Brain and Cognition 82 (2013) 43–57

Contents lists available at SciVerse ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

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

Robert Davis Moore [a], Chien-Ting Wu [b], Matthew B. Pontifex [c], Kevin C. O'Leary [a], Mark R. Scudder [a], Lauren B. Raine [a], Christopher R. Johnson [b], Charles H. Hillman [a,*]

[a] Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, Illinois, United States
[b] Department of Exercise Science and Sport Management, Schreiner University, Kerrville, Texas, United States
[c] Department of Kinesiology, Michigan State University, East Lansing, Michigan, United States

ARTICLE INFO

Article history:
Accepted 4 February 2013
Available online 16 March 2013

Keywords:
Exercise
Cognitive control
Ex-Gaussian
Intelligence Quotient
Event-related brain potential
P3

ABSTRACT

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

1. Introduction

Physical activity, which is essential to maintain overall health and function, has been found to benefit weight control, bone mass, muscle strength, and reduce the risk of heart disease and certain cancers (USDHHS, 2008). Unfortunately, in today's industrial and technological society, children are becoming increasingly sedentary, exacerbating the prevalence of certain physical diseases including cardiovascular disease, colon cancer, and type-2 diabetes (Department of Health and Human Service and Department of Education, 2000). Beyond such physiological ramifications, physical activity has also been observed to relate to cognitive health across the life span (see Hillman, Erickson, & Kramer, 2008 for review). More specifically, in adult populations, aerobic exercise training is associated with modest improvements in attention, processing speed, cognitive control, and memory (Smith et al., 2010), with a disproportionate benefit observed during tasks requiring greater cognitive control (Colcombe & Kramer, 2003; Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Kramer et al., 1999). However, the specificity of the relation between fitness and cognitive health in developing populations continues to unfold (Buck, Hillman, & Castelli, 2008; Castelli et al., 2007; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Hillman, Castelli, & Buck, 2005; Sibley & Etnier, 2003; Pontifex et al., 2011; Tomporowski, 2003) such that further inquiry is necessary to gain a greater understanding of the nature of the benefits of physical fitness on neurocognitive development.

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

* Corresponding author. Address: Department of Kinesiology & Community Health, 317 Louise Freer Hall, 906 South Goodwin Avenue, University of Illinois, Urbana, IL 61801, United States. Fax: +1 217 244 7322.
E-mail address: chhillma@illinois.edu (C.H. Hillman).

0278-2626/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.bandc.2013.02.006

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

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

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

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