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The association between aerobic fitness and language processing in children: Implications for academic achievement

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ABSTRACT

Event-related brain potentials (ERPs) have been instrumental for discerning the relationship between children's aerobic fitness and aspects of cognition, yet language processing remains unexplored. ERPs linked to the processing of semantic information (the N400) and the analysis of language structure (the P600) were recorded from higher and lower aerobically fit children as they read normal sentences and those containing semantic or syntactic violations. Results revealed that higher fit children exhibited greater N400 amplitude and shorter latency across all sentence types, and a larger P600 effect for syntactic violations. Such findings suggest that higher fitness may be associated with a richer network of words and their meanings, and a greater ability to detect and/or repair syntactic errors. The current findings extend previous ERP research explicating the cognitive benefits associated with greater aerobic fitness in children and may have important implications for learning and academic performance.

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1. Introduction

As much as a century ago, scientific evidence demonstrated higher rates of degenerative diseases in individuals with sedentary occupations (Paffenbarger, Blair, & Lee, 2001). Despite the refinement of this knowledge over subsequent decades, changes in technology and lifestyle have led to continued or even increased prevalence of sedentary behaviors in individuals of all ages (Vayman & Gomez-Pinilla, 2006), with arguably the most negative outcomes accruing to children and adolescents. Since 1980, the number of overweight children and adolescents in the United States has doubled and tripled, respectively (Baskin, Ard, Franklin, & Allison, 2005), while relative maximal oxygen consumption (VO_{2max}, a gold-standard measure of aerobic fitness) has decreased by 20% in adolescent females (Eisenmann & Malina, 2002). Many speculate that this trend is exacerbated by the decreased amount of time children spend being physically active at school, and correspondingly indicates that schools are the ideal environment for intervention (Donnelly et al., 2009; Hillman, Erickson, & Kramer, 2008). Such ideas have generated a strong interest in attempting to unravel the association between children's health and their endeavors at school, most notably academic achievement.

1.1. Children's aerobic fitness and cognition

A growing body of research has focused on the relationship between children's aerobic fitness and academic performance using field estimates and classroom evaluations in school. Although a causal relationship has not yet been established, a number of findings have demonstrated that more aerobically fit children perform better on standardized achievement tests and receive higher grades (see CDC, 2010, for review). Such findings have considerable implications for children's health and their accomplishments in school, especially given that early academic achievement often predicts future engagement and success. This relationship has been particularly well established for language and reading abilities. Superior skills (phonological awareness, word decoding, reading comprehension, and spelling) and early performance have been linked to better grades and greater reading engagement during high school (e.g., Cunningham & Stanovich, 1997; Lonigan, Burgess, & Anthony, 2000), as well as improved mastery of a second language (which many children also encounter in the school curriculum; Sparks, Patton, Ganschow, Humbach, & Javorsky, 2008).

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However, most previous research investigating the relationship between fitness and academic achievement has relied exclusively on behavioral outcomes, which account for overt performance but, as end-state measures, summate across multiple cognitive processes that may change as a function of fitness. Thus, when higher fit children outperform their lower fit peers on tests like reading achievement, it is unclear whether this is due to factors such as motivation and attention-to-task, or because fitness has more direct effects on specific language subprocesses. For this reason, event-related brain potentials (ERPs) have played a critical role in research on fitness effects, as this method provides a time-sensitive record of the brain's response during cognitive engagement. Aspects of the ERP response "components" have been linked to specific cognitive processes, and those responses are multidimensional in nature, consisting of changes in amplitude, latency, and/or topography across groups and/or experimental conditions. Therefore, ERPs provide a set of functionally specific dependent measures that can help reveal the neural basis of fitness-related associations with academic achievement and cognitive processing in a way that is not possible with behavioral outcomes alone.

For example, recent investigations focusing on the P3b (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Pontifex et al., 2011) in children have successfully demonstrated an association between aerobic fitness and specific, core aspects of cognition. The P3b is elicited when people attend to or discriminate between stimuli (Polich & Kok, 1995). The amplitude and latency of this response are influenced by the availability of attentional resources and the time necessary to evaluate and update stimulus context (e.g., Donchin & Coles, 1998; Polich, 2007). P3b responses have been collected from higher and lower fit children using paradigms including oddball tasks (Hillman et al., 2005) and modified versions of the Eriksen flanker task (Eriksen & Eriksen, 1974; Hillman et al., 2009; Pontifex et al., 2011), each of which challenges participants to attend to specific stimuli, inhibit pre-potent tendencies or distracting information, and respond both quickly and accurately. In addition to greater response accuracy and shorter response times (RT), higher fit children exhibit larger P3b amplitude and shorter latency compared to those with lower fitness. These findings link better behavioral performance in higher fit children to differences in attention and inhibitory control, with higher fit children able to efficiently and effectively allocate greater attentional resources to support task performance (Hillman et al., 2005, 2009; Pontifex et al., 2011).

