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FROM COGNITIVE MOTOR PREPARATION TO VISUAL PROCESSING: THE BENEFITS OF CHILDHOOD FITNESS TO BRAIN HEALTH

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Abstract—The association between a fit body and a fit brain in children has led to a rise of behavioral and neuroscientific research. Yet, the relation of cardiorespiratory fitness on premotor neurocognitive preparation with early visual processing has received little attention. Here, 41 healthy, lower and higherfit preadolescent children were administered a modified version of the Eriksen flanker task while electroencephalography (EEG) and behavioral measures were recorded. Event-related potentials (ERPs) locked to the stimulus onset with an earlier than usual baseline (−900/−800 ms) allowed investigation of both the usual post-stimulus (i.e., the P1, N1 and P2) as well as the pre-stimulus ERP components, such as the Bereitschaftspotential (BP) and the prefrontal negativity (pN component). At the behavioral level, aerobic fitness was associated response accuracy, with higherfit children being more accurate than lowerfit children. Fitness-related differences selectively emerged at prefrontal brain regions during response preparation, with larger pN amplitude for higher than lowerfit children, and at early perceptual stages after stimulus onset, with larger P1 and N1 amplitudes in higher relative to lowerfit children. Collectively, the results suggest that the benefits of being aerobically fit appear at the stage of cognitive preparation prior to stimulus presentation and the behavioral response during the performance of a task that challenges cognitive control. Further, it is likely that enhanced activity in prefrontal brain areas may improve cognitive control of visuo-motor tasks, allowing for stronger proactive inhibition and larger early allocation of selective attention resources on relevant external stimuli.

Key words: ERP, cognition, fitness, adolescence, motor preparation.

INTRODUCTION

Interest in physical activity as a health behavior to improve or maintain brain health first emerged in the aging literature, where a large body of literature exists (Colcombe et al., 2004; Hillman et al., 2008; Erickson et al., 2013), whereas physical activity and cognition research in preadolescent children is still in the early stages. Several studies have consistently shown that children with higher cardiovascular or aerobic fitness[†] have better academic achievement (see Keeley and Fox, 2009; Fedewa and Ahn, 2011 for reviews) and perform better on tasks tapping aspects of cognitive control and memory (Buck et al., 2008; Chaddock et al., 2011; Wu et al., 2011; Raine et al., 2013; Crova et al., 2014). In the last decade, a neuroscientific line of research has flourished, highlighting the impact of fitness-enhancing physical exercise (Davis et al., 2011; Hillman et al., 2014; Krafft et al., 2014) and exercise-related fitness (Hillman et al., 2009; Pontifex et al., 2009; Kamijo et al., 2010) on children's brain function and health (see Ahn and Fedewa, 2011; Chaddock et al., 2011; Hillman et al., 2011 for reviews) that also generalizes to special populations as overweight children (Davis et al., 2011; Krafft et al., 2014). The present work investigates aerobic fitness-related effects on the neural correlates of cognitive control in preadolescent children during a modified flanker task, which modulates cognitive control requirements through manipulation of interference control and response inhibition parameters. To this aim, we used event-related potentials (ERPs), which directly measure the electrical responses of the cortex to sensory, cognitive or motor events with a high temporal resolution.

Accordingly, Hillman and colleagues (2005) observed that in a stimulus discrimination (i.e., oddball) task, higherfit preadolescent children had larger amplitude of the P3-ERP component and better task performance than lowerfit children. The P3 is a positive component occurring between 300 and 800 ms after stimulus onset over central-parietal brain areas, whose amplitude is related to the allocation of attentional resources during stimulus engagement, and its latency is associated with stimulus classification and evaluation and processing speed (Verleger et al., 2005; Polich, 2007). In subsequent

[†] The term "fitness" refers to aerobic or cardiovascular fitness throughout the manuscript.

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Abbreviations: ANOVA, analysis of variance; CNV, contingent negative variation; EEG, electroencephalography; EOG, electrooculography; ERN, error-related negativity; ERPs, event-related potentials; PB, Bereitschaftspotential; pN, prefrontal negativity; pP, prefrontal positivity.

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studies, the authors (Hillman et al., 2009, 2014; Pontifex et al., 2011) confirmed that higherfit children had larger P3 amplitude and were more accurate than their lowerfit counterparts during a modified flanker task. These results indicated that performance accuracy is sensitive to individual differences in children's fitness, and that more efficient cognitive control subtends this behavioral outcome of fitness. Childhood fitness effects have also been observed in response-locked ERPs, showing more flexible attention toward errors and higher performance accuracy in higher compared to lowerfit children (Hillman et al., 2009; Pontifex et al., 2011).

