6$, $p$'s $> .07$.

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[1] Given the significant relation between RT latency and variability during the incompatible condition of the task, we conducted additional, exploratory analyses to ensure that the fitness-moderated differences in variability were not due to fitness-moderated differences in response speed. We accomplished this by entering *mu* as the first step in the regression analysis. *Mu* significantly added to the model predicting *sigma* for all conditions except for the incompatible–congruent condition, but did not influence fitness, which significantly predicted *sigma* across all conditions. Thus, the results demonstrate that even after adjusting for *mu*, fitness was still significantly predictive of variability, and therefore cannot be attributed to fitness-related differences in response speed.
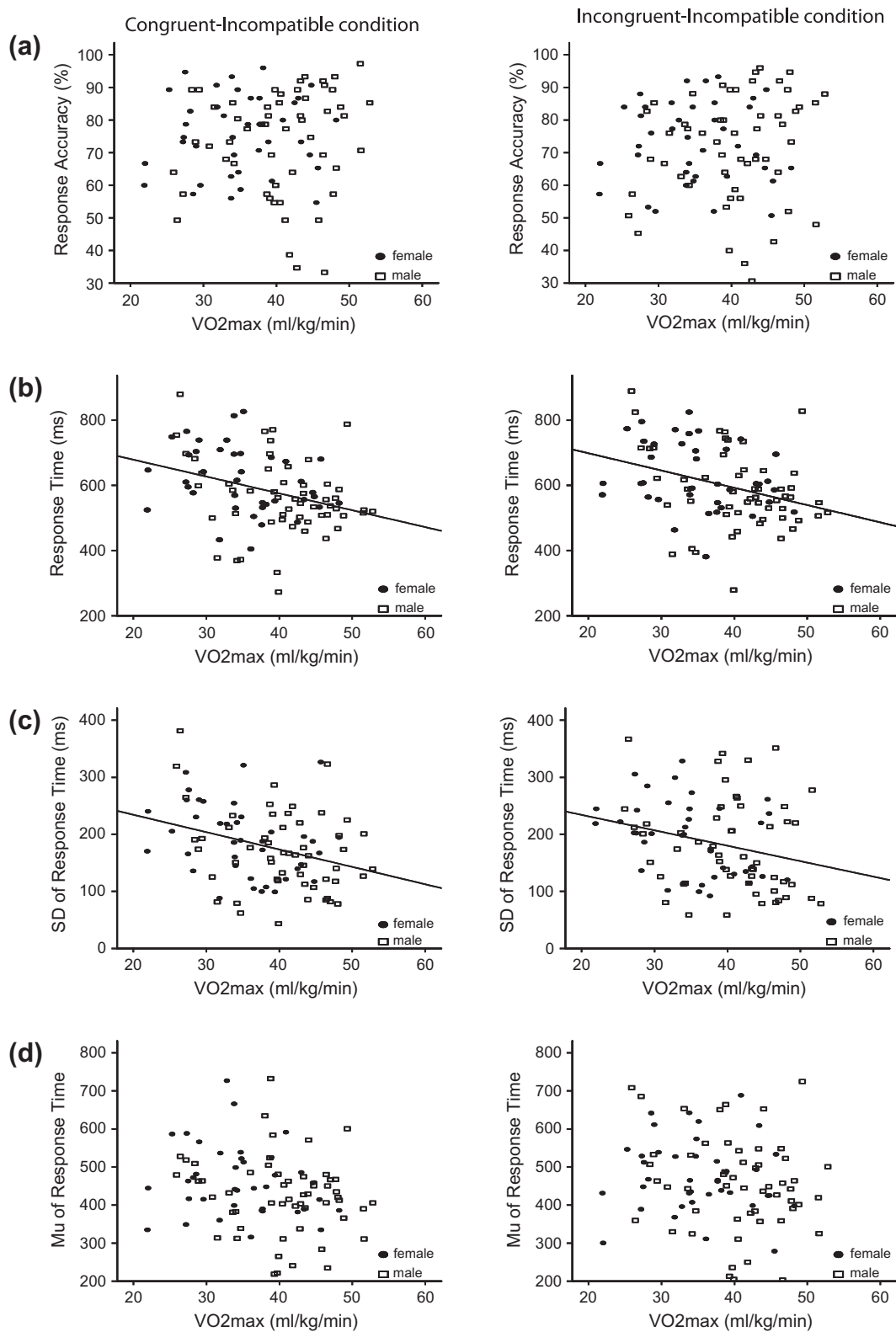
**Fig. 4.** Scatter plots depicting the relation between fitness with Gaussian and ex-Gaussian variables for the incompatible condition of the flanker task.

