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Aerobic Fitness and the Attentional Blink in Preadolescent Children

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Objective: Given the growing concern that children in today's industrialized and technologically advanced society are becoming more sedentary and less fit, a greater understanding of the extent to which aerobic fitness relates to brain health and cognition during development is of increasing importance. Accordingly, this study sought to use neuroelectric and behavioral measures during an attentional blink task to examine the temporal dynamics of attention as a function of children's aerobic fitness. ***Method:*** Using a cross-sectional design, response accuracy and event-related brain potentials were assessed in preadolescent children with different levels of aerobic fitness. ***Results:*** Results indicated that higher fit children exhibited greater task performance and better attentional resources distribution, as measured via the P3 component, compared to lower fit children. ***Conclusion:*** These findings indicate that aerobic fitness may benefit aspects of cognitive health that involve temporal dynamics of attentional processes during preadolescent maturation.

Keywords: P3, temporal dynamics, attention, cognitive, ERPs

Recent studies have indicated a positive effect of physical activity on weight control, bone mass, muscle strength, and the reduced risk of heart disease and certain cancers (U.S. Department of Health and Human Services, 2008). In children, physical activity has many benefits, such as improved physical fitness and reduced risk of disease (Strong et al., 2005). Unfortunately, children have become increasingly sedentary and unfit, exacerbating the prevalence of certain physical diseases (U.S. Department of Health and Human Services & Department of Education, 2000). Further, school policy is reducing opportunities for physical activity to create additional instruction on formal academic subjects (Thomas, 2004). As such, childhood physical inactivity and a sedentary lifestyle often persist across the life span (Janz, Dawson, & Mahoney, 2000), potentially resulting in ill health in later life (Andersen, Crespo, Barlett, Cheskin, & Pratt, 1998; Freedman, Khan, Dietz, Srinivasan, & Berenson, 2001; Sisson et al., 2009). Accordingly, overwhelming evidence has suggested that physical inactivity during childhood is associated with decreased health and function across the life span.

In addition to the relationship linking children's physical activity/inactivity and health, a growing body of research has emerged indicating a positive relationship between physical activity, cognition, and brain health across the life span (see Hillman, Erickson, & Kramer, 2008, for review). In older adults, it has been well-established that aerobic fitness relates to improvements in cognitive functions (Colcombe & Kramer, 2003). Relative to children, a limited metaanalytical review initially indicated that physical activity has a small, but positive effect on cognition (Sibley & Etnier, 2003). A more recent review of longitudinal studies with children indicated improved cognitive performance following participation in physical activity training (Tomporowski, Davis, Miller, & Naglieri, 2008). As such, several aspects of cognition, including cognitive control, attention, perceptual motor skills, visual–motor coordination, and academic performance have been investigated to elucidate its relation with aerobic fitness in children (Sibley & Etnier, 2003; Tomporowski et al., 2008). However, given that the study of physical activity to brain health and cognition is in its infancy, our knowledge base regarding several areas of study, including those captured by the use of neuroimaging measures, remains limited.

Specifically, the temporal dynamics of visual attention in children has not been examined as a function of fitness, and thus our knowledge of fitness effects on attention remains incomplete. The temporal dynamics of visual attention describes how attention recovers over time once it has been allocated to a stimulus or event (Raymond, Shapiro, & Arnell, 1992). In the last 2 decades, researchers have been intensely interested in the mechanisms and processes of deploying attention across time (see Dux & Marois, 2009; Martens & Wyble, 2010; Shapiro, Raymond, & Arnell, 1997, for review) through the rapid serial visual presentation (RSVP) paradigm (Raymond et al., 1992). An RSVP presents sequential stimuli and requires participants to identify two unspecified letters (the targets, referred to as T1 and T2, respectively) embedded within a stream of distractors. Of interest is the performance of participants on T2 detection, given that they have correctly identified T1 (denoted as T2|T1). As such, the attentional blink (AB) refers to the reduced accuracy of reporting either the presence or identity of T2 when it occurs 200–500 ms after T1 (the AB time window; Broadbent & Broadbent, 1987; Raymond et al., 1992; Shapiro, Raymond, & Arnell, 1994; Vogel, Luck, & Sha-

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piro, 1998), whereas T2|T1 gradually recovers when the lag increases. Generally, the AB is thought to occur because of competition between the two targets for limited attentional resources (Shapiro, Raymond, et al., 1997) and particular difficulty in consolidating T2 into a reportable working memory representation (Luck, Vogel, & Shapiro, 1996; Martens, Wolters, & Van Raamsdonk, 2002; Vogel et al., 1998). However, the precise adaptive significance behind the AB remains unclear.

Irrespective of which model best fits the mechanisms underlying the AB, a multifactorial origin of AB has been concluded. Specifically, the AB reflects the competition between targets for attentional resources, not only for working memory encoding, episodic registration, and response selection (and perhaps additional processes that have yet to be identified) but also for the enhancement of target representations and the inhibition of distractors (see Dux & Marois, 2009, for review). Recently, an individual difference approach that has been widely used is to compare specific groups of participants that demonstrate varying degrees of AB magnitude (see Martens & Wyble, 2010, for review). For instance, the AB magnitude has relevance to clinical settings, given that it helps elucidate cognitive limitations in patients (Husain & Rorden, 2003; Husain, Shapiro, Martin, & Kennard, 1997), elderly (Lahar, Issak, & McArthur, 2001; Maciokas & Crognale, 2003), and children with attention-deficit/hyperactivity disorder (ADHD; Hollingsworth, McAuliffe, & Knowlton, 2001; Li, Lin, Chang, & Hung, 2004), who show a deeper or wider AB than their healthy (or older) counterparts. That is, the AB is greater in magnitude or temporally more extended. Regarding normal populations, an attenuated AB magnitude has been shown after 3 months of intensive mental training (Slagter et al., 2007) and in people who often play or have been under training of the action video games (Green & Bavelier, 2003), suggesting that temporal dynamics of attentional processes are allocated differently as a function of lifestyle or health factors. With respect to children, previous studies have found that AB duration is progressively longer across adolescence through the study of 7-, 12-, and 15-year-old children (Garrad-Cole, Shapiro, & Thierry, 2011). Such findings are consistent with the work of Dye and Bavelier (2010), who observed 7–13-year-olds needed more time to recover attentional resources than 14–22-year-olds. Taken together, the data suggests that AB magnitude might be a useful index of the temporal resolution of visual attention to examine group differences as a function of development or aging.

With respect to the neural network involved in the AB, neuroimaging studies have evidenced an interactive network consisting of lateral–frontal (for the processing and maintenance of goals and target specifications), inferotemporal (for target identification), posterior–parietal (for target selection), and occipital (for extraction of stimulus characteristics) brain regions, suggested to be associated with the dynamics of attentional selection and processing that result in the AB (see Hommel et al., 2006; Martens & Wyble, 2010, for review). Regarding the role of the frontal cortex in the AB, it may be conceived as the maintenance of task goals requiring the provision of functional top-down support (see Hommel et al., 2006, for a review). Indeed, the activation of the lateral–frontal cortex has been associated with selection problems induced by temporally close distractors (Marois, Chun, & Gore, 2000) or competing targets (Feinstein, Stein, Gastillo, & Paulus, 2004; Marcantoni, Lepage, Beaudoin, Bourgouin, Richer, 2003; Marois, Yi, & Chun, 2004). For instance, increased activation of the anterior cingulate in the AB task was associated with success in detecting a temporally close T2 (Gross et al., 2004; Marois et al., 2000; 2004). Taken together, the frontal lobe may play an important role in AB performance based on previous neuroimaging studies.

