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Acute aerobic exercise alters executive control network in preadolescent children

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EL EJERCICIO AERÓBICO AGUDO ALTERA LA RED DE CONTROL EJECUTIVO EN NIÑOS PREADOLESCENTES

KEYWORDS: Acute aerobic exercise, preadolescent children, executive control network.

ABSTRACT: The present study aimed to investigate the effect of acute aerobic exercise on executive function (EF) and executive control network (ECN) in preadolescent children, and further explored the neural basis of acute aerobic exercise on EF in these children. We used a within-subjects design with a counterbalanced order. Nine healthy, right-handed children were scanned with resting-state functional magnetic resonance imaging and performed an EF task both in baseline session and exercise session. The exercise session was consisted of 30 minutes of aerobic exercise on a bicycle ergometer at 60% of their estimated maximum heart rate. Compared with the baseline session, acute aerobic exercise benefitted performance in the EF task, increased the functional connectivity between right dorsolateral prefrontal and left cerebellum, further, the increment of functional connectivity was negatively correlated with the EF' s behavioral performance change. These findings suggest that acute aerobic exercise enhances children's EF, and the neural basis may be related to functional connectivity changes in the ECN elicited by acute aerobic exercise.

Executive function (EF) lies at the core of cognitive function and plays a crucial role in children's learning, reasoning, problem solving, and intellectual activity (Diamond, 2013). Deficits in EF will seriously harm the development of children's physical, mental, and social achievements; conversely, individuals, local communities, and society will benefit from well-developed EF (Elliott, 2003; Zelazo, Carlson, and Kesek, 2008). Several studies have shown that EF is the result of the dynamic interactions of distributed brain areas operating in executive control networks (ECN) (Bressler and Menon, 2010; Duncan, 2013; Niendam et al., 2012).Behavioral findings have suggested that acute aerobic exercise improves children's EF (Chen, Yan, Yin, Pan, and Chang, 2014; Chang, Labban, Gapin, and Etnier, 2012; Li, O'Connor, O'Dwyer, and Orr, 2017). However, there is still very little knowledge about whether a single session of aerobic exercise can alter functional connectivity (FC) in ECN.

Therefore, we investigated the effect of acute moderate-intensity aerobic exercise on EF and ECN in preadolescent children, and further explored the neural basis of acute aerobic exercise on EF in these children.

Method

Participants

Nine healthy children in fifth grade (10 years old; 5 males, 4 females) were recruited through primary school advertising. They had normal or corrected-to-normal vision and were right-handed, as assessed by the Edinburgh Test (Oldfield, 1971). They also completed a set of questions about history of drug abuse or inherited disease and general intelligence (Wechsler Intelligence Scale for Children-IV-Chinese Version) (Zhang, 2009). Exclusions included any medical condition that would limit physical activity or affect study results (including neurological or psychiatric disorders). The study was conducted

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in accordance with the Declaration of Helsinki. The study protocol was approved by the Institutional Review Board of the Brain Imaging Center of the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University. Written informed consent was obtained from all participants and their legal guardians after experimental procedures were fully explained.

Aerobic exercise protocol

Exercise was performed on a bicycle ergometer (MONARK 834, Sweden) with moderate intensity, which has been shown to benefit children's cognition (Chen et al., 2014; Hillman et al., 2009). This study used 60–69% of the predicted maximal heart rate, defined as 220 minus age in years, to determine the exercise intensity target heart rate. Participants spent 2 min cycling to warm up, 30 min exercising at moderate intensity, and finally, 3 min cooling down at a self-determined pace. Heart rate was monitored in real time using a Polar heart rate monitor (RS800XSD, Finland) throughout the acute aerobic exercise protocol, which was led by the same instructor, one-on-one.

