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 higher fit 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 (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 higher fit children being more accurate than lower fit children. Fitness-related differences selectively emerged at prefrontal brain regions during response preparation, with larger pN amplitude for higher than lower fit children, and at early perceptual stages after stimulus onset, with larger P1 and N1 amplitudes in higher relative to lower fit 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. © 2015 IBRO. Published by Elsevier Ltd. All rights reserved.

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., 2010, 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, higher fit preadolescent children had larger amplitude of the P3-ERP component and better task performance than lower fit 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 studies, the authors (Hillman et al., 2009, 2014; Pontifex et al., 2011) confirmed that higher fit children had larger P3 amplitudes for a given stimulus variation; EEG, electroencephalography; EOG, electrooculography; ERN, error-related negativity; ERPs, event-related potentials; BP, Bereitschaftspotential; pN, prefrontal negativity; pP, prefrontal positivity.

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The term “fitness” refers to aerobic or cardiovascular fitness throughout the manuscript.
amplitude and were more accurate than their lower fit 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 subsumes 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 lower fit 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 higher fit 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, lower fit 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., 2013), 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., 2013). 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 lower fit (N = 20) and higher fit (N = 21) on the basis of whether their VO₂max fell below the 75th percentile or below the 30th percentile, according to normative data provided by Shwartz 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 3-cm tall white arrows constituting a 16.5-cm wide array
with a vertical visual angle of 1.32° and a horizontal visual angle of 7.26°, which were presented focally for 200 ms on a black background with a fixed inter-stimulus interval of 1700 ms. Participants were instructed to make a left or right button press depending on the direction of a centrally presented arrow amid either congruous (e.g., \(< \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \times \time...
RESULTS

Behavioral results

The mean response times and accuracy for each group are presented in Table 1. The repeated-measures ANOVA revealed neither a main effect for aerobic fitness, nor a significant Aerobic fitness \( \times \) Compatibility interaction \((F_{1,39} = 3.3, p = 0.08, \eta^2 = 0.06)\) for RT. However, there was a main effect for aerobic fitness on accuracy \((F_{1,39} = 10.0, p = 0.002, \eta^2 = 0.21)\), with higher fit children being more accurate than lower fit children, and a significant Aerobic fitness \( \times \) Compatibility interaction \((F_{1,39} = 6.7, p = 0.01, \eta^2 = 0.15)\). Post hoc analysis revealed a significant difference between compatible and incompatible conditions for the lower fit group \((p = 0.02)\) and between higher and lower fit groups in the incompatible condition \((p = 0.001)\).

Electrophysiological results

Fig. 1 shows the grand averaged ERP waveforms at the representative prefrontal (FPz), central (Cz), and parietal-occipital (PO8) sites, where the considered components were maximal. Before stimulus onset, a slow-rising negativity (pN) over the prefrontal regions was detectable and modulated by both aerobic fitness and compatibility. Indeed, the amplitude of the pN is larger in higher than lower fit children, and in the incompatible relative to the compatible condition. At the medial central site (Cz), the BP is also present, showing a slow-rising negativity that reflects motor readiness or preparation. The BP component looks similar regardless of aerobic fitness group or compatibility condition. After stimulus onset, another large component over the prefrontal cortex is detectable: the pP, whose delta amplitude (from the previous negative peak to the actual prefrontal positive peak) is not modulated by compatibility or aerobic fitness. Over parietal-occipital sites, the typical visual components of the ERPs, such as the P1, N1 and P2, can be observed with a voltage baseline in the typical early pre-stimulus period (from 200 to 0 ms). With respect to the P1 component, differences in amplitude can be observed as a function of aerobic fitness, whereas the differences in amplitude of the N1 and the P2 as a function of the considered variables are less pronounced.

Statistical analysis of the pN mean amplitude showed a main effect for aerobic fitness \((F_{1,39} = 4.4, p = 0.04, \eta^2 = 0.10)\), with larger pN amplitude in higher \((–7.0 \pm 1.5 \mu V)\) compared to lower fit \((–2.6 \pm 1.5 \mu V)\) children, and for compatibility \((F_{1,39} = 5.9, p = 0.02, \eta^2 = 0.13)\), with larger amplitude in the incompatible \((–5.5 \pm 1.1 \mu V)\) compared to the compatible \((–4.0 \pm 1.1 \mu V)\) condition. The ANOVA did not reveal a significant Aerobic fitness \( \times \)Compatibility interaction \((F_{1,39} = 2.5, p = 0.1, \eta^2 = 0.06)\). Statistical analysis of the BP mean amplitude did not yield significant results as a function of Aerobic fitness \((F_{1,39} = 0.8, p = 0.8, \eta^2 = 0.001)\), or Compatibility \((F_{1,39} = 1.3, p = 0.3, \eta^2 = 0.03)\), or their interaction \((F_{1,39} = 1.3, p = 0.3, \eta^2 = 0.03)\). Analysis of the delta pP amplitude did not indicate a main effect or interaction (all ps > 0.3).