With its excellent temporal resolution, event-related brain potentials (ERPs) may tap distinct aspects of stimulus processing (i.e., T1, T2, and distractors) in the AB paradigm. In general, beyond the assessment of task performance measures, ERPs represent an additional means of gaining insight into the underlying mechanisms involved in cognitive function. That is, ERPs provide information regarding a subset of processes that occur between stimulus engagement and response execution. For instance, the P3 (also known as P300 or P3b) represents neuronal activity associated with revision of the mental representation of the previous event within the stimulus environment (Donchin, 1981). The amplitude of P3 is thought to reflect the allocation of attentional resources when working memory is updated (Donchin & Coles, 1988), such that the P3 is sensitive to the allocation of attentional resources during stimulus engagement (Polich, 2007). P3 timing, marked by its peak latency, is considered to represent stimulus classification and evaluation speed (Duncan-Johnson, 1981; Verleger, 1997). Accordingly, the assessment of ERPs may allow for better understanding of the neural correlates of AB. On the basis of several leading models (i.e., Chun & Potter, 1995; Shapiro et al., 1994), cognitive accounts of AB have commonly held that there is a capacity-limited stage in stimulus processing and that competition between different stimuli for limited processing resources underlies the AB effect. Consistent with this idea, the distribution of limited brain resources has been linked with the T1-elicited P3 component. Previous ERP studies found that the ability to accurately identify T2 is related to the latency, amplitude, or both of the T1-elicited P3 (Martens, Munneke, Smid, & Johnson, 2006; Sergent, Baillet, & Dehaene, 2005; Shapiro, Schmitz, Martens, Hommel, & Schnitzler, 2006; Slagter et al., 2007). Specifically, smaller T1-elicited P3 amplitude has been observed in trials in which T2 was correctly identified as compared to trials in which it was incorrectly identified (Sergent et al., 2005). In addition, a T1-elicited P3 with smaller amplitude (Shapiro et al., 2006) or shorter latency (Martens et al., 2006) has been observed in people who exhibited a relatively smaller AB magnitude, suggesting a greater ability to allocate limited resource or to identify targets more rapidly, which may lead to an earlier consolidation of relevant information. Taken together, these findings indicated that T1-elicited P3 may reflect the level of competition between T1 and T2.

Thus far, there are only two studies (Martens et al., 2006; Slagter et al., 2007) using ERP methods to compare specific groups of participants. Specifically, Slagter et al. (2007) conducted a longitudinal study investigating the effects of 3 months of intensive mental training on the distribution of limited attentional resources through the AB paradigm. Results revealed that participants with 3 months of mental training exhibited an attenuated AB and reduced brain-resource allocation to T1, as reflected by decreased T1-elicited P3 amplitude (Slagter et al., 2007). Slagter et al. (2007) suggested that the ability to accurately identify T2 might depend on the efficient deployment of resources to T1 and further

concluded that mental training may facilitate increased control over the distribution of limited brain resources.

It is interesting that similar to the benefit of mental training on neural resources allocation, recent neuroelectric studies using ERPs have supported the positive relation of aerobic fitness with neurocognitive function across the life span (see Hillman et al., 2008; Kramer & Hillman, 2006; Hillman, Kamijo, & Scudder, 2011, for review). This relation has been extended to child populations (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Pontifex et al., 2011). Specifically, the P3 component has been compared in preadolescent children with different levels of fitness during cognitive tasks (i.e., oddball task, flanker task), with larger P3 amplitude (Hillman et al., 2005, 2009) and shorter P3 latency (Hillman et al., 2005) observed in higher fit children compared with their lower fit counterparts. These findings were replicated in Pontifex et al. (2011), as they observed overall larger P3 amplitude in higher fit children through a manipulation of stimulus–response compatibility (i.e., cognitive flexibility) during a flanker task. Collectively, these ERP studies using cognitive tasks requiring either the distribution of attentional resources or cognitive control suggested that aerobic fitness may promote better cognitive and brain health through the effective allocation of attentional resources, reflected in increased P3 amplitude, shorter P3 latency, or both.

Despite these seemingly disparate bodies of literature, there are some striking similarities between the aspects of cognition that are related to aerobic fitness and those that exhibit AB-related deficits. However, to date, no prior research has investigated the relationship between aerobic fitness and AB in children or adults. The main purpose of this study was to examine whether the T1-elicited P3 component, T2-elicited P3 component, and AB magnitude reflect the positive relation of aerobic fitness with cognitive processes during a temporal dynamics of attentional processes task. Given that previous studies have mainly used variations of a flanker task to demonstrate that aerobic fitness may benefit aspects of cognition subserving attentional control, as reflected by larger P3 amplitude (i.e., a neuroelectric indicator of attentional resource allocation; Hillman et al., 2005, 2009; Pontifex et al., 2011), it is expected that a fitness-related advantage in cognitive functioning may be reflected in either better resource allocation or more parsimonious temporal distribution of resources depending on task demands. That is, when the temporal constraints of an attentional task warrant efficiency or economy of resources for successful task performance, it is posited that fitness may benefit such attentional resource distribution, as reflected by a reduction in P3 amplitude.

Method

Participants and Recruitment

Demographic and fitness data for all participants are provided in Table 1. A total of 19 higher fit (10 female) and 20 lower fit (11 female) preadolescent children between the ages of 9 and 10 years from the East Central Illinois area were recruited to participate through advertisements. Participants were bifurcated into higher fit or lower fit groups on the basis of whether their VO_2 max fell above the 70th percentile or below the 30th percentile based on age-specific norms (Shvartz & Reibold, 1990). All participants and their legal guardians provided written informed assent–consent in accordance with the institutional review board of the University of Illinois at Urbana-Champaign. Prior to testing, legal guardians completed a health history and demographics questionnaire; reported that their child was free of neurological diseases, attentional disorders (as indexed by scores below 14 and 22 for girls and boys, respectively, on the ADHD Rating Scale IV; DuPaul, Power, Anastopoulos, & Reid, 1998), or physical disabilities; and indicated normal or corrected-to-normal vision based on the minimal 20/20 standard. Participants were administered the Kaufman Brief Intelligence Test (K–BIT; Kaufman & Kaufman, 1990) by a trained experimenter to obtain a composite IQ score, as well as the Eidenburgh Handedness Inventory (Oldfield, 1971) to determine hand dominance. Socioeconomic status (SES) was determined using 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 (Birnbaum et al., 2002). Given that modulations in temporal dynamics of attentional processes have previously been found following training of action video games (Green & Bavelier, 2003), screen time was assessed to monitor the potential influence of this factor. To ensure that all study participants were in the earliest stages of puberty or have not yet begun pubertal changes, any participant with a score greater than 2 on the modified Tanner Staging Scales (Taylor et al., 2001) was excluded.

Table 1
*Demographic Information for All Participants and Categorized by Fitness (*Ms ± SD*)*

Measure	Lower fit	Higher fit
n	20 (11 females)	19 (10 females)
Age (in years)	10.1 ± 0.5	10.1 ± 0.4
Tanner	1.4 ± 0.4	1.2 ± 0.4
K-BIT composite (IQ)	113.2 ± 10.9	117.7 ± 10.1
SES	2.2 ± 0.8	2.5 ± 0.5
ADHD	6.7 ± 2.9	6.7 ± 3.3
Video-game playing (weekdays)	1.2 ± 0.9	1.1 ± 0.3
Video-game playing (weekends)	1.7 ± 1.4	1.8 ± 0.6
VO_2max (ml/kg/min)	37.0 ± 4.2*	50.4 ± 3.3*
VO_2max Percentile	10.2 ± 6.6*	80.0 ± 3.2*

Note. Tanner = scores indicate that pubertal status was at or below a score of 2 (prepubescent) on the 5-point scale from the Tanner Staging System (Taylor et al., 2001). Socioeconomic scores (SES) reflect a trichotomous index based on participation in free or reduced-price lunch program at school, the highest level of education obtained by the mother and father and the number of parents who worked full-time (Birnbaum et al., 2002). Video-game playing reflects how many hours (on average) an individual spends playing during the week and the weekend. ADHD = scores on the Attention Deficit Hyperactivity Disorder Rating Scale IV. VO_2max- maximum oxygen consumption. VO_2max Percentile = scores reflect normative values, based on age and sex for VO_2max (Shvartz & Reibold, 1990).
* $p \leq .001$.

Cardiorespiratory Fitness Assessment

Maximal oxygen consumption (VO_2max) 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. A modified Balke protocol (American College of Sports Medicine, 2010) was used to

measure children's cardiorespiratory fitness. Specifically, a motor-driven treadmill was administrated at a constant speed with increases in grade increments of 2.5% every 2 min until volitional exhaustion. To measure the participant's heart rate (HR), a Polar heart rate monitor (Polar WearLink®+ 31, Polar Electro, Finland) was used throughout the test. In addition, ratings of perceived exertion (RPE) were assessed every 2 min using the children's OMNI scale (Utter, Roberson, Nieman, & Kang, 2002). Relative peak oxygen consumption was expressed in ml/kg/min and was based on maximal effort as evidenced by (a) a plateau in oxygen consumption corresponding with an increase of less than 2 ml/kg/min despite an increase in workload; (b) a peak heart rate ≥185 bpm (American College of Sports Medicine, 2010) or a HR plateau (Freedson & Goodman, 1993); (c) RER ≥1.0 (Bar-Or, 1983); or (d) ratings on the children's OMNI scale of perceived exertion ≥8 (Utter et al., 2002).