Flanker task

A modified Eriksen flanker task was employed to examine EF (Eriksen and Eriksen, 1974). This task has been found to be sensitive to acute exercise (Chen et al., 2014; Hillman et al., 2009). The flanker task involved two types of trials, congruent and incongruent. The congruent trials consisted of a horizontally arranged array of the same five letters (e.g., LLLLL or FFFFF); the incongruent trials consisted of a horizontally arranged array of five letters in which the middle letter was different (e.g., LLFLL or FFLFF). During the flanker task, the participant was asked to press the "F" or "L" with their left or right index finger, respectively, based on the middle letter presented in the trial. The total task duration was approximately 6 min. The response times in the congruent and incongruent trials were recorded and used to create an index of inhibition, defined as the response time difference between incongruent and congruent trials. Shorter response time differences reflected better performance.

Experimental Design and Procedures

This experiment had a completely within-subjects design. It was conducted in the Imaging Center for Brain Research at Beijing Normal University. During the first visit, participants and their legal guardians completed all paperwork, including written informed assent/consent, as previously described. Following paperwork completion, a flanker task practice was administered to each participant, and the experimenter checked their performances to ensure that the participants understood the task. If a participant's task performance was below 80% (ACC), the same practice was re-administered. In the formal experiment, all participants attended two sessions (i.e., baseline and exercise), with the order counterbalanced across participants at the same time on two separate days (a 7-day interval) in which they had not participated in physical education or other structured physical activity. Half participants received the baseline session on the first day and the exercise session on the second day. The other half received the exercise session on the first day and the baseline session on the second day. The baseline session consisted of 30 min of seated rest, during which all participants were fitted with a heart rate monitor and their resting heart rates were recorded. Following the seated rest period, participants were scanned with resting state-fMRI, and then completed a flanker task. The exercise session consisted of a 30-min rest, with the resting heart rate recorded, and an acute aerobic exercise protocol during which HR was recorded in real time. Following the completion of the acute aerobic exercise protocol, once participants' HRs returned to within 10% of their resting heart rate levels, the flanker task was performed after resting state-fMRI scanning. Upon completion of both sessions, participants and their legal guardians received fair remuneration for their involvement in the experiment.

Functional MRI Data Acquisition and image processing

Participants were scanned for the whole brain by a 3T Siemens Magnetom Trio system with total imaging matrix in the Imaging Center for Brain Research, Beijing Normal University. Functional images were obtained using an echo-planar imaging (EPI) sequence, with the following scan parameters: TR = 2,000 ms, TE = 30 ms, gap = 1 mm, FA = 90°, slice thickness = 3.0 mm, FOV = 200 × 200 mm, and inplane resolution = 64 × 64. Resulting data included 148 brain volumes with 33 axial slices. During the fMRI scans, all participants were instructed to stay relaxed and move as little as possible. Structural images were acquired using a magnetization-prepared rapid gradient echo, three-dimensional T1-weighted sequence (TR = 2000 ms, TE = 3.39 ms, T1 = 1100 ms, FA = 7°, thickness = 1.33 mm, FOV = 200 × 200 mm, acquisition matrix = 256 × 256).

Image processing and analysis

Functional image preprocessing and statistical analyses were conducted with DPABI (http://rfmri.org/dpabi), based on SPM8. The first ten volumes of functional images were discarded and subsequent functional images underwent the following preprocessing steps: slice-timing correction, realignment, co-registration, New Segment +DARTEL with high-resolution structural scans and smoothed. No participant included in this study exhibited head motion of more than 2.0 mm maximum translation and 2.0° rotation throughout the pre-training and post-training scans. Detrending and filtering was performed to reduce the effects of low-frequency drifts and high-frequency physiological noise. We also regressed out several sources of artifacts including the six head-motion profiles, global signal, white matter signal, and cerebrospinal fluid signal.

ROI selection

An ECN has been shown to have separable right and left hemisphere components (Shirer, Ryali, Rykhlevskaia, Menon, and Greicius, 2012). Thus, left executive control network (LECN) and right executive control network (RECN) templates were downloaded from Stanford's Functional Imaging in Neuropsychiatric Disorders lab (http://findlab.stanford.edu/functional ROIs.html). We selected ROIs from their templates: prefrontal cortex, parietal cortex, temporal cortex and basal ganglia (see Figure 1). Functional connections among different ROIs were analyzed in the left and right ECNs, separately. The connections between left and right ECNs and the FC among all ROIs were also calculated. For each ROI, a representative BOLD time course was obtained by averaging the signal of all the voxels within the ROI.