*3.6.2. Stimulus-locked ERP analysis*
*3.6.2.1. Mean and SD of P3 components.* *3.6.2.1.1. P3 amplitude.* Analysis revealed that fitness did not significantly add to the prediction of the mean of P3 amplitude, $p$'s > .30. Further, fitness did not significantly add to the prediction of SD of P3 amplitude across all conditions, $p$'s > .23.

*3.6.2.1.2. P3 latency.* Analysis revealed that fitness did not significantly add to the prediction of the mean of P3 latency for congruent or incongruent trials during the compatible condition, $p$'s > .07. However, analysis of mean of P3 latency for congruent trials during the incompatible condition revealed a significant effect (see Table 5), indicating that longer mean P3 latency was associated
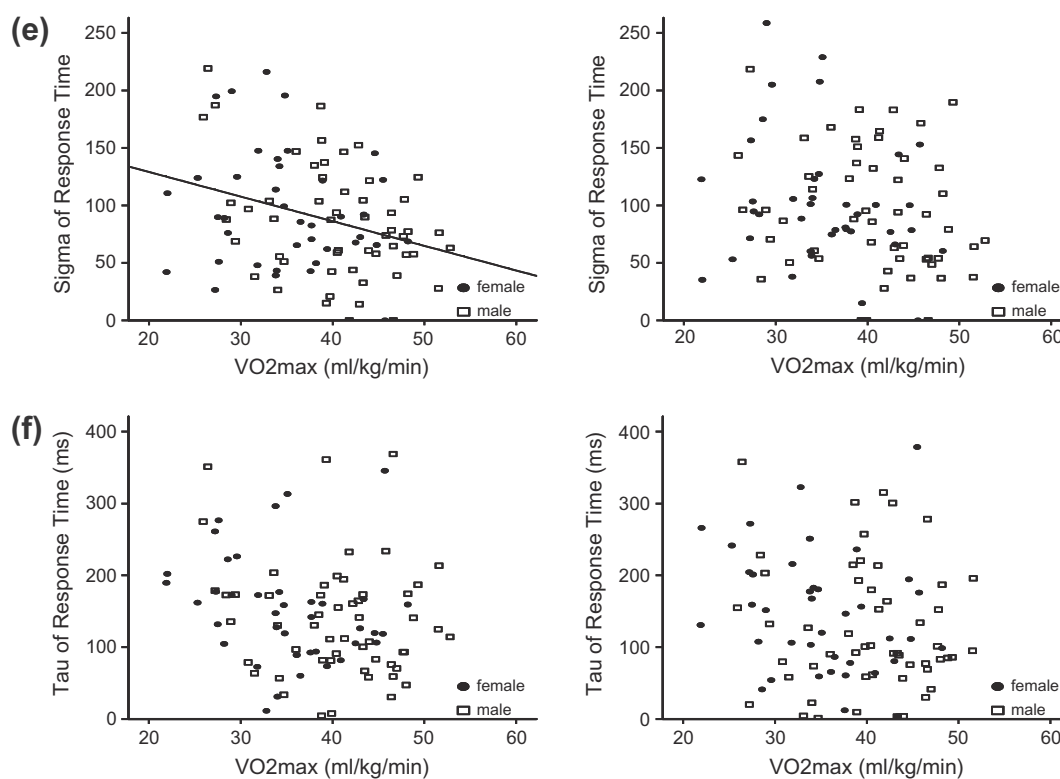
Fig. 4. (continued)

with higher fitness. No fitness effect was observed for incongruent trials during the incompatible condition, $\Delta F(1, 89) < 1.7$, $p > .20$ (see Table 5). Furthermore, fitness did not significantly add to the prediction of SD of P3 latency across task conditions, $p$'s > .22.

## 4. Discussion

The current study examined behavioral and neuroelectric IIV in preadolescent children with varying levels of fitness during a modified flanker task. More generally, the current study sought to evaluate behavioral and neuroelectric variability across conditions requiring varying levels of cognitive control. Across participants, congruent, relative to incongruent conditions, were associated with greater response accuracy and less IIV of RT. Furthermore, shorter RT, and less IIV of RT, P3 amplitude, and P3 latency, were observed for the compatible, relative to the incompatible condition of the task. With regard to fitness, the current findings revealed that higher fitness was associated with shorter and less variable RT only for the incompatible condition. Lastly, no fitness-related differences were observed in terms of IIV of P3 amplitude or latency.