Attentional Blink Task

This study used a modified attentional blink paradigm with the same experimental settings and methodology as those used by Slagter et al. (2007). Stimuli were presented in a white font on a black background at the center of a computer screen. The AB task consisted of identifying two numbers (Targets; referred to as T1 and T2) in an RSVP stream of letters (distractors). Before each trial, a fixation cross was presented for 1,780 ms in the middle of the screen, followed by the RSVP stream consisting of 15 or 19 stimuli. The fixation cross was included to minimize possible eyeblink and movement artifacts in the EEG at the end of the RSVP stream. Each stimulus was presented for 50 ms, followed by a 34-ms interstimulus interval (ISI) used to avoid forward masking. On each trial, each letter was randomly drawn from the alphabet (except B, I, O, Q, and S). Relative to targets, one (single-target task) or two (dual-target task) of the letters were replaced with a number, randomly drawn (without replacement) from 2–9. When only one letter was replaced by a number, a second letter was replaced with a blank screen (referred as single-target trials or T2-absent trials). In T2-present trials (or dual-target trials), the temporal distance between T1 and T2 was short (336 ms, referred to as Lag 4) or long (672 ms, referred to as Lag 8). These specific lags were chosen on the basis of previous work (Slagter et al., 2007). Specifically, T2 was likely to be *blinked* (i.e., not identified) at Lag 4, whereas little or no reduction in T2 accuracy was usually observed at Lag 8. T2 and the blank screen were presented at temporal position 3–5 from the end of the stream.

Participants were instructed that there could be one or two numbers in the letter stream, and 1,000 ms after the stream ended, to report these numbers into a microphone. Participants were instructed to report T2 and to guess whether they thought that T2 had been presented but were not entirely sure of its identity. If they were absolutely sure that no T2 was presented, they answered "none" for that trial. A new trial began 200 ms after the second response. A short practice block (composed of 20 trials) preceded the task. The practice block was repeated until participants achieved 85% accuracy. Participants then performed four blocks of 102 trials each, consisting of 192 short-interval (Lag 4) dual-target trials, 72 long-interval (Lag 8) dual-target trials, 72 short-interval (Lag 4) single-target trials, and 72 long-interval (Lag 8) single-target trials, all randomized within blocks. Behavioral data were collected on T2 response accuracy (i.e., number of correct and error responses) for Lag 4 and Lag 8 across task blocks. The AB magnitude was measured on T2 accuracy given a correctly identified T1 (denoted as T2|T1). Stimulus presentation, timing, and measurement of behavioral response accuracy were controlled by Neuroscan Stim (v 2.0) software.

Neuroelectric Assessment

Participants were prepared for neuroelectric assessment in accordance with the guidelines of the Society for Psychophysiological Research (Picton et al., 2000). Electroencephalographic (EEG) activity was recorded from 64 Ag-AgCl electrode sites (FPz, Fz, FCz, Cz, CPz, Pz, POz, Oz, FP1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/2/4/6/8, PO7/5/3/4/6/8, O1/2) arranged in an extended montage based on the International 10–10 system (Chatrian, Lettich, & Nelson, 1985) using a Neuroscan Quik-cap (Compumedics, Charlotte, NC). A midpoint between Cz and CPz was used as referenced sites during recording, with AFz serving as the ground electrode and impedance less than 10 kΩ. Additional electrodes were placed above and below the left orbit and the outer left and right canthi to monitor electrooculogram (EOG) activity with bipolar recording. Continuous data were digitized at a sampling rate of 500 Hz, amplified 500 times with a DC to 70-Hz filter, and a 60-Hz notch filter using a Neuroscan Synamps2 amplifier (Neuro, Charlotte, NC).

Procedure

On arrival to the laboratory, participants and their legal guardians completed the previously described questionnaires. Participants were then briefed on the purpose of the fitness assessment, and the Children's Omni Ratings of Perceived Exertion Scale (Utter et al., 2002) was explained. Children were given an orientation to the treadmill and mouthpiece, as well as provided an opportunity to practice with each prior to the aerobic fitness test. This session lasted an hour, and participants received $10 remuneration for their participation. On the second visit to the laboratory, participants were outfitted with an electrode cap and given task instructions prior to each task condition in a sound attenuated testing chamber. Twenty practice trials were provided, and participants' performance was assessed before the initiation of testing. When all task conditions were completed, participants were briefed on the purpose of the experiment and received $10/hr for their participation.

ERP Reduction

Offline EEG processing included EOG correction with a spatial filter (Compumedics, 2003). Following EOG correction, neuroelectric processing including rereferencing to average mastoids, creation of stimulus-locked epochs (−200 to 1600 ms relative to T1 onset), baseline removal (−200 ms proceeding to T1; Slagter et al., 2007), low-pass filtering (20 Hz; 24dB/octave), and artifact rejection (epochs with signal that exceeded ± 75 μV will be rejected) were completed. Artifact-free waveforms in which both targets were correctly identified were averaged. That is, in accordance with previous studies (Martens et al., 2006; Slagter et al., 2007), our study mainly compared P3 components on no-blink

trials. Specifically, the blink trials were not averaged together with the no-blink trials, isolating the effects on the trials in which an AB actually occurred. On Lag 4 trials, T1-elicited P3 components were evaluated as the largest positive-going peak within a 350- to 650-ms latency window, whereas T2-elcited P3 components were evaluated as the largest positive-going peak within a 900- to 1,100-ms latency window (Slagter et al., 2007). On Lag 8 trials, T2-elcited P3 components were evaluated as the largest positive-going peak within a 1,200- to 1,400-ms latency window (Slagter et al., 2007). The mean number of no-blink trials at Lag 4 were 75.1 and 64.3 for higher and lower fit participants, respectively (see Table 2 for a summary of higher and lower fit participants at Lag 4 and Lag 8 condition).

Amplitude was measured as the difference between the mean prestimulus baseline and maximum peak amplitude; peak latency was defined as the time point corresponding to the maximum amplitude. Each participant's data were then output in ASCII format for statistical analyses using IBM SPSS 19.0.

Statistical Analysis

All statistical analyses were conducted using a significance level of $p = .05$. Prior to hypothesis testing, preliminary analysis was conducted to ensure that the higher fit and lower fit groups did not significantly differ on any factors known to influence cognitive function in this age group (e.g., SES, age, pubertal timing, sex, video-game playing, etc.). Task performance of dual-target trials (including T1 accuracy and the AB magnitude; T2|T1), were submitted to separate 2 (Fitness: higher fit, lower fit) × 2 (Lag: Lag 4, Lag 8) multivariate mixed-model analyses of variance (ANOVAs). T1 accuracy on single-target trials were also submitted to a 2 (Fitness: higher fit, lower fit) × 2 (Lag: Lag 4, Lag 8) multivariate mixed-model ANOVA. The P3 components (i.e., T1-elicited P3 amplitude, T1-elicited P3 latency, T2-elicited P3 amplitude, T2-elicited latency) were assessed separately using five midline electrode sites for amplitude and latency using a 2 (Fitness: higher fit, lower fit) × 2 (Lag: Lag 4, Lag 8) × 5 (Site: Fz, FCz, Cz, CPz, Pz) multivariate mixed-model ANOVA. Post hoc comparisons were conducted by using Bonferroni corrected *t* tests.

Results

Participant Characteristics

Participant demographics and fitness data for all participants are provided in Table 1. No significant differences between groups were observed for age, pubertal timing, IQ, SES, and time spent playing video games, $ts(37) \leq 1.7$, $p > .19$; with the exception of fitness level including both VO_2max scores, $t(37) = 10.9$, $p < .001$, and VO_2max percentile, $t(37) = 41.6$, $p < .001$ (see Table 1), confirming the efficacy of the participant matching procedure.

Table 2
Number of No-Blink and Blink Trials by Fitness and Lag (Ms ± SD)

	Lag 4		Lag 8	
No. of trials	Higher fit	Lower fit	Higher fit	Lower fit
No-blink trails	75.1 ± 9.6	64.3 ± 11.6	38.5 ± 7.3	36.7 ± 8.4
Blink trials	18.7 ± 7.0	22.2 ± 12.3	19.9 ± 5.8	21.2 ± 4.6

Task Performance

All participants exhibited decreased T2|T1 accuracy on Lag 4 relative to Lag 8, whereas all participants exhibited equal T1 accuracy across lags, confirming the efficacy of the AB paradigm. Table 3 provides mean (*SD*) values for behavioral measures as a function of task condition.

T1 accuracy on single-target trials. No main effects or interactions involving fitness or lag were observed for T1 accuracy, $Fs(1, 37) \leq 1.5$, $p \geq .56$, $\eta_p^2 \leq .04$.

T1 accuracy on dual-target trials. No main effects or interactions involving fitness or lag were observed for T1 accuracy, $Fs(1, 37) \leq 2.0$, $p \geq .80$, $\eta_p^2 \leq .05$.