Data analysis

First, behavioral improvements in RT and Acc for Flanker task across the two sessions were analyzed by paired t-test with SPSS. Second, functional connectivity changes elicited by acute aerobic exercise were analyzed. We conducted a paired t-test on the z-FC images between two sessions (baseline and exercise).Third, we calculated the Pearson’s correlation coefficient (r) between the time course of the seed and the time series of each voxel across the whole brain. After a Fisher's r-to-z transformation of correlation coefficient maps to z maps, a voxel-wise one-sample t-test (P < 0.05, AlphaSim corrected) was performed to generate the functional connectivity map of the ECN ROI, both before and after exercise between both sessions.

Results

Acute aerobic exercise-related behavioral performance differences

The analysis for RT indicated a significantly positive effect, t（8）=7.50，P<0.05，r^2_{pb}=0.88, with shorter RT for exercise session (M =12.78, SE = 2.45) relative to baseline session (M =22.78, SE = 3.04).

Acute aerobic exercise-related connectivity changes

We calculated the functional connectivity between twelve regions in ECNs, and applied a paired t-test to examine the exercise effect on each of the one hundred and forty-four connectivity pairs (uncorrected, P<0.05). Results revealed a significant increment for the connectivity between left dorsolateral prefrontal-right dorsolateral prefrontal, t(8)=-2.46，P=0.039, left dorsolateral prefrontal-right inferior parietal lobule, t(8) = -3.73，P=0.006, left Inferior frontal gyrus-right caudate nucleus, t(8)= -4.85，P=0.001, left middle temporal gyrus-right caudate nucleus, t(8)= -2.65，P=0.029, left Inferior parietal lobule-right caudate nucleus, t(8)= -2.72，P=0.026, right cerebellum-right Inferior frontal gyrus, t(8)= -3.26，P=0.012, right cerebellum-right caudate nucleus, t(8)= -2.35, P=0.047 and a significant decrement for the connectivity between left thalamus-right inferior frontal gyrus, t(8)= -2.54，P=0.035.

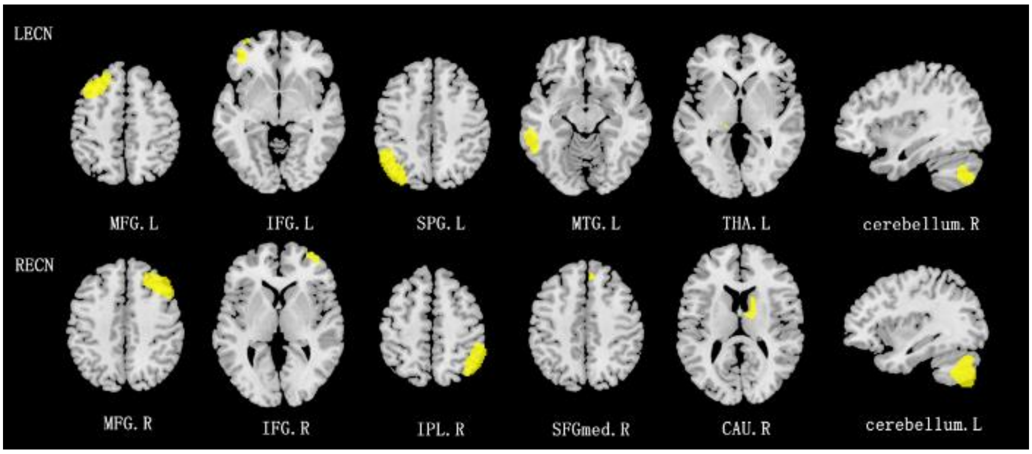
Correlations between acute aerobic exercise-related connectivity increment and behavioral improvements

The result demonstrated that higher functional connectivity levels in the left cerebellum-right inferior frontal gyrus at exercise session correlated significantly with better performance on the EF(r= -0.68, P=0.043) in all subjects(see Figure 2).