### 4.1. Task performance

Replicating previous research (Hillman et al., 2009; Mezzacappa, 2004; Ridderinkhof & van der Molen, 1995), preadolescent children, regardless of fitness level, and irrespective of response-compatibility, exhibited greater response accuracy and shorter mean RT for congruent relative to incongruent trials, suggesting that conditions requiring greater amounts of interference control are associated with decrements in task performance. Beyond mean levels of performance, the current variability findings (SD and sigma of RT) are in accord with previous studies (Li & Lindenberger, 1999; Shammi et al., 1998; West et al., 2002), which observed

greater RT variability during conditions requiring the up-regulation of cognitive control. In addition, shorter RT was observed during the compatible, relative to the incompatible condition, furthering previous results (Friedman et al., 2009; Nessler, Friedman, Johnson, & Bersick, 2007; Ridderinkhof et al., 1997) and suggesting that the stimulus–response manipulation engendered greater cognitive control requirements. Novel to the current investigation was the measurement of variability during the stimulus–response manipulation. Findings revealed greater IIV (SD and sigma of RT) during the incompatible relative to the compatible condition of the task, demonstrating the utility of IIV analysis for further differentiating performance during the stimulus–response manipulation. Inconsistent responding during the incompatible condition may reflect what Botvinick et al. (2001) termed 'response override', which necessitates greater inhibition of the incorrect, but prepotent, response tendency (Friedman et al., 2009).

Interestingly, there were no differences in terms of congruency or compatibility manipulations for tau of RT for ex-Gaussian analysis. However, greater mu and sigma parameters values were observed for both the incongruent and incompatible, relative to the congruent and compatible conditions, respectively. Thus, the increased dispersions resulted from a positive shift of the distribution's leading edge, rather than an increase in the degree of positive skew in the tail of the distribution, suggesting a pervasive increase in variability for conditions requiring greater cognitive control. Previous studies using ex-Gaussian analysis to evaluate cognitive control and conflict resolution (e.g., Botvinick et al., 2001) have revealed a characteristic and replicable pattern (Heathcote et al., 1991; Spieler et al., 1996, 2000) in which the mu and sigma parameters reveal a pronounced congruency effect, but the tau parameter does not. Spieler et al. (2000) concluded that with the exception of the classic Stroop task, the exponential component (tau parameter) is not affected by experimental conditions of cognitive control tasks. The current study, which utilized a variant of the flanker task, supports the findings of Spieler et al.

**Table 5**
Summary of regression analysis for variables predicting mean RT, SD RT, sigma RT and mean P3 latency during the incompatible flanker task.