T2 accuracy on dual-target trials. Analyses revealed a significant lag effect, $F(1, 37) = 43.1$, $p < .001$, $\eta_p^2 = .54$, with decreased T2 accuracy (T2|T1) for Lag 4 (54.7 ± 1.8%) relative to Lag 8 (65.1 ± 2.3%) trials. Further, a main effect of fitness was observed, $F(1, 37) = 9.0$, $p = .005$, $\eta_p^2 = .20$, with lower T2 accuracy (T2|T1) for lower fit (54.2 ± 2.7%) relative to higher fit (65.6 ± 2.7%) participants. These effects were superseded by a Fitness × Lag interaction, $F(1, 37) = 6.8$, $p = .013$, $\eta_p^2 = .16$. Decomposition of the Fitness × Lag interaction revealed lower T2 accuracy (T2|T1) for lower fit participants (47.0 ± 2.7%) relative to higher fit participants (62.4 ± 2.3%), only for the Lag 4 trials, $t(1, 37) = 4.3$, $p < .001$ (see Figure 1), suggesting that lower fit children exhibited a larger AB magnitude compared with higher fit children.

Event-Related Brain Potentials

Figure 2 illustrates the grand average stimulus-locked ERP waveforms at five midline electrode sites (Fz, FCz, Cz, CPz, Pz) for each fitness group and lag. In addition, Figure 3 illustrates topographic plots of P3 amplitude for each fitness group and task condition. Table 4 and Table 5 provide mean (*SD*) values for neuroelectric measures as a function of task condition. All statistical results reported herein were based on no-blink trails.

T1-elicited P3.

Amplitude. Analysis of T1-elicited P3 amplitude revealed a main effect of fitness, $F(1, 37) = 8.1$, $p = .007$, $\eta_p^2 = .18$, with increased T1-elicited P3 amplitude for lower fit (7.8 ± 0.6 μV) relative to higher fit (5.3 ± 0.6 μV) participants (see Figure 4A). A main effect of site was also observed, $F(4, 34) = 49.0$, $p < .001$, $\eta_p^2 = .85$, with smaller T1-elicited P3 amplitude at Fz relative to all other electrode sites, $ts(38) \geq 8.2$, $p \leq .001$; at FCz relative to the Cz and CPz electrode sites, $ts(38) \geq 2.4$, $p \leq .01$; and at CPz relative to the Pz electrode site, $t(38) = 0.68$, $p = .01$. No effect of lag was observed, $F(1, 37) = 0.3$, $p = .57$, nor did any variable interact, $Fs(4, 34) < 1.2$, $p > .74$.

Latency. No main effects or interactions involving fitness, lag, or site were observed for T1-elicited P3 latency, $Fs\ (1, 37) \leq 1.8$, $p \geq .08$, $\eta_p^2 \leq .11$.

T2-elicited P3.

Amplitude. Analysis of T2-elicited P3 amplitude revealed a main effect of fitness, $F(1, 37) = 5.4$, $p = .025$, $\eta_p^2 = .13$, with

Table 3
Task Performance Measures by Task Condition (Ms ± SD)

Measure	Lower fit		Higher fit	
	Lag 4	Lag 8	Lag 4	Lag 8
Response accuracy (%) for T1 on single-target trials	72.6 ± 9.6	72.0 ± 11.6	72.2 ± 13.3	74.0 ± 15.4
Response accuracy (%) for T1 on dual-target trials	74.7 ± 10.0	75.9 ± 8.6	78.5 ± 7.8	80.2 ± 10.6
Response accuracy (%) for T2|T1 on dual-target trials	47.0 ± 12.1	61.5 ± 12.9	62.4 ± 10.0	68.7 ± 15.5

increased T2-elicited P3 amplitude for lower fit (15.7 ± 1.5 μV) relative to higher fit (10.7 ± 1.5 μV) participants (see Figure 4B). A main effect of site was also observed, $F(4, 34) = 55.9$, $p < .001$, $\eta_p^2 = .87$, with smaller T2-elcited P3 amplitude at Fz relative to all other electrode sites, $ts(38) \geq 8.5$, $p \leq .001$; and at FCz relative to the Cz, CPz, and Pz electrode sites, $ts(38) \geq 7.3$, $p \leq .001$.

Latency. Analysis of T2-elicited P3 latency revealed a main effect of Lag, $F(1, 37) = 529.5$, $p < .001$, $\eta_p^2 = .94$, with increased latency for Lag 8 (1262.3 ± 9.9 ms) relative to Lag 4 trials (992.8 ± 14.4 ms). A main effect of site was also observed, $F(4, 34) = 48.6$, $p < .001$, $\eta_p^2 = .85$, with the shortest T2-elcited P3 latency at Fz relative to all other electrode sites, $ts(38) \geq 10.5$, $p \leq .001$; and at FCz relative to the Cz electrode site, $t(38) \geq 44.7$, $p < .001$. These effects were superseded by a Lag × Site interaction, $F(4, 34) = 3.4$, $p = .019$, $\eta_p^2 = .29$. Decomposition of the Lag × Site interaction revealed shorter latency at Fz relative to all other electrode sites, only for Lag 4, $t(38) \geq 9.2$, $p < .001$.

Discussion

In this study, we examined whether aerobic fitness was associated with the ability to process two temporally close and meaningful items in the environment. The key finding suggested that fitness was positively associated with temporal dynamics of attentional processes in preadolescent children, providing novel evidence that children who are aerobically fit are more likely to exhibit better behavioral and neuroelectric indices of performance in tasks requiring temporal resolution of visual attention. Specifically, children with a higher level of aerobic fitness were found to exhibit a relatively attenuated AB magnitude (i.e., greater T2|T1 accuracy) compared with lower fit children. In addition, neuroelectric findings revealed that higher fit children exhibited overall smaller P3 amplitude across task conditions relative to lower fit children. Accordingly, the results suggest that aerobic fitness might serve to facilitate increased control over the distribution of limited brain resources. Thus, these data support the relation of aerobic fitness to the temporal dynamics of visual attention and indicate that higher amounts of aerobic fitness may positively relate to cognitive and brain health and effective functioning during preadolescent maturation.

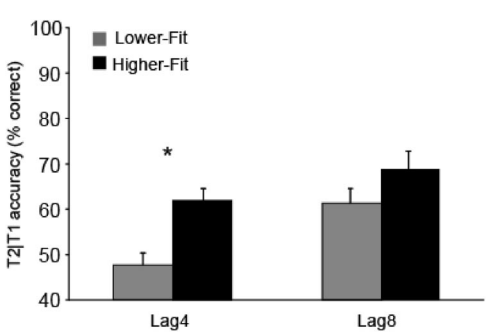

Figure 1. Mean accuracy (±*SE*) for T2|T1 on dual-target trials for each group by lag.

Task Performance

Consistent with previous investigations, all participants exhibited the A-B timing difference—an attentional blink (see Martens & Wyble, 2010, for review), which refers to reduced accuracy of reporting the identity of T2 when it occurs 200–500 ms after T1, whereas T2|T1 recovers when the lag increases (Chun & Potter, 1995; Raymond et al., 1992; Shapiro et al., 1994). Consistent with previous studies examining children (Dye & Bavelier, 2010; Garrad-Cole et al., 2011), these results indicated decreased response accuracy (T2|T1) at Lag 4 relative to Lag 8, confirming that the AB task might be a useful index of the temporal resolution of visual attention to examine cognitive development in children.

Germane to the focus of this investigation, however, was to determine the extent to which aerobic fitness may be associated with the AB performance within specific task conditions. As expected, a selective relation of fitness to behavioral indices of temporal dynamics of attentional processes was found, particularly within the AB task condition (i.e., T2|T1 accuracy at Lag 4) requiring efficient attentional resources distribution, working memory encoding, episodic registration, response selection, enhancement of target representations, and inhibition of distractors (see Dux & Marois, 2009, for review). Thus, these findings add to a growing body of research demonstrating that aerobic fitness is beneficial for cognitive development in preadolescent children (Castelli, Hillman, Buck, & Erwin, 2007; Chaddock et al., 2010a, 2010b; Hillman et al., 2008, 2009; Pontifex et al., 2011; Sibley & Etnier, 2003) and suggest that the beneficial relation of fitness may be extended to different domains of cognitive functioning (i.e., temporal dynamic of attention).