Discussion

This study investigated the effect of acute aerobic exercise on EF and ECN in preadolescent children, and further explored the neural basis of acute aerobic exercise on EF in these children. As above results indicated that children’s flanker task performance in the exercise session was better than in the baseline session—in agreement with previous studies. Accordingly, the present behavior results have been again verified: acute aerobic exercise beneficially enhances children’s EF. Then, the FC results revealed both significant increment and decrement for the connectivity in children’s ECNs. These results are fully consistent with our prediction that a single session of exercise significantly altered children’s connectivity in ECNs. Similarly, a recent study suggested that significant increment on connectivity in sensorimotor-related brain networks after acute aerobic exercise in young healthy adults (Rajab et al., 2014). Additionally, we found that greater functional connectivity in the left cerebellum-right inferior frontal gyrus, the better performance on EF in exercise session. At this point, we speculate on the neural basis of EF enhancement induced by acute aerobic exercise is the functional reorganization in ECNs.

These data extend the current knowledge by indicating that acute aerobic exercise enhances children' s EF, and the neural basis may be related to FC changes in the ECNs elicited by acute aerobic exercise.



Note: Left Middle Frontal Gyrus, MFG.L, Left Inferior Frontal Gyrus, IFG.L, Left Superior Parietal Gyrus, SPG.L, Left Middle Temporal Gyrus, MTG.L, Left Thalamus, THA,L, Right Middle Frontal Gyrus, MFG.R, Right Inferior Frontal Gyrus, IFG.R, Right Superior medial Frontal Gyrus, SFGmed.R, Right Caudate nucleus, CAU.R.

Figure 1. ROIs in the left and right ECNs

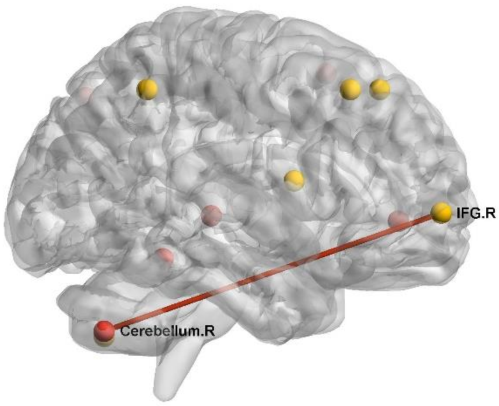


Figure 2. Functional connectivity between right cerebellum and right inferior frontal gyrus

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PALABRAS CLAVE: Ejercicio aeróbico agudo, preadolescentes, red de control executivo.

RESUMEN: El objetivo de esta investigación es estudiar la influencia del ejercicio aeróbico agudo en la función ejecutiva (EF) y la red de control ejecutiva (REC) en niños preadolescentes, además explorar la base neutral de estos ejercicios aeróbicos en los niños. Hemos utilizado un diseño de orden equilibrado. Nueve niños diestros saludables fueron escaneados con resonancia magnética funcional y se llevaron a cabo tareas de EF, sesiones de ejercicio y sesiones de medición basal. Comparado con las sesiones de base, la sesión de ejercicio consistió en 30 minutos de ejercicios aeróbicos en bicicleta ergométrica al 60% del ritmo cardiaco máximo estimado. Comparado con la sesión basal, el ejercicio aeróbico agudo benefició el desempeño en la tarea EF, aumentó la conectividad funcional entre el prefrontal dorsolateral derecho y el cerebelo izquierdo, además, el incremento de conectividad funcional se correlacionó negativamente con el cambio en el comportamiento del EF. Los resultados de estos estudios demuestran que el ejercicio aeróbico agudo refuerza, y puede provocar ciertos cambios.

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