| | $B$ | SE $B$ | $\beta$ | $R^2$ | $R^2$ change | $F$ change |
|---|---|---|---|---|---|---|
| *Con mRT* | | | | | | |
| Step 1 | | | | .13 | .13 | 6.89** |
| Sex | −62.72 | 22.74 | −0.27** | | | |
| Age | −54.23 | 18.85 | −0.29** | | | |
| Step 2 | | | | .19 | .06 | 6.25* |
| Sex | −39.95 | 23.91 | −0.18 | | | |
| Age | −49.70 | 18.41 | −0.26** | | | |
| VO$_{2max}$ | −4.02 | 1.61 | −0.26* | | | |
| *Inc mRT* | | | | | | |
| Step 1 | | | | .14 | .14 | 4.99** |
| Sex | −54.48 | 23.00 | −0.24* | | | |
| Age | −47.81 | 19.17 | −0.25* | | | |
| SES | −23.92 | 12.32 | −0.19 | | | |
| Step 2 | | | | .20 | .06 | 6.27* |
| Sex | −31.16 | 24.21 | −0.13 | | | |
| Age | −43.80 | 18.69 | −0.23* | | | |
| SES | −20.16 | 12.07 | −0.16 | | | |
| VO$_{2max}$ | −4.10 | 1.64 | −0.26* | | | |
| *Con SD RT* | | | | | | |
| Step 1 | | | | .13 | .13 | 4.61** |
| Sex | −21.36 | 13.54 | −.16 | | | |
| SES | −12.85 | 8.35 | −.17 | | | |
| K-BIT | −1.26 | 0.67 | −.21 | | | |
| Step 2 | | | | .20 | .07 | 7.14** |
| Sex | −7.12 | 14.14 | −.05 | | | |
| SES | −10.39 | 8.13 | −.14 | | | |
| K-BIT | −1.25 | 0.64 | −.21 | | | |
| VO$_{2max}$ | −2.59 | 0.97 | −.27* | | | |
| *Inc SD RT* | | | | | | |
| Step 1 | | | | .17 | .17 | 6.14** |
| Sex | −15.63 | 14.59 | −.10 | | | |
| SES | −10.35 | 9.00 | −.13 | | | |
| K-BIT | −2.11 | 0.72 | −.33** | | | |
| Step 2 | | | | .21 | .04 | 4.72* |
| Sex | −3.00 | 15.43 | −.02 | | | |
| SES | −8.18 | 8.87 | −.10 | | | |
| K-BIT | −2.10 | 0.70 | −.32** | | | |
| VO$_{2max}$ | −2.30 | 1.06 | −.22* | | | |
| *Con sigma RT* | | | | | | |
| Step 1 | | | | .10 | .10 | 4.78* |
| Sex | −10.92 | 10.13 | −.11 | | | |
| K-BIT | −1.27 | 0.44 | −.29** | | | |
| Step 2 | | | | .17 | .07 | 8.00** |
| Sex | 0.15 | 10.52 | .001 | | | |
| K-BIT | −1.18 | 0.42 | −.27** | | | |
| VO$_{2max}$ | −2.03 | 0.72 | −.29** | | | |
| *Inc sigma RT* | | | | | | |
| Step 1 | | | | .01 | .01 | 0.58 |
| Sex | −8.80 | 11.59 | −.08 | | | |
| Step 2 | | | | .04 | .04 | 3.60 |
| Sex | −0.13 | 12.31 | −.001 | | | |
| VO$_{2max}$ | −1.59 | 0.84 | −.21 | | | |
| *Con P3 latency* | | | | | | |
| Step 1 | | | | .002 | .002 | 0.22 |
| Sex | −2.35 | 10.13 | −.11 | | | |
| Step 2 | | | | .05 | .04 | 4.09* |
| Sex | −6.29 | 5.26 | −.13 | | | |
| VO$_{2max}$ | 0.72 | 0.36 | .22* | | | |
| *Inc P3 latency* | | | | | | |
| Step 1 | | | | .09 | .09 | 4.42* |
| Sex | −8.80 | 11.59 | −.08 | | | |
| K-BIT | | | | | | |
| Step 2 | | | | .11 | .02 | 1.65 |
| Sex | −9.28 | 4.82 | −.21 | | | |
| K-BIT | −0.51 | 0.19 | −.27* | | | |
| VO$_{2max}$ | 0.42 | 0.33 | .14 | | | |

*Note*: VO$_{2max}$ = maximum oxygen consumption. Tanner refers to pubertal timing; K-BIT is a composite score for IQ. SES = socioeconomic status. mRT = mean response time; Con = congruent trials; Inc = incongruent trials.
* $p < .05$.
** $p < .01$.

(2000), and also suggests that modulations of mu and sigma are most reflective of congruency effects. The current study extends the findings of Spieler et al. (2000), however, by demonstrating that the response compatibility manipulation leads to a similar pattern in terms of mu and sigma as the classic congruency manipulation. Thus, future studies utilizing ex-Gaussian analysis to evaluate performance across multiple conditional manipulations may enable a finer discrimination of cognitive control processing. Specific to preadolescent cognition, the current data suggests that ex-Gaussian analysis may enable a greater understanding of the development of inhibitory control.

Furthermore, our results indicated that RT decreased as age increased, supporting the notion that children continue to increase the speed and efficiency of cognitive control processing throughout development (Mezzacappa, 2004; Ridderinkhof et al., 1997; Rueda et al., 2004). With respect to fitness, higher fitness was associated with quicker and less variable responding during the incompatible, but not the compatible, condition. Indeed, most fitness-related differences were observed in response to the manipulation of stimulus–response compatibility furthering the suggestion of Pontifex et al. (2011) that manipulating response compatibility may deepen our understanding of how fitness relates to cognitive control in developing populations. In tandem with the findings of Samson et al. (2008), who observed that sedentary older adults were more variable than active adults, the present finding of increasing SD of RT with decreasing fitness suggests that higher fitness may relate to more stable responding across the life span. Given the relationship between response variability and normal development (Tamnes et al., 2012; Williams et al., 2005), greater fitness may engender neural maturation, leading to systematic changes in brain morphology, including white matter integrity, gray matter density, and synaptic alterations resulting in reduced neural noise and greater cognitive efficiency (Gogtay et al., 2004). This maturation effect may be most pronounced for prefrontal areas as behavioral variability has been recently correlated with prefrontal brain volume (Lövdén et al., 2012). Thus, the current findings extend previous research, which suggests that higher fitness may be associated with greater integrity of cognitive control systems during development. However, further research specifically designed to evaluate the neural benefits of fitness in relation to response stability is necessary.