Of interest, it is important to note that previous nonfitness studies have revealed individual variability in the AB magnitude. That is, several reports have indicated that the temporal dynamics of attentional resources are differentially allocated as a function of lifestyle or health factors (Green & Bavelier, 2003; Martens et al., 2006; Slagter et al., 2007). With regard to nonfitness-induced enhancement in temporal dynamics, intensive mental training (Slagter et al., 2007) and action video-game playing (Green & Bavelier, 2003) have been found to attenuate AB magnitude. For instance, Slagter et al. (2007) conducted a longitudinal study and found that 3 months of intensive mental training resulted in a

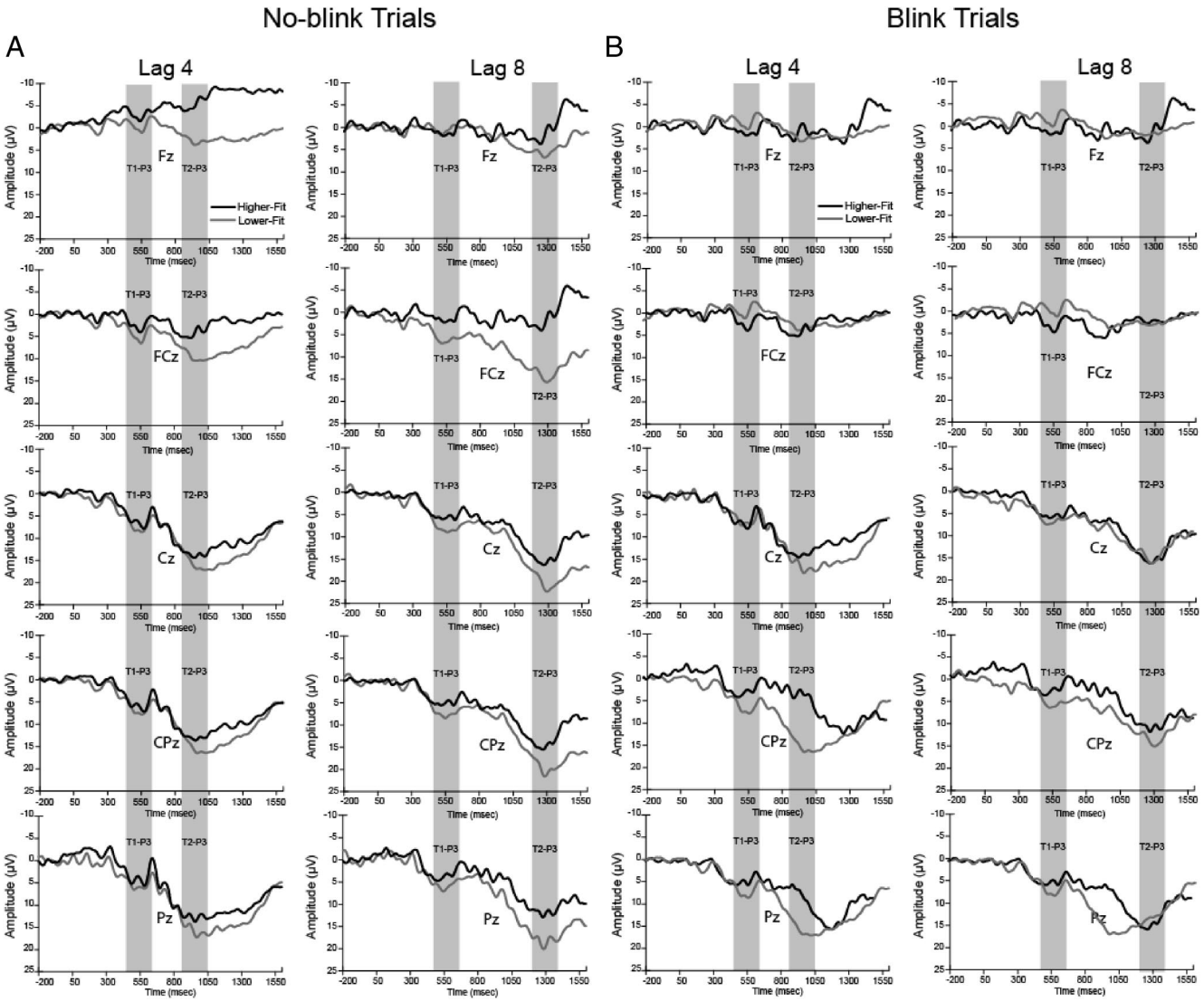

Figure 2. Stimulus-locked grand-average waveforms on each lag for higher and lower fit participants for no-blink (A) and blink (B) trials. The gray shading represents the latency windows within which T1- and T2-elicited P3 maximum peak amplitude and peak latency were identified.

smaller AB magnitude. In a related study, similar improvement was found after intensive action video-game playing (Green & Bavelier, 2003). Taken together, it is possible that the temporal dynamics of attentional processes might be "shaped" by demographic, lifestyle, or health factors, as reflected by a smaller AB magnitude. It is further known that aerobic fitness may facilitate these cognitive processes during development. As such, being aerobically fit might be a healthier alternative to improve temporal dynamics of attentional processes relative to video-game playing or mental training, given that aerobic fitness can also improve physical health (see U.S. Department of Health and Human Services, 2000, for review).

Event-Related Brain Potentials

Along with better task performance (i.e., smaller AB magnitude), this study found that higher-fit children exhibited reduced attentional resource allocation to the first target at Lag 4, as reflected by a smaller T1-elicited P3 amplitude within the AB time window. That is, higher fit children might perform better in their detection of the T2 (i.e., an attenuated AB magnitude at Lag 4) through the reduction of brain-resource allocation to T1. Given that (a) the ability to accurately identify T2 depends on the efficient deployment of resources to T1; and (b) the AB-related deficit results from suboptimal resource sharing (Martens et al., 2006; Sergent et al., 2005; Shapiro et al., 2006; Slagter et al., 2007; Vogel et al., 1998;), our results suggest that higher level of aerobic fitness might facilitate increased control over the distribution of limited brain resources.

It is noted that the fitness-related differences in P3 amplitude were observed over the midline sites, in accordance with previous fitness studies. For instance, using an oddball task, Hillman et al. (2005) examined preadolescent children and found a fitness effect

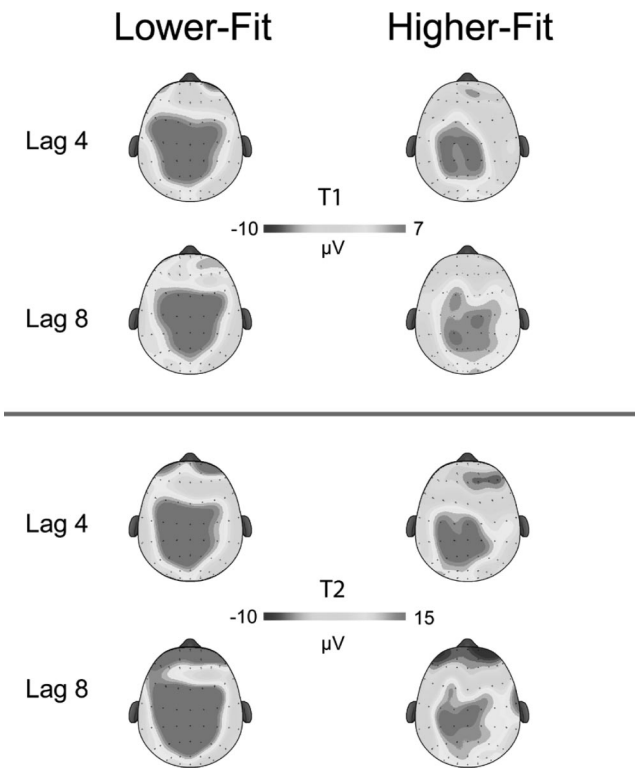

Figure 3. Topographic plots of P3 amplitude for each fitness group and task condition.

for P3 amplitude across the midline sites, suggesting that higher fit children may be able to efficiently recruit attentional resources toward the stimulus environment. Further, using a modified flanker task, a task requiring variable amounts of attentional control, Pontifex et al. (2011) also found an overall fitness-related effect for P3 amplitude. Collectively, results across studies (Hillman et al., 2005, 2011) would suggest that higher levels of cardiorespiratory fitness relate to a global change in the allocation of attentional resources in preadolescent children, with the direction of change affected by task demands.