While the analysis on the P1 latency did not indicate a significant effect, P1 amplitude indicated a main effect for Aerobic fitness \((F_{1,39} = 4.3, p = 0.04, \eta^2 = 0.09)\), with larger amplitude for higher \((13.8 \pm 1.5 \mu V)\) compared to lower fit \((9.4 \pm 1.5 \mu V)\) children. The P1 amplitude was affected by site \((F_{1,39} = 7.8, p = 0.007, \eta^2 = 0.16)\), with larger amplitude for PO8 \((12.8 \pm 1.1 \mu V)\) than PO7 \((10.3 \pm 1.1 \mu V)\).

Analysis of the N1 latency did not yield significant results. Although the N1 peak amplitude was not affected by Aerobic fitness \((F_{1,39} = 0.3, p = 0.6, d = 0.0)\), it was affected by Compatibility \((F_{1,39} = 5.3, p = 0.03, \eta^2 = 0.12)\), with larger amplitude in the incompatible \((–3.8 \pm 1.0 \mu V)\) compared to the compatible \((–2.6 \pm 1.0 \mu V)\) condition. Further, the interaction of Aerobic fitness \( \times \)Condition \( \times \)Site was significant \((F_{1,39} = 4.4, p = 0.04, \eta^2 = 0.10)\). In particular, Bonferroni post hoc analysis revealed larger N1 amplitude at the PO8 (mean amplitude \(–3.8 \pm 1.3 \mu V)\) relative to the PO7 (mean amplitude \(–2.6 \pm 0.8 \mu V)\) site in both compatible and incompatible conditions for both higher fit \((p = 0.005 \text{ and } p < 0.001, \text{ respectively})\) and lower fit \((p = 0.017 \text{ and } p < 0.001, \text{ respectively})\) children.

Analysis of P2 latency and amplitude did not yield significant results (all ps > 0.35).

Table 1. Mean and standard error (SE) of the response time (ms) and response accuracy (percent correct responses) as a function of Fitness and Compatibility

<table>
<thead>
<tr>
<th></th>
<th>Lower fit</th>
<th>Higher fit</th>
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<tr>
<td></td>
<td>Compatible condition</td>
<td>Incompatible condition</td>
</tr>
<tr>
<td>RT (mean ± SE)</td>
<td>532.0 ± 23.0</td>
<td>567.0 ± 30.0</td>
</tr>
<tr>
<td>Accuracy (mean ± SE)</td>
<td>79.9 ± 1.8</td>
<td>73.6 ± 2.6</td>
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</tbody>
</table>
Topographical maps

Three-dimensional topographical maps are displayed in Fig. 2. The maps in the top row show the negative activity over the prefrontal cortex in the -600/0 ms time window, known as pN, and the BP over medial central sites. The second row maps show the topography of the P1 over visual areas. The third row displays the maps for the N1 component, which is more laterally localized than the P1. The last row shows the maps for the P2 component, which is very strong in all of the conditions over bilateral parieto-occipital sites. No topographical differences can be appreciated in any component across Conditions and Aerobic fitness.

DISCUSSION

The present study investigated premotor neurocognitive and early perceptual processing in preadolescent children to further our understanding of the relation of cardiorespiratory fitness to cognitive function within the preparation–perception–action cycle. Specifically, the findings indicated that aerobic fitness was selectively related to larger pN and P1 amplitude as well as better task performance. On the whole, the results show that the benefits of being aerobically fit start early in the processing stream during the performance of a task that challenges cognitive control, with differences observed at the stage of cognitive preparation of the behavioral response before the onset of the stimulus that triggers the response.

The participants were administered a modified version of a flanker task, which requires modulation of cognitive control and specifically challenges perceptual interference and response inhibition. At the behavioral level, aerobic fitness was related to accuracy, with higher fit children being more accurate than lower fit children. No significant group differences were observed for response times. These findings confirm the sensitivity of accuracy in task performance to the aerobic fitness status of preadolescent children in tasks that require cognitive control (Hillman et al., 2009; Pontifex et al., 2011; see also Hillman et al., 2011 for a review).

The current findings add novel evidence to neurocognitive pathways through which cardiovascular fitness leads to increased performance on tasks requiring the flexible modulation of cognitive control processes. Previous studies have demonstrated that cardiovascular fitness leads to more efficient modulation of attentional resource allocation (i.e., P3 amplitude) to the task conditions at later stages of stimulus processing. The present findings indicate that aerobic fitness also modulates brain activity early in the processing stream, specifically at pre-stimulus stages of motor preparation and very early stages of visual stimulus processing.