### 4.2. P3 amplitude

In the current study, increased variability (SD of P3 amplitude) was observed for all participants during the incompatible relative to the compatible condition. The manipulation of stimulus congruency, however, did not modulate neuroelectric variability. Thus, compatibility manipulations requiring the upregulation of cognitive control (i.e., incompatible versus compatible stimulus–response condition) appear to result in greater variability (SD) of P3 amplitude. Importantly, as P3 amplitude has been associated with the allocation of attentional resources during stimulus engagement (Polich, 2007), the current data suggest that independent of mean levels of quantification, P3 amplitude variability may provide valuable information regarding the regulation of attentional resources during cognitive operations. As such, evaluating P3 variability across a variety of tasks and task manipulations may yield a finer understanding of neurocognitive processing across the lifespan.

At first glance, the current fitness results may appear to be in opposition to those previously reported by Pontifex et al. (2011), who observed that higher-relative to lower-fit children exhibited larger P3 amplitudes during the incompatible relative to compatible condition of a flanker task. In the current investigation, fitness was not significantly related to mean P3 amplitude. However dif-

ferences in experimental design and participant sampling may account for the current discrepancy, as Pontifex et al. (2011) used a cross-sectional design that specifically compared individuals of high (mean percentile = 83.3) and low (mean percentile = 8.8) fitness, whereas the current investigation examined continuous differences across a sample, which was for the most part, was lower fit. As such, group differences were not sought in this investigation, and the current sample may have been too low fit and homogenous for a fitness effect to emerge in terms of mean P3 amplitude.

### 4.3. P3 latency

Consistent with previous research (Hillman et al., 2009; Verleger, 1997), longer mean P3 latency was observed for the incompatible relative to the compatible condition, providing additional support to previously observed delays in stimulus classification speed as a function of cognitive control demands. In addition, greater variability (SD) of P3 latency was observed for the incompatible relative to the compatible condition. While mean P3 latency has been associated with stimulus classification and evaluation speed (Verleger, 1997), only one prior investigation has utilized variability of P3 latency to examine cognition as a function of age (Fjell et al., 2009). As such, further research is necessary to better understand the relation between P3 latency variability and neurocognitive function in developing populations. With regard to fitness, relative to lower-fit children, higher-fit children exhibited longer mean P3 latency for congruent trials during the incompatible condition. This unexpected fitness effect was not observed among all other P3 component analyses. Given the number of variables and conditions analyzed and the lack of coherence of this finding with previous research; it appears likely that this single, unexpected fitness-related effect may be spurious. Further replication is necessary.

### 4.4. IQ and task performance

In addition to fitness, the current results also demonstrated an intriguing relationship between IQ and flanker performance. First, correlational analyses indicated that IQ was negatively related to SD, sigma, and tau of RT for the incompatible (see Table 5), but not the compatible condition of the flanker task (see Table 4). Second, regression analyses also revealed that irrespective of age, IQ was a good predictor of behavioral variability (see Table 5) during the incompatible condition of the task. To the best of our knowledge, no prior research has investigated the relationship between IQ and cognitive variability in preadolescent children. Thus the current results are novel in suggesting that higher-IQ children may exhibit more stable responding than lower-IQ children during tasks requiring inhibitory control. Accordingly, the current results also provide an additional means to investigate the relationship between intelligence and cognitive control in children.

### 4.5. Limitations

Several limitations of the current investigation should be noted, including the correlational design and restricted age range. Future investigations employing longitudinal designs will be better positioned to make more causal statements. Also, cross-sectional studies including participants from a wider range of fitness levels are necessary to evaluate and discriminate potential dose–response and threshold effects. Furthermore, the current study employed a fixed block design in which the compatible condition of the task always preceded the incompatible condition of the task. Such an approach presents potential confounds of both compatibility and time-on-task, which may impair the internal validity of the current results. However, the current compatibility manipulation procedure was adopted in accordance with previous research to engender a prepotent stimulus–response mapping that would later need to be over-ridden (i.e., Pontifex et al., 2011). Future research should attempt to counterbalance task conditions to avoid internal validity issues.

### 4.6. Summary

In sum, the current results speak broadly to the nature of behavioral and neuroelectric variability during development, and more specifically to the relation of fitness and neurocognitive development. The current findings suggest that higher aerobic fitness during childhood is related to decreased response variability during environmental transactions requiring increased cognitive control. Given that the fitness-related differences in IIV were observed only for behavioral measures, these fitness effects may not occur during stimulus engagement, but occur during downstream processes such as those required for response selection. Accordingly, the current dataset furthers the extant body of research by suggesting that in addition to evaluating mean levels of responding, assessing IIV can provide additional insight into the relation between fitness and neurocognitive development.

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### Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandc.2013.02.006.

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