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The association between aerobic fitness and congruency sequence effects in preadolescent children

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ABSTRACT

Aerobic fitness has previously been related to cognitive control in preadolescents; however, these investigations have generally relied on global measures of performance. Thus, we have little understanding of how aerobic fitness may relate to trial-by-trial modulations in cognitive control. This study utilized congruency sequence effects (CSEs), which characterize how behavior on the current trial is influenced by the previous trial, to investigate the relation of aerobic fitness on varying levels of cognitive control. One hundred eighty-seven children completed tests of aerobic fitness and a flanker task. Regressions were performed to determine relationships between CSE sequences and aerobic fitness while controlling for other potential confounding factors (e.g., age, sex, IQ). Lower-fit children were less able to modulate cognitive control during sequences requiring relatively less cognitive control. Additionally, lower-fit children were less able to adjust for variable levels of cognitive control during relatively more difficult sequences. Lastly, lower-fit children had longer reaction times (RTs) for all sequences in the condition requiring greater amounts of cognitive control. These findings corroborate the importance of aerobic fitness for cognitive control in school-aged children, and extend the literature by demonstrating a relationship between fitness and trial-by-trial modulations in control demands.

1. Introduction

Reduced aerobic fitness levels in children (Olds, Tomkinson, Leger, & Cazorla, 2006; Salmon & Timperio, 2007) remain a growing concern as opportunities for physical activity are continuously being obviated from the school day (Castelli et al., 2014; Howie & Pate, 2012). Such a trend is particularly worrisome as sedentary behaviors have increased (Vaynman & Gomez-Pinilla, 2006) along with rates of obesity and type-2 diabetes (Eisenmann, 2003). Surprisingly, these changes have occurred despite findings that less aerobically fit children exhibit poorer performance on tests of academic achievement and other cognitive outcomes (Buck, Hillman, & Castelli, 2008; Castelli, Hillman, Buck, & Erwin, 2007; Chaddock, Erickson, Prakash, Kim, et al., 2010; Chaddock, Hillman, Buck, & Cohen, 2011; Chomitz et al., 2009; Dwyer, Sallis, Blizzard, Lazarus, & Dean, 2001; Eveland-Sayers, Farley, Fuller, Morgan, & Caputo, 2009; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Monti, Hillman, & Cohen, 2012; Scudder et al., 2014), leading many to suggest that schools should reconsider sacrificing daily physical activity opportunities for additional classroom time (Durant et al., 2009). Additionally, previous research has indicated that aerobic fitness plays an important role in the brain health of children (Chaddock, Pontifex, Hillman, & Kramer, 2011).

Cognitive control is one aspect of cognition that has received much attention due to its relationship with educational outcomes (Diamond, Barnett, Thomas, & Munro, 2007; Howie & Pate, 2012) and health behaviors (Diamond, 2013). It refers to top-down, goal directed behavior, and is comprised of inhibitory control (the ability to gate out distracting information or refrain from executing a prepotent response), working memory (the ability to store, maintain, and manipulate information within a brief period of time), and cognitive flexibility (the ability to shift attention and alter response strategy in response to changing task demands). Cognitive control is of considerable importance in children due to its underlying beneficial associations with academic performance (Diamond & Lee, 2011; Diamond et al., 2007) and protracted devel-

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opmental trajectory throughout childhood (Luna, 2009). Further, health behaviors and outcomes such as physical activity, aerobic fitness, and body composition have been found to relate to cognitive control performance (Hillman, Khan, & Kao, 2015). As such, there is continued interest in gaining a more comprehensive understanding of the beneficial relationship between aerobic fitness and cognitive control in children.

The Eriksen flanker task has been used extensively to study aspects of cognitive control, (Eriksen & Eriksen, 1974) and has helped reveal the importance of demographic factors, such as socioeconomic status (SES), that influence its development (Mezzacappa, 2004). In one version of this paradigm, participants are presented with an array of five arrows and are instructed to respond according to the directionality of the central, target arrow. Stimulus-congruent trials, which place low demand on cognitive control, involve flanking stimuli that are oriented in the same direction as the central target stimulus, whereas stimulus-incongruent flanking stimuli are oriented opposite to the target and require greater cognitive control to overcome perceptual interference. As a result, stimulus-incongruent trials result in greater difficulty as evidenced by longer reaction time (RT) and lower accuracy compared to stimulus-congruent trials (Hillman, Pontifex, et al., 2009; Pontifex et al., 2011; Voss et al., 2011). Task difficulty can be further increased by introducing a response-compatibility manipulation, wherein participants are instructed to respond either in the same direction (response-compatible) or in the opposite direction (response-incompatible) of the central target stimulus (Friedman, Nessler, Cycowicz, & Horton, 2009). Studies investigating fitness effects on cognitive control as indexed using the flanker task have found that lower-fit children demonstrate poorer overall performance (longer RT and decreased accuracy) when compared to their higher-fit peers (Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Chaddock, Hillman, et al., 2012; Hillman et al., 2009; Pontifex et al., 2011; Scudder et al., 2014; Voss et al., 2011). Additionally, lower-fit children are disproportionately affected by tasks that require greater cognitive control demands, resulting in poorer performance compared to higher-fit children in stimulus-congruency manipulations (Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Kamijo et al., 2011; Scudder et al., 2014; Voss et al., 2011) as well as response-compatibility manipulations (Pontifex et al., 2011; Scudder et al., 2014).

