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Research article

The relationship between childhood aerobic fitness and brain functional connectivity

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HIGHLIGHTS

- We examined the association between childhood fitness and functional connectivity.
- Lower-fit and higher-fit children performed a visual search task.
- Functional connectivity was assessed using phase-locking values (PLVs).
- Higher fitness was associated with greater brain functional connectivity.

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ABSTRACT

Several studies have indicated that higher levels of childhood aerobic fitness is associated with superior cognitive function, and this association is disproportionately observed in tasks requiring greater top-down control. We designed the current study to clarify the relationship between childhood fitness and top-down control in terms of functional connectivity among brain regions, by evaluating phase-locking values (PLVs), which is a measure of frequency-specific phase synchrony between electroencephalographic signals during a visual search task. Lower-fit and higher-fit children performed a visual search task that included feature search and conjunction search conditions. The conjunction search condition required greater top-down control to reduce interference from task-irrelevant distractors that shared a basic feature with the target. Results indicated that higher-fit children exhibited higher response accuracy relative to lower-fit children across search conditions. The results of PLVs showed that higher-fit children had greater functional connectivity for the conjunction relative to the feature search condition, whereas lower-fit children showed no difference in functional connectivity between search conditions. Furthermore, PLVs showed different time courses between groups; that is, higher-fit children sustained upregulation of top-down control throughout the task period, whereas lower-fit children transiently upregulated top-down control after stimulus onset and could not sustain the upregulation. These findings suggest that higher levels of childhood aerobic fitness is related to brain functional connectivity involved in the sustained upregulation of top-down control.

1. Introduction

Higher levels of aerobic fitness have been associated with superior cognitive function in children [1,2]. Being physically active is known to be positively associated with aerobic fitness [3]. However, it is likely that aerobic fitness relates more strongly to childhood cognitive function than physical activity [4]. For example, it has been suggested that physical activity leading to increases in aerobic fitness during childhood plays a role in cognitive health and development [5,6]. These findings are important because of growing concerns about the epidemic of childhood inactivity [7,8]. Some studies have indicated that the positive association between childhood aerobic fitness and cognitive function is disproportionately observed in task conditions requiring greater top-down control [4,9–11]. Given that brain regions involved in top-down control have demonstrated protracted development relative to other regions associated with more basic functions [12], the strong relationship between aerobic fitness and top-down control appears

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to be reasonable. Top-down cognitive control is crucial for various aspects of an individual's life, such as success in school during childhood, as well as mental and physical health [13]. Therefore, the relationship between childhood fitness and top-down control need to be further elucidated. We designed the current study to investigate the relationship between childhood aerobic fitness and top-down control in terms of functional connectivity among brain regions, by evaluating phase locking values (PLVs) during a visual search task.

The visual search task consisted of two task conditions: feature search and conjunction search (Fig. 1A). In the feature search condition, distractors shared no feature with the target, whereas in the conjunction search condition, distractors shared one of two basic features with the target, either color or orientation. A conjunction search task requires greater top-down control to reduce interference from task-irrelevant distractors that share a basic feature with the target [14]. To investigate the mechanisms of top-down control in visual search tasks, Phillips and Takeda [15] assessed PLV, a measure of frequency-specific phase synchrony between electroencephalograms (EEGs) from two electrodes, that is considered to reflect long-distance functional connectivity between brain regions [16]. Phillips and Takeda [15] observed greater frontal-parietal PLVs during the conjunction search condition relative to the feature search condition, at a frequency band of 22–34 Hz. Similarly, a monkey study [17] demonstrated that the coherence of local field potentials between frontal and parietal regions was greater during a conjunction search task than a feature search task. A simulation of the neural mass model suggested that the 22–34 Hz frequency band reflects bidirectional information transfer between brain regions, which is assumed to be involved in top-down control [18]. Taken together, these studies suggest that PLVs at the frequency band of 22–34 Hz reflect top-down control. We previously examined the association between physical activity levels and top-down cognitive control using PLVs in young adults [19,20]. Results indicated that physically active individuals exhibited greater PLVs for task conditions requiring greater top-down control relative to physically inactive individuals, suggesting that higher levels of physical activity are related to greater functional connectivity among brain regions involved in top-down control. The present study is a novel examination of the association of physical activity/fitness and cognition in children by means of neuroelectric measures of top-down control.