Novel to this investigation was the assessment of fitness-induced modulations in both T1- and T2-elicited P3 components in children. Findings revealed that higher fit children exhibited reduction for both T1- and T2-elicited P3 amplitude relative to lower fit children. First, the findings reported herein do not reflect the same pattern observed by Slagter et al. (2007), who observed enhancements in AB magnitude and reduction in T1-elicited P3 amplitude (no significant reduction observed in T2-elicited P3 amplitude) following 3 months of intensive mental training. However, the disparity between the current data and those of Slagter et al. (2007) might result from a specific neural mechanism in which fitness might improve attentional resources distribution. Further, a number of methodological factors might also be responsible for the discrepancy observed within the present investigation. For instance, using a mental training intervention (i.e., meditation), Slagter et al. (2007) found that the training-induced reduction was not observed for T2-elicited P3 amplitude, suggesting that intensive mental training might selectively reduce brain-resource allocation to T1. However, the AB deficit has also been suggested to reflect the failure of distractor inhibition. For instance, Dux and Marois (2008) argued that distractor inhibition predicts individual differences in the attentional blink. With that in mind, the nonspecific effects (reflected by smaller T1- and T2-elicited P3 amplitude) reported in our study may reflect enhanced processing of the distractor stimuli rather than the T1 or T2 stimuli as a function of fitness. Accordingly, it is possible that meditation and fitness might improve temporal dynamics of attentional processes through different mechanisms within the brain. In addition, differences in the age of participants and the experimental design (i.e., cross-sectional vs. intervention) may be responsible of differential outcomes between the present study and those of Slagter et al. (2007).

Second, findings from cross-sectional studies (Hillman et al., 2009; Pontifex et al., 2011) suggest that greater preadolescent fitness may improve cognitive functioning through overall improvements (i.e., larger P3 amplitude) in the allocation of attentional resources that support goal-directed behavior. However, in contrast to the previous developmental studies (Hillman et al., 2009; Pontifex et al., 2011), which employed a flanker task and found greater fitness-related allocation of resources (as reflected by larger P3 amplitude), this study showed reduced P3 amplitude as an indicator of better attentional resource distribution as a function of the temporal constraints of the attentional task. Therefore, novel to this study, the fitness-related advantage in cognitive functioning may be reflected in either enhanced resource alloca-

Table 4
T1-Elicited P3 Components at Each Electrode Site by Task Condition (Ms ± SD)

Measure	Lower fit		Higher fit	
	Lag 4	Lag 8	Lag 4	Lag 8
T1-elicited P3 amplitude at Fz	1.8 ± 5.1	3.2 ± 4.2	−0.6 ± 6.4	−0.4 ± 2.4
T1-elicited P3 amplitude at FCz	7.2 ± 4.3	8.4 ± 5.7	4.9 ± 3.3	4.1 ± 2.9
T1-elicited P3 amplitude at Cz	9.9 ± 4.0	10.8 ± 5.6	8.4 ± 2.3	7.8 ± 3.2
T1-elicited P3 amplitude at CPz	9.1 ± 4.7	10.0 ± 5.3	7.8 ± 2.6	7.2 ± 3.7
T1-elicited P3 amplitude at Pz	8.9 ± 4.7	9.0 ± 3.3	6.2 ± 2.5	7.0 ± 2.3
T1-elicited P3 latency at Fz	545.6 ± 32.0	538.3 ± 53.3	550.8 ± 35.7	551.8 ± 47.1
T1-elicited P3 latency at FCz	539.9 ± 32.4	531.5 ± 53.3	544.4 ± 22.9	550.9 ± 39.2
T1-elicited P3 latency at Cz	533.4 ± 35.9	541.0 ± 45.0	551.0 ± 31.4	543.3 ± 42.1
T1-elicited P3 latency at CPz	532.9 ± 36.5	544.2 ± 38.7	549.3 ± 29.8	543.8 ± 40.0
T1-elicited P3 latency at Pz	549.1 ± 40.4	544.5 ± 38.7	546.5 ± 29.3	532.5 ± 34.1

Table 5
*T2-Elicited P3 Components at Each Electrode Site by Task Condition (*Ms ± SD*)*

Measure	Lower fit		Higher fit	
	Lag 4	Lag 8	Lag 4	Lag 8
T2-elicited P3 amplitude at Fz	6.1 ± 9.8	7.2 ± 8.6	−2.3 ± 8.5	−4.4 ± 6.9
T2-elicited P3 amplitude at FCz	12.6 ± 9.4	15.4 ± 10.2	6.7 ± 3.4	5.8 ± 8.0
T2-elicited P3 amplitude at Cz	19.3 ± 10.5	20.5 ± 11.0	18.0 ± 5.2	17.7 ± 5.2
T2-elicited P3 amplitude at CPz	18.5 ± 10.9	18.6 ± 11.4	17.3 ± 5.6	16.9 ± 5.5
T2-elicited P3 amplitude at Pz	19.4 ± 11.4	19.3 ± 11.4	16.6 ± 6.5	14.5 ± 13.3
T2-elicited P3 latency at Fz	939.6 ± 99.0	1210.0 ± 122.4	941.2 ± 114.1	1113.5 ± 130.7
T2-elicited P3 latency at FCz	970.5 ± 100.5	1264.7 ± 97.2	988.6 ± 123.5	1265.9 ± 55.0
T2-elicited P3 latency at Cz	1023.4 ± 72.5	1316.2 ± 47.6	1030.4 ± 102.9	1298.4 ± 72.5
T2-elicited P3 latency at CPz	1003.2 ± 55.9	1300.3 ± 56.8	1007.3 ± 125.2	1290.2 ± 67.9
T2-elicited P3 latency at Pz	1011.0 ± 98.0	1288.3 ± 53.4	1012.6 ± 129.7	1275.8 ± 104.6

tion or more parsimonious temporal distribution of resources depending on the demands of the cognitive task. Given that aerobic fitness has been found to positively relate to aspects of cognition in which the AB paradigm requires (i.e., attentional resource distribution), the current study found that higher level of aerobic fitness attenuated the AB magnitude and efficiently reduced neuroelectric indices (i.e., P3 amplitude) of attentional resource allocation. Collectively, the flexible allocation of attentional resources observed in higher fit individuals might imply changes in the neuronal activity as a function of aerobic fitness. For instance, based on the current results, it is proposed that P3 amplitude is increased under certain conditions (e.g., such as those that support attentional control) and reduced during other conditions (such as those that support the temporal dynamics of attention). That is, the commonality across aspects of attention is the capability of more fit individuals to flexibly titrate or optimize resources to meet the demands of the task. The current findings suggest that higher fit children might have more efficient temporal dynamics of attentional processes through the flexible allocation of attentional resources to meet the time sensitive nature of the task.

Last, in our study we found that aerobic fitness may modulate the P3 component elicited by T2; findings from this investigation revealed a general, yet selective, relation of fitness to the P3 components. Specifically, larger T2-elicited P3 amplitude was observed, indicating more diffuse activation for lower fit children relative to higher fit children. P3 amplitude is thought to be proportional to the amount of attentional resources devoted to a given stimulus or task. With regard to the relationship between task performance and P3 amplitude, lower fit children exhibited overall increased T2-elicited amplitude, along with larger AB magnitude (reflected as decreased T2|T1). These results suggest that lower fit children may have greater difficulty in distributing attentional resources, with excessive recruitment of neural resources and an inefficiency of top-down control to meet the challenges imposed by the AB task. In addition, the attentional blink deficit is thought to occur because of limitations in capacity, such that each stimulus competes for a limited pool of attentional resources. Greater T2-elicited P3 amplitude may reflect a relatively inefficient attentional resource distribution given the limited brain resources underlying the AB paradigm. As mentioned above, fitness may serve to facilitate the distribution of attentional resources as reflected by reductions in P3 amplitude during the AB task. Another possibility may account for the different pattern observed in these results relative to previous fitness-related ERP studies (Hillman et al., 2005, 2009; Pontifex et al., 2011). Specifically, previous studies have used stimulus discrimination tasks (i.e., flanker tasks, go/no-go tasks) to examine a different domain of cognitive function (i.e., cognitive control). In such tasks, Polich (1990) posited that P3 amplitude decreases with high target probability at short ISIs because the processing system has not fully recovered from the previous component generation when the next target stimulus is presented. Accordingly, the P3 amplitude is sensitive to the type of cognitive tasks and the temporal dynamics of the paradigm. Given the drastically shorter ISI in the current

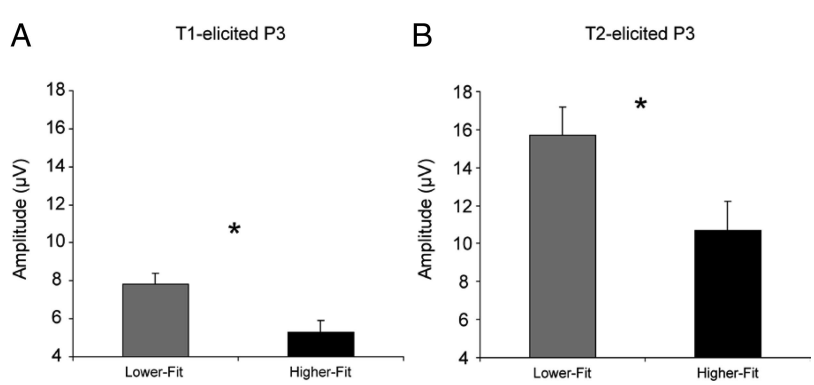

Figure 4. Mean P3 amplitude (±*SE*) for T1 (A) and T2 (B) for each group across lags and sites.