Pontifex et al. (2011) manipulated cognitive load of the flanker task through the inclusion of compatible and incompatible stimulus–response conditions. They found larger P3 and smaller error-related negativity (ERN) amplitude in high-fit than low-fit children, as well as a greater modulation of P3 and ERN between compatible and incompatible conditions, that were paralleled by higher accuracy especially under the incompatible condition. The authors interpreted the results in support of the *dual mechanism of cognitive control theory* proposed by Braver et al. (2007), postulating that cognitive control during working memory tasks operates via two strategies: proactive control (i.e., anticipatory process over the duration of a given task) and reactive control (i.e., transient process after stimulus perception). To interpret their fitness-related finding, Pontifex et al. (2011) proposed that higherfit children had greater reliance on the proactive control strategy, because they were able to flexibly up-regulate their control across conditions, while maintaining stable response accuracy. On the contrary, lowerfit children seemed to rely on a more reactive control strategy, because they presented difficulties in both the up-regulation required to process increased task demands and the flexible modulation required by the proactive control. Together, these results suggest that aerobic fitness may modulate task strategy, fostering the allocation of attentional resources during stimulus engagement and reducing the resource load devoted to action monitoring, which was associated with a more successful task performance through an efficient proactive control strategy. Another research has examined the contingent negative variation (CNV), which is a negative slow wave elicited during the interval between warning (S1) and imperative (S2) stimuli associated with the cognitive preparatory process during stimulus anticipation. A fitness-related enhancement of the CNV has been observed in children (Kamijo et al., 2011), adolescents (Stroth et al., 2009), and young adults (Kamijo et al., 2010), whereas fitness effects on brain function of preadolescent children during the pre-stimulus response preparation and early post-stimulus ERP periods have not been investigated yet.

Recently, studies conducted with young and older adults (Berchicci et al., 2012, 2013, 2014; Perri et al., 2014a,b) have distinguished the contribution of two main components during the preparation of a motor response during visuo-motor discrimination tasks: the Bereitschaftspotential (BP) over medial central sites, which is a slow-rising negativity beginning more than 1 s prior to movement onset and reflecting motor preparation, and the prefrontal negativity (pN), maximal over prefrontal sites, which is a negative component beginning immediately prior to the BP and reflecting cognitive preparation of the response. Following stimulus onset, another large positive component – peaking between 200 and 300 ms over the prefrontal cortex – known as the prefrontal positivity (pP) has been proposed to reflect the stimulus–response mapping processing. In a recent study combining ERP and functional magnetic resonance imaging (fMRI) measures (Di Russo et al., 2014), the origin of pN was localized in the inferior frontal gyrus within the prefrontal cortex, and this activity was associated with proactive control during response inhibition processes and predicted stimulus onset. Further, the pP was localized in the anterior insula, whose activity may represent the accumulation of evidences needed to complete the final stage of the decision-making process that leads to overt responding. The BP origin has been localized in the supplementary motor area and in the cingulated motor area (Shibasaki and Hallett, 2006; Di Russo et al., 2014). Nevertheless, the contribution of the prefrontal cortex during cognitive-motor control in preadolescents is still scarcely understood.

Critical questions remain regarding (1) how functional maturation in preadolescence is manifested during both motor and cognitive anticipatory processes (BP and pN components) and early perceptual processing (pP, P1, N1 and P2 components) in the preparation–perception–action cycle, and (2) how these processes and their behavioral outcomes are modulated by aerobic fitness. We hypothesized to find aerobic fitness-related changes in early visual processing, because of the specific fitness-related improvements in visual discrimination abilities, visual-search skills and visual concentration to environmental demands (Zwierko et al., 2014).

EXPERIMENTAL PROCEDURES

Participants

Forty-one healthy preadolescent children (mean ± SD: 10.0 ± 0.6 years of age; 23 female) were recruited for this study. Participants were classified as lowerfit (N = 20) and higherfit (N = 21) on the basis of whether their VO_2max fell above the 70th percentile or below the 30th percentile, according to normative data provided by Shvartz and Reibold (1990), which apply to most of the industrial world. Thus, the adjective "fit" that identifies the groups specifically refers to aerobic or cardiovascular fitness. All participants were right handed (Edinburgh Handedness Inventory; Oldfield, 1971). The participants were free of neurological diseases, attentional disorders and physical disabilities, and had normal or corrected-to-normal vision, as reported by the participants' guardians. Legal guardians provided written informed consent and participants provided written informed assent in accordance with the Institutional review Board of the University of Illinois at Urbana-Champaign.

Task

Participants completed a modified version of the Eriksen flanker task (Eriksen and Eriksen, 1974). The stimuli were

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