Accordingly, the functional capabilities of ERPs are well-suited for examining skills such as reading, which unfold rapidly and across time. In addition, as described next, ERPs provide functionally well-specified measures of core language processes; thus, with ERPs it is possible to look for relationships between fitness and specific language processing abilities. Therefore, the current study aims to extend research examining fitness and children's cognition by investigating ERP indices of meaning processing (the N400 component) and the analysis of language structure or grammar (frontal negativities and the P600).

1.2. The N400 component and N400 effects

The N400 is an ERP component that is elicited by words in all modalities, as well as other types of meaningful stimuli, and has been linked to the access of meaning information from long-term memory (e.g., Lau, Phillips, & Poeppel, 2008; see review in Kutas & Federmeier, 2011). In the thirty years since its discovery (Kutas & Hillyard, 1980), this response has been well-established as a reliable measure of semantic processing. As its name implies, the N400 is a negative-going ERP component observed approximately between 300 and 500 ms (peaking around 400 ms) after stimulus presentation, and is widely-distributed over the scalp with a topographic maximum over central and parietal regions (Holcomb, Coffey, & Neville, 1992). The N400 can be observed in children as young as 19 months (Friedrich & Friederici, 2004), and its latency and amplitude index different aspects of language abilities along with their changes across the lifespan. Across multiple studies and participant populations, evidence suggests that N400 latency decreases over the course of childhood (Hahne, Eckstein, & Friederici, 2004; Holcomb et al., 1992; Juottonen, Revonsuo, & Lang, 1996), as language abilities increase. The relationship between N400 latency and language fluency has also been documented in studies of bilingual participants, which allow a within participant comparison between languages with which these participants are more or less fluent. These studies show that the N400 peaks later in the less dominant language and that, more generally, shorter N400 latencies are associated with greater language proficiency (e.g., Moreno & Kutas, 2005).

The amplitude of the N400 varies with the amount of lexico-semantic activation elicited by an incoming word (see Kutas & Federmeier, 2011, for review). N400 amplitude is increased for words with more orthographic neighbors (the number of words known to the reader that share all but one letter in common with the stimulus), higher neighborhood frequency (the average frequency of the orthographic neighbors), and more lexical associates (Holcomb, Grainger, & O'Rourke, 2002; Laszlo & Federmeier, 2007, 2011; Laszlo & Plaut, 2012). N400 amplitudes are also larger for concrete than abstract words (see review in Lee & Federmeier, 2012) and for known than unknown words, both in toddlers (Mills, Coffey-Corina, & Neville, 1993, 1997; Mills, Conboy, & Paton, 2005) and adults learning a second language (McLaughlin, Osterhout, & Kim, 2004). Thus, all else being equal, words that make contact with a larger set of lexical items and/or semantic features elicit larger N400 responses. Correspondingly, N400 component amplitude provides a measure of language ability. For example, in school-age children, Coch and Holcomb (2003) found larger N400 amplitudes in high compared to low ability readers across a range of different word types presented in isolation.

Relative to its "baseline" level, the amount of N400 activity a given word elicits can be reduced by factors that ease lexico-semantic processing. N400 amplitudes are reduced by repetition (and similarly, by higher word frequency when words are presented in isolation) and when context information (of many types) renders words more plausible. For example, N400 amplitudes are smaller for "*shoes*" than for "*songs*" in the sentence context "*You wear shoes/songs on your feet*" (see Kutas & Federmeier, 2011 for review). This difference between a word in an incongruent versus congruent context is typically referred to as the "N400 effect". The size of the N400 effect, independent of overall N400 amplitude, provides a measure of how well the available context information is being used during comprehension. As such, N400 effect size has been used to document changes in the ability to make use of sentence context information with normal aging (Wlotko, Lee, & Federmeier, 2010) and schizophrenia (Sitnikova, Salisbury, Kuperberg, & Holcomb, 2002). In the literature on language learning, pictures have been used as context, with the N400 effect to matching versus mismatching words then constituting an implicit vocabulary measure (e.g., Byrne, Dywan, & Connolly, 1995; Byrne et al., 1999; but see Henderson, Baseler, Clarke, Watson, & Snowling, 2011, for a failure to replicate this correlation with vocabulary).

In summary, measurements of the N400 can provide multiple, complementary indices of language comprehension abilities. The size and timing of the N400 component reflect, respectively, the richness of the mental lexicon and the speed with which it can be accessed. Assessments of the N400 effect (facilitation for plausible relative to unexpected/incongruent words) in a particular experimental context can additionally speak to a person's ability