A study conducted by Pontifex et al. (2011) found that lower-fit children were less able to flexibly modulate cognitive control as evidenced by a lack of modulation of the event related negativity (ERN) component, which is thought to reflect action-monitoring processes to enact top-down compensatory mechanisms in response to conflict or erroneous behaviors (Gehring, Liu, Orr, & Carp, 2011). Additionally, these children experienced greater response conflict, reduced attentional allocation, and slower processing speed, as indexed by increased N2 amplitude, decreased P3 amplitude, and increased latencies, respectively (Pontifex et al., 2011). Taken together, these findings suggest that not only is lower aerobic fitness associated with decreased overall cognitive control performance and less optimal neuroelectric profiles, but that these associations are greatest as task demands increase. Despite the robustness of these findings, researchers have yet to understand why this pattern of behavior occurs. Although some studies have suggested that higher- and lower-fit participants may elicit different cognitive control strategies to maintain performance (Pontifex et al., 2011; Voss et al., 2011), the observed findings may also be explained, in part, by the ability to overcome specific cognitive control demands encountered from sequential modulation of trial-by-trial congruency, also known as the 'Gratton Effect' or 'congruency sequence effect'.

Congruency sequence effects (CSEs) allow insight into cognitive control ability under varying levels of cognitive demand, making them particularly useful for unveiling further details about the selective differences observed between higher- and lower-fit children. CSEs identify trial sequences that require greater levels of cognitive control, and are more likely to cause a behavioral misstep resulting in an incorrect response or delayed RT. The initial discovery of CSEs was reported by Gratton, Coles, and Donchin (1992), who discovered that stimulus-incongruent trials preceded by a stimulus-incongruent trial showed better performance than those preceded by stimulus-congruent trials. Typically, stimulus-congruent trials (n) preceded by a stimulus-congruent or stimulus-incongruent trial ($n-1$) are described as cC and iC, respectively, with the preceding trial represented by a lower case letter. Similarly, stimulus-incongruent trials (n) preceded by a stimulus-congruent or stimulus-incongruent trial ($n-1$) are described as cI and iI, respectively. Typical CSEs findings show that cC sequences are associated with the fastest and most accurate responses, while cI sequences are associated with the slowest and least accurate responses. Additionally, iC and iI sequences result in RTs that fall in the middle, with iI sequences having longer RTs and lower accuracy.

One interpretation of CSEs is described by the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cogen, 2001), which holds that CSEs arise when conflicting information (i.e., conditions requiring greater amounts of inhibitory control) is detected and inhibitory control is modulated to meet these demands. As such, inhibitory control is temporarily upregulated following greater amounts of conflict and temporarily downregulated following lower amounts of conflict. As such, CSEs provide a window in which to examine online adjustments in inhibitory control (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014). An alternative explanation is provided by the feature integration hypothesis (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003), which holds that during a trial, stimulus and response features become temporarily bound together into a single episodic memory representation. Thus, on subsequent trials, if common features of the stimulus-response representation are detected then the other features will automatically be activated. As a consequence, the necessity of updating working memory may be different between sequences with complete stimulus repetition and sequences with partial stimulus repetition. That is, cC and iI sequences involve complete stimulus repetitions and require less working memory updating, resulting in superior task performance. In contrast, iC and cI sequences involve only partial stimulus repetitions and require more working memory updating, resulting in reduced task performance.

Kamijo and Takeda (2013) found that when comparing active versus inactive participants, the inactive participants did not show the expected improvements in iI sequences compared to cI sequences, possibly due to the inability to take advantage of the upregulation of cognitive control. Accordingly, the present study sought to investigate whether CSEs are influenced by aerobic fitness given previous findings that lower-fit children demonstrate poorer performance on measures of cognitive control (Chaddock, Erickson, Prakash, Kim, et al., 2010; Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Chaddock, Hillman, et al., 2011; Chaddock, Hillman, et al., 2012; Hillman et al., 2009; Pontifex et al., 2011; Scudder et al., 2014; Voss et al., 2011), particularly during high cognitive demand trials (Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Pontifex et al., 2011; Voss et al., 2011). As such, this study sought to manipulate multiple levels of cognitive control by utilizing both stimulus-congruency and response-compatibility manipulations. It was hypothesized that lower-fit children would exhibit poorer performance during sequences with the highest cognitive demands. In particular, lower-fit children would demonstrate longer RT and reduced accuracy during the cI sequence, as they would be less able to