RSVP paradigm, is it possible that higher fit children exhibited economy of information processing relative to lower fit children to prepare for the second target (T2), reflected in overall smaller P3 amplitude. However, future research is necessary to better address potential mechanisms to gain insight into the fitness-induced changes in temporal dynamics.

The AB is a product of a widely distributed network (see Martens & Wyble, 2010, for review). As such, understanding how fitness influences this network is difficult and beyond the scope of ERP research. However, other imaging studies have indicated a number of mechanisms that have been identified to account for the observed fitness-related enhancements in temporal dynamics. On the one hand, Colcombe et al. (2004, 2006) have found that aerobic fitness was positively associated with larger volumes of prefrontal and temporal gray matter, as well as anterior white matter volumes (Gordon et al., 2008; Marks et al., 2007). On the other hand, with regard to the neural correlates of AB, previous studies have indicated that the AB-related deficit is involved with an interactive network of areas consisting of lateral–frontal, inferotemporal, posterior–parietal, and occipital brain regions (see Hommel et al., 2006; Martens & Wyble, 2010, for review). Accordingly, this study suggests that fitness might alter the neural circuitry involved in the AB, relating to changes in temporal dynamics.

In sum, aerobic fitness may facilitate temporal dynamics of attentional processes through efficient allocation of attentional resources. Further, early physical activity intervention to promote aerobic fitness might be an ideal means for improving not only physical health but also cognitive health as well. Given that recent trends in school policy are reducing opportunities for physical activity (e.g., physical education, recess) from the school day to create additional instruction on formal academic subjects (Thomas, 2004), these data speak to the importance of physical activity for the maturation of neural networks underlying aspects of temporal dynamics of attentional processes and have implications for maximizing cognitive health and function in real-world settings during development.

Although in our study we reported on relationships among fitness and neuroelectric and behavioral indices of temporal dynamics, there are a number of limitations to our study. For instance, the cross-sectional nature of this study yields the possibilities that the observed fitness-related differences may have resulted from other factors. However, this possibility was minimized given that data were collected on a number of demographic factors known to influence cognition and fitness, and any relationships between these factors and the dependent measures were examined to help limit other potential influences. In addition, given the early nature of this research, future studies should consider using randomized control interventions to establish a causal relationship between fitness and temporal dynamics of attentional processes in children. In spite of these limitations, our data extend fitness and cognition research by suggesting that the AB magnitude and P3 amplitude might be useful tools to examine the relationship between fitness and the maturation of temporal dynamics of attentional processes during preadolescence. Such findings add support for the beneficial relation of fitness to cognitive and brain health and function and may have implications for scholastic performance.

References

American College of Sports Medicine. (2010). *ACSM's guidelines for exercise testing and prescription* (8th ed.). New York, NY: Lippincott Williams & Wilkins.

Andersen, R. E., Crespo, C. J., Bartlett, S. J., Cheskin, L. J., & Pratt, M. (1998). Relationship of physical activity and television watching with body weight and level of fatness among children: Results from the Third National Health and Nutrition Examination Survey. *JAMA: Journal of the American Medical Association, 279,* 938–942. doi:10.1001/jama.279.12.938

Bar-Or, O. (1983). *Pediatric sports medicine for the practitioner: From physiologic principles to clinical applications*. New York, NY: Springer-Verlag. doi:10.1007/978-1-4612-5593-2

Birnbaum, A. S., Lytle, L. A., Murray, D. M., Story, M., Perry, C. L., & Boutelle, K. N. (2002). Survey development for assessing correlates of young adolescents' eating. *American Journal of Health Behavior, 26,* 284–295. doi:10.5993/AJHB.26.4.5

Broadbent, D. E., & Broadbent, M. H. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics, 42,* 105–113. doi:10.3758/BF03210498

Castelli, D. M., Hillman, C. H., Buck, S. M., & Erwin, H. E. (2007). Physical fitness and academic achievement in third- and fifth-grade students. *Journal of Sport & Exercise Psychology, 29,* 239–252.

Chaddock, L., Erickson, K. I., Prakash, R. S., Kim, J. S., Voss, M. W., VanPatter, M., . . . Kramer, A. F. (2010a). A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children. *Brain Research, 1358,* 172–183. doi:10.1016/j.brainres.2010.08.049

Chaddock, L., Erickson, K. I., Prakash, R. S., VanPatter, M., Voss, M. W., Pontifex, M. B., . . . Kramer, A. F. (2010b). Basal ganglia volume is associated with aerobic fitness in preadolescent children. *Developmental Neuroscience, 32,* 249–256. doi:10.1159/000316648

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity. *American Journal of EEG Technology, 25,* 83–92.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21*(1), 109–127. doi:10.1037/0096-1523.21.1.109

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., . . . Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology: Series A: Biological Sciences and Medical Sciences, 61,* 1166–1170. doi:10.1093/gerona/61.11.1166

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science, 14,* 125–130. doi:10.1111/1467-9280.t01-1-01430

Colcombe, S. J., Kramer, A. F., Erickson, K. I., Scalf, P., McAuley, E., & Cohen, N. J. (2004). Cardiovascular fitness, cortical plasticity, and aging. *Proceedings of the National Academy of Sciences of the United States of America, 101,* 3316–3321. doi:10.1073/pnas.0400266101

Compumedics. (2003). *Offline analysis of acquire data* (SCAN 4.3–Vol. II, EDIT 4.3) [Software Manual]. El Paso, TX: Author.

Donchin, E. (1981). Surprise! . . . Surprise? *Psychophysiology, 18,* 493–513. doi:10.1111/j.1469-8986.1981.tb01815.x

Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of cognitive updating? *Behavioral and Brain Sciences, 11,* 357–427. doi:10.1017/S0140525X00058027

Duncan-Johnson, C. C. (1981). Young Psychophysiologist Award address, 1980. P300 latency: A new metric of information processing. *Psychophysiology, 18,* 207–215.

DuPaul, G. J., Power, T. J., Anastopoulos, A. D., & Reid, R. (1998). *ADHD Rating Scale—IV: Checklists, norms, and clinical interpretation*. New York, NY: Guilford Press.

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception, & Psychophysics, 71,* 1683–1700. doi:10.3758/APP.71.8.1683

Dye, M. W. G., & Bavelier, D. (2010). Differential development of visual attention skills in school-age children. *Vision Research, 50,* 452–459. doi:10.1016/j.visres.2009.10.010

Feinstein, J. S., Stein, M. B., Castillo, G. N., & Paulus, M. P. (2004). From sensory processes to conscious perception. *Consciousness and Cognition, 13,* 323–335. doi:10.1016/j.concog.2003.10.004

Freedman, D. S., Khan, L. K., Dietz, W. H., Srinivasan, S. R., & Berenson, G. S. (2001). Relationship of childhood obesity to coronary heart disease risk factors in adulthood: The Bogalusa Heart Study. *Pediatrics, 108,* 712–718. doi:10.1542/peds.108.3.712

Freedson, P. S., & Goodman, T. L. (1993). Measurement of oxygen consumption. In T. W. Rowland (Ed.), *Pediatric laboratory exercise testing: Clinical guidelines* (pp. 91–113). Champaign, IL: Human Kinetics.

Garrad-Cole, F., Shapiro, K. L., & Thierry, G. (2011). Developmental aspects of temporal and spatial visual attention: Insights from the attentional blink and visual search tasks. *Child Neuropsychology, 17,* 118–137. doi:10.1080/09297049.2010.509716

Gordon, B. A., Rykhlevskaia, E. I., Brumback, C. R., Lee, Y., Elavsky, S., Konopack, J. F., . . . Fabiani, M. (2008). Neuroanatomical correlates of aging, cardiopulmonary fitness level, and education. *Psychophysiology, 45,* 825–838.