Specifically, we focused on the activity over the prefrontal cortex and the motor-related brain regions before stimulus onset. This is a novel approach, because, to our knowledge, no prior studies have looked at the cognitive-motor preparation processing in this age group during flanker task performance. The only prior studies focused on the motor preparation during self-paced movements (Warren and Karrer, 1984a,b) and did not employ an individual difference approach to the study of fitness. Indeed, the authors could not detect the typical BP component, but they observed a monophasic positive waveform preceding movement in
preadolescents, whereas in younger children they showed a positive–negative–positive complex over the central sites starting 600–650 ms before the movement onset. We instead showed that the BP or readiness potential arising from the supplementary motor area is well detectable in this population and is similar in morphology to that of older participants obtained in different visuo-motor tasks (Berchicci et al., 2013, 2014; Sánchez-López et al., 2014), but it is not modulated by aerobic fitness in this specific task. However, a more recent study (Kamijo et al., 2011) found that increased cardiorespiratory fitness is associated with improvements in the cognitive control of working memory in preadolescent children in the phase that precedes target stimulus onset, as reflected in larger CNV over frontal areas. Nonetheless, the relationship between prefrontal brain activity preceding the stimulus and the motor onset and cardiovascular fitness in preadolescents during a cognitive-motor task is not clear yet.

The involvement of the prefrontal areas is particularly important when high-order stimulus–responses rules (as in the present task) are required (Bunge and Zelazo, 2006; Lamm et al., 2006; Moore et al., 2014; see Tau and Peterson, 2010 for a review); its activity has been associated with proactive inhibitory control through which a "no-go" state is maintained prior to stimulus presentation, and the motor system is released from inhibition only.

![Fig. 2. Three-dimensional topographical maps obtained in the time window of the considered components. The maps are displayed in the chronological order of the components from the top to the bottom (pN-BP, P1, N1, and P2), whereas the column of maps corresponds to the group.](image-url)
if there is sufficient evidence for action (Di Russo et al., 2013). Although the development of prefrontal brain function is still a matter of debate (Tsujimoto, 2008), present results show that the prefrontal control is already present in 10-year-old children and it is enhanced by aerobic fitness. We have observed aerobic fitness-related differences selectively at a site over the prefrontal cortex during response preparation, with larger pN amplitude in higher compared to lower fit children, indicating enhanced cognitive preparation for the response. The observed differences extend to preadolescent children, indicating modulation of this component as a function of age and aerobic fitness in young, middle-aged and older adults (Berchicci et al., 2013, 2014).

The aerobic fitness-related modulation of brain function as early as the premotor stage gives further support to the hypothesis, raised by Pontifex et al. (2011) and further developed by Voss et al. (2011), that higher fit children are more likely to engage in proactive cognitive control, while their lower fit counterparts engage a more reactive control strategy. Our results may extend this explanation by adding that higher fit children optimize behavioral responses (i.e., higher fit are more accurate than lower fit) during cognitive control performance proactively, by means of a phasic engagement of cognitive processes for motor preparation prior to the onset of the task-relevant stimulus (i.e., larger pN in higher than lower fit children). This proactive preparation that generalizes across task conditions would particularly benefit task performance in the more complex inconsistent condition (i.e., larger pN in incompatible than compatible stimulus–response condition). The utilization of this proactive, phasic preparation strategy is made possible by more efficient cognitive control brain networks.

We have further showed modulation of the early perceptual components (i.e., P1 and N1) after stimulus onset as a function of aerobic fitness, unfolding different cognitive control strategies before and, consequently, after stimulus presentation. Amplitude of the ERP components related to visual processing mechanisms (P1 and N1) may be influenced by various factors (Moore et al., 2014). Among these, cardiovascular fitness induced by physical activity benefits visual information processing already at early stages, as evidenced by the modulation of the P1 component. It seems that higher fit children are able to draw more attention to task-relevant stimuli, as reflected in larger P1 amplitude, while lower fit children demonstrate less allocation of attentional resources in response to task conditions requiring cognitive control, regardless of complexity, as suggested by smaller P1 amplitude. Further, the N1 peak amplitude was modulated by the complexity of the task. The N1 is thought to index discriminative processing of visual stimuli and is modulated by attention (Baines et al., 2011). The discriminative processes required by the incompatible condition are more effortful than those needed to accomplish the more simplistic compatible condition, justifying the larger amplitude of the N1 component during the more challenging incompatible condition.

Collectively, the present findings linking aerobic fitness to pre- and early post-stimulus components of the cognitive processing stream suggest that enhanced activity in the prefrontal brain areas may improve cognitive control in visuo-motor tasks allowing stronger proactive inhibition and greater allocation of selective attention on relevant external stimuli. These modulations in brain function could explain, in part, the beneficial relation of aerobic fitness to behavioral performance. In order to track qualitative and quantitative changes in functional brain circuitry across the life span, future research should collect data from older subjects (i.e., young and older adults) during the same task.

**CONCLUSION**

The present findings support the relevance of physical activity for the promotion of cognitive and brain health at a young age. Physical activity is a multidimensional behavior important for learning, enjoyment, social interaction and physiological health. The worldwide imbalance in the educational system in favor of sedentary learning at the expense of physical activity has implication not only for children’s physical health (Malina, 2013), but also for their cognitive and brain health. The consistent evidence of a positive relationship between physical activity, aerobic fitness, cognitive and brain function and, consequently, academic performance (Kwak et al., 2009; Donnelly and Lambourne, 2011; Tomporowski et al., 2011) should motivate policy makers to develop opportunities for increasing physical activity in the classroom and across the school day (Mahar et al., 2006).

**REFERENCES**


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