We employed a cross-sectional design, comparing task performance measures and PLVs of lower-fit and higher-fit children during a visual search task. If childhood fitness is associated with top-down processes, higher-fit children should exhibit superior task performance (i.e., higher response accuracy and shorter reaction time, or RT) and greater PLVs for the conjunction search condition relative to their lower-fit peers, and this group difference should be smaller for the feature search condition.

2. Materials and methods

2.1. Participants

We recruited children aged between 10 and 14 years old from elementary and middle schools in Kanoya city (southwest Japan). The schools provided a list of children who were interested in participating, as well as information about the children's scores on a field test of aerobic capacity (i.e., Progressive Aerobic Cardiovascular Endurance Run, or PACER, also known as the 20-m shuttle run test). PACER was performed at the participants' schools approximately 4 months before the current experiment, according to the protocol of Leger, et al. [21]. The recorded score was the total number of laps completed, with a higher number of laps indicating a higher level of aerobic capacity.

Table 1
Mean (*SD*) values for participant demographics and fitness data.

Measure	Lower-Fit		Higher-Fit	
No. of participants	16	(8 girls)	16	(8 girls)
Age (years)	11.8	(1.0)	12.4	(1.2)
PACER (no. of laps)[a]	37.2	(9.4)	87.9	(19.7)
PACER (percentile)[a]	16.8	(9.2)	85.9	(10.1)
Body mass index (kg/m^2)	18.8	(2.5)	18.1	(1.9)
Body mass index (percentile)	56.7	(26.3)	42	(20.3)
Maternal education	2.4	(1.1)	3	(0.9)

Note: Maternal education was assessed using a five-point scale ranging from 1 (*did not complete high school*) to 5 (*earned an advanced degree*).
[a] Unpaired *t*-test, $p < .05$. PACER: Progressive Aerobic Cardiovascular Endurance Run.

A total of 38 children participated in this study. They were bifurcated into lower-fit and higher-fit groups on the basis of whether their PACER scores fell below the 30th percentile or above the 70th percentile of normative data provided by the Japanese Ministry of Education, Culture, Sports, Science and Technology [22]. Data from six participants were discarded due to incompletion of the visual search task, technical problems, or excessive noise in the EEG signal. Analyses were conducted for 16 lower-fit and 16 higher-fit children. Table 1 lists the participants' demographic and fitness information. Because socioeconomic status has been associated with cognitive function [23], we assessed maternal educational attainment as a proxy for socioeconomic status [24,25]. Except for the fitness measures, the other demographic measures did not differ between groups, $ts(30) \leq 1.8$, $ps \geq 0.09$. Prior to testing, legal guardians reported that their children were free of neurological diseases, attention disorders (≤80th percentile on the ADHD Rating Scale IV) [26], and physical disabilities, and all had normal or corrected-to-normal vision. None of the children received special education services related to cognitive or attentional disorders. All participants and their legal guardians provided written informed consent in accordance with the ethics committee of the National Institute of Fitness and Sports in Kanoya. We also asked participants to perform a source memory task in order to assess their memory function. Those data are beyond the scope of this paper and will be reported elsewhere.

2.2. Visual search task

Fig. 1A shows a schematic illustration of the sequence of events in the visual search task used in this study. Each trial consisted of four phases: fixation (1500 ms), target cue (1000 ms), second fixation delay (1000 ms), and search display (2500 ms). The display background was black, and the viewing distance was approximately 57.3 cm. The fixation was a filled white circle (visual angle 0.3° in diameter). During the target cue phase, a red or blue rectangular bar was presented horizontally or vertically at the center of the display. The four types of target cue (i.e., 2 colors × 2 orientations) were presented in a randomized order. The rectangular bar subtended 2.4° × 0.3°. During the search display phase, four rectangular bars (1 target and 3 distractors) were presented simultaneously at four locations (upper left, upper right, lower left, lower right). The target location was randomly changed from trial to trial. The center-to-center distances between two adjacent rectangular bars were constant (visual angle of 6°). This task required participants to identify the location of the target during the search display phase by pressing a key on the computer keyboard using their index or middle finger: A (upper left), K (upper right), Z (lower left), or M (lower right). Both speed and accuracy were stressed. Participants completed 80 trials in the feature search condition and 80 trials in