Green, C. S., & Bavelier, D. (2003, May 29). Action video game modifies visual selective attention. *Nature, 423,* 534–537. doi:10.1038/nature01647

Gross, J., Schmitz, F., Schnitzler, I., Kessler, K., Shapiro, K., Hommel, B., & Schnitzler, A. (2004). Modulation of long-range neural synchrony reflects temporal limitations of visual attention in humans. *Proceedings of the National Academy of Sciences of the United States of America, 101,* 13050–13055. doi:10.1073/pnas.0404944101

Hillman, C. H., Buck, S. M., Themanson, J. R., Pontifex, M. B., & Castelli, D. M. (2009). Aerobic fitness and cognitive development: Event-related brain potential and task performance indices of executive control in preadolescent children. *Developmental Psychology, 45,* 114–129. doi:10.1037/a0014437

Hillman, C. H., Castelli, D. M., & Buck, S. M. (2005). Aerobic fitness and neurocognitive function in healthy preadolescent children. *Medicine and Science in Sports and Exercise, 37,* 1967–1974. doi:10.1249/01.mss.0000176680.79702.ce

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience, 9,* 58–65. doi:10.1038/nrn2298

Hillman, C. H., Kamijo, K., & Scudder, M. (2011). A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Preventive Medicine, 52,* S21–S28. doi:10.1016/j.ypmed.2011.01.024

Hollingsworth, D. E., McAuliffe, S. P., & Knowlton, B. J. (2001). Temporal allocation of visual attention in adult attention deficit hyperactivity disorder. *Journal of Cognitive Neuroscience, 13,* 298–305. doi:10.1162/08989290151137359

Hommel, B., Kessler, K., Schmitz, F., Gross, J., Akyurek, E., Shapiro, K., . . . Schnitzler, A. (2006). How the brain blinks: Towards a neurocognitive model of the attentional blink. *Psychological Research, 70,* 425–435. doi:10.1007/s00426-005-0009-3

Husain, M., & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nature Reviews Neuroscience, 4,* 26–36. doi:10.1038/nrn1005

Husain, M., Shapiro, K., Martin, J., & Kennard, C. (1997, January 9). Abnormal temporal dynamics of visual attention in spatial neglect patients. *Nature, 385,* 154–156. doi:10.1038/385154a0

Janz, K. F., Dawson, J. D., & Mahoney, L. T. (2000). Tracking physical fitness and physical activity from childhood to adolescence: The Muscatine study. *Medicine and Science in Sports and Exercise, 32,* 1250–1257. doi:10.1097/00005768-200007000-00011

Kaufman, A. S., & Kaufman, N. L. (1990). *Kaufman Brief Intelligence Test manual*.

Kramer, A. F., & Hillman, C. H. (2006). Aging, physical activity, and neurocognitive function. In E. Acevado & P. Ekkekakis (Eds.), *Psychobiology of physical activity* (pp. 45–59). Champaign, IL: Human Kinetics.

Lahar, C. J., Isaak, M. I., & McArthur, A. D. (2001). Age differences in the magnitude of the attentional blink. *Aging, Neuropsychology, and Cognition, 8,* 149–159. doi:10.1076/anec.8.2.149.842

Li, C. S., Lin, W. H., Chang, H. L., & Hung, Y. W. (2004). A psychophysical measure of attention deficit in children with attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology, 113,* 228–236. doi:10.1037/0021-843X.113.2.228

Luck, S. J., Vogel, E. K., & Shapiro, K. L. (1996, October 17). Word meanings can be accessed but not reported during the attentional blink. *Nature, 383,* 616–618. doi:10.1038/383616a0

Maciokas, J. B., & Crognale, M. A. (2003). Cognitive and attentional changes with age: Evidence from attentional blink deficits. *Experimental Aging Research, 29,* 137–153. doi:10.1080/03610730303715

Marcantoni, W. S., Lepage, M., Beaudoin, G., Bourgouin, P., & Richer, F. (2003). Neural correlates of dual task interference in rapid visual streams: An fMRI study. *Brain and Cognition, 53,* 318–321. doi:10.1016/S0278-2626(03)00134-9

Marks, B. L., Madden, D. J., Bucur, B., Provenzale, J. M., White, L. E., Cabeza, R., . . . Huettel, S. A. (2007). Role of aerobic fitness and aging on cerebral white matter integrity. *Annals of the New York Academy of Sciences, 1097,* 171–174. doi:10.1196/annals.1379.022

Marois, R., Chun, M. M., & Gore, J. C. (2000). Neural correlates of the attentional blink. *Neuron, 28,* 299–308. doi:10.1016/S0896-6273(00)00104-5

Marois, R., Yi, D. J., & Chun, M. M. (2004). The neural fate of consciously perceived and missed events in the attentional blink. *Neuron, 41,* 465–472. doi:10.1016/S0896-6273(04)00012-1

Martens, S., Munneke, J., Smid, H., & Johnson, A. (2006). Quick minds don't blink: Electrophysiological correlates of individual differences in attentional selection. *Journal of Cognitive Neuroscience, 18,* 1423–1438. doi:10.1162/jocn.2006.18.9.1423

Martens, S., Wolters, G., & van Raamsdonk, M. (2002). Blinks of the mind: Memory effects of attentional processes. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1275–1287. doi:10.1037/0096-1523.28.6.1275

Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience and Biobehavioral Reviews, 34,* 947–957. doi:10.1016/j.neubiorev.2009.12.005

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97–113. doi:10.1016/0028-3932(71)90067-4

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Jr., . . . Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology, 37,* 127–152. doi:10.1111/1469-8986.3720127

Polich, J. (1990). P300, probability and interstimulus interval. *Psychophysiology, 27,* 396–403. doi:10.1111/j.1469-8986.1990.tb02333.x

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118,* 2128–2148. doi:10.1016/j.clinph.2007.04.019

Pontifex, M. B., Raine, L. B., Johnson, C. R., Chaddock, L., Voss, M. W., Cohen, N. J., . . . Hillman, C. H. (2011). Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *Jour-*

nal of Cognitive Neuroscience, 23, 1332–1345. doi:10.1162/jocn.2010.21528

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860. doi:10.1037/0096-1523.18.3.849

Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience, 8,* 1391–1400. doi:10.1038/nn1549

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 357–371. doi:10.1037/0096-1523.20.2.357

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1997). The attentional blink. *Trends in Cognitive Sciences, 1,* 291–296. doi:10.1016/S1364-6613(97)01094-2

Shapiro, K., Schmitz, F., Martens, S., Hommel, B., & Schnitzler, A. (2006). Resource sharing in the attentional blink. *NeuroReport, 17,* 163–166. doi:10.1097/01.wnr.0000195670.37892.1a

Shvartz, E., & Reibold, R. C. (1990). Aerobic fitness norms for males and females aged 6 to 75 years: A review. *Aviation Space and Environmental Medicine, 61,* 3–11.

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exercise Science, 15,* 243–256.

Sisson, S. B., Church, T. S., Martin, C. K., Tudor-Locke, C., Smith, S. R., Bouchard, C., . . . Katzmarzyk, P. T. (2009). Profiles of sedentary behavior in children and adolescents: The US National Health and Nutrition Examination Survey, 2001–2006. *International Journal of Pediatric Obesity, 4,* 353–359. doi:10.3109/17477160902934777

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., . . . Davidson, R. J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5,* e138. doi:10.1371/journal.pbio.0050138

Strong, W. B., Malina, R. M., Blimkie, C. J. R., Daniels, S. R., Dishman, R. K., Gutin, B., . . . Trudeau, F. (2005). Evidence based physical activity for school-age youth. *The Journal of Pediatrics, 146,* 732–737. doi:10.1016/j.jpeds.2005.01.055

Taylor, S. J. C., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001). Performance of a new pubertal self-assessment questionnaire: A preliminary study. *Paediatric and Perinatal Epidemiology, 15,* 88–94. doi:10.1046/j.1365-3016.2001.00317.x

Thomas, K. T. (2004). Riding to the rescue while holding on by a thread: Physical activity in the schools. *Quest, 56,* 150–170. doi:10.1080/00336297.2004.10491820

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review, 20,* 111–131. doi:10.1007/s10648-007-9057-0

U.S. Department of Health and Human Services. (2008). *Physical activity guidelines for Americans*. Washington, DC: U. S. Government Printing Office.

U.S. Department of Health and Human Service and Department of Education. (2000). *Promoting better health for young people through physical activity and sports. A report to the President from the Secretary of Health and Human Services and the Secretary of Education*. Silver Spring, MD: Centers for Disease Control.

Utter, A. C., Roberson, R. J., Nieman, D. C., & Kang, J. (2002). Children's OMNI scale of perceived exertion: Walking/running evaluation. *Medicine & Science in Sports & Exercise, 34,* 139–144. doi:10.1097/00005768-200201000-00021

Verleger, R. (1997). On the utility of P3 latency as an index of mental chronometry. *Psychophysiology, 34,* 131–156. doi:10.1111/j.1469-8986.1997.tb02125.x

Vogel, E. K., Luck, S. J., & Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1656–1674. doi:10.1037/0096-1523.24.6.1656

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