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Positive effect of acute mild exercise on executive function via arousal-related prefrontal activations: An fNIRS study

Kyeongho Byun [a], Kazuki Hyodo [a], Kazuya Suwabe [a], Genta Ochi [a], Yosuke Sakairi [b], Morimasa Kato [c], Ippeita Dan [d], Hideaki Soya [a,*]

[a] Laboratory of Exercise Biochemistry and Neuroendocrinology, Faculty of Health and Sports Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8574, Japan
[b] Laboratory of Sports Psychology, Faculty of Health and Sports Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8574, Japan
[c] Department of Health and Nutrition, Yamagata Prefectual Yonezawa Women's Junior College, Yonezawa 992-002, Japan
[d] Applied Cognitive Neuroscience Lab., Research and Development Initiatives, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan

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A B S T R A C T

Despite the practical implication of mild exercise, little is known about its influence on executive function and its neural substrates. To address these issues, the present study examined the effect of an acute bout of mild exercise on executive function and attempted to identify potential neural substrates using non-invasive functional near-infrared spectroscopy (fNIRS). Twenty-five young individuals performed a color-word matching Stroop task (CWST) and a two-dimensional scale to measure changes of psychological mood states both before and after a 10-minute exercise session on a cycle ergometer at light intensity (30% VO_{2peak}) and, for the control session, without exercise. Cortical hemodynamic changes in the prefrontal area were monitored with fNIRS during the CWST in both sessions. The acute bout of mild exercise led to improved Stroop performance, which was positively correlated with increased arousal levels. It also evoked cortical activations regarding Stroop interference on the left dorsolateral prefrontal cortex and frontopolar area. These activations significantly corresponded with both improved cognitive performance and increased arousal levels. Concurrently, this study provides empirical evidence that an acute bout of mild exercise improves executive function mediated by the exercise-induced arousal system, which intensifies cortical activation in task-related prefrontal sub-regions.

Introduction

There has been an increasing interest in the beneficial influence of physical activity on cognitive brain functions especially in executive function. Recent studies have shown that chronic exercise can not only lead to structural changes of the brain (Colcombe et al., 2006; Erickson et al., 2011; Hillman et al., 2008), but also lower the risks of age-related cognitive decline and neurological diseases later in life (Lautenschlager et al., 2008; Rovio et al., 2005; Verghese et al., 2003). These positive effects of chronic exercise have brought about an increase in research interest into the acute effects of exercise on cognition and brain function.

It has been reported that exercise leads to increase an arousal response in proportion to exercise intensity. Exercise-induced arousal affects the physiological and psychological states of being awake, which is thought to involve the activation of the reticular-activating system (RAS), regulating ascending projections to the prefrontal cortex in the brain (Audiffren et al., 2008; Kahneman, 1973; Sanders, 1983). Several studies have reported that these arousal-induced neuromodulatory responses occur in the nervous system (Chaouloff, 1989; Meeusen and De Meirleir, 1995). When it comes to increased arousal, cognitive performance is expected to improve to an optimal point, after which further exercise would cause neural noise and hence a decline in the performance (Hockey et al., 1986; Humphreys and Revelle, 1984; Kahneman, 1973; Sanders, 1983; Yerkes and Dodson, 1908).

Based on this theoretical concept for acute exercise–cognition interaction, the majority of studies have focused on the effects of moderate-intensity exercise on cognitive function in young adults. Many studies have revealed facilitative effects of exercise on executive information processing (Ferris et al., 2007; Kamijo et al., 2004, 2007; Yanagisawa et al., 2010), and, uncommonly, that high-intensity but intermittent exercise has a beneficial impact on learning or attention in physically active students (Budde et al., 2012; Winter et al., 2007). However, a routine of relatively high intensity exercise is often difficult to maintain: the intensity of exercise has been found to negatively correlate with adherence to a long-term exercise program in several studies (Cox et al., 2003; Duncan et al., 2005; Jones et al., 2010; Lee et al., 1996). It would further be expected that physically inactive people in the modern

* Corresponding author at: Laboratory of Exercise Biochemistry and Neuroendocrinology, Faculty of Sports and Health and Sports Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8574, Japan. Fax: +81 29 853 2620.
E-mail address: hsoya@taiiku.tsukuba.ac.jp (H. Soya).

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era may be reluctant to participate in any type of regular exercise with a relatively high intensity and volume.

From a practical perspective, mild exercise might be more attractive to both young and old adults who have a sedentary lifestyle, which is known to increase the risk of cognitive decline and neurological diseases (Rovio et al., 2005; Weuve et al., 2004). Interestingly, recent studies have reported that long-term interventions with mild-intensity exercise have had beneficial effects on cognitive function, as have those with moderate-intensity exercise (Hassmén et al., 1992; Ruscheweyh et al., 2011; Stevenson and Topp, 1990). In addition, several animal studies have reported that mild exercise is sufficient for enhancing hippocampal neuronal activities (Soya et al., 2007) and functions, such as neurogenesis and spatial memory, without a stress response (Carro et al., 2001; Okamoto et al., 2012).

Moreover, there has been an increasing amount of evidence that extracellular acetylcholine, known as a neurotransmitter that helps mediate arousal, attention, and sleep, is released in the cerebral cortex during exercise with a relatively light-intensity, such as walking (Kimura et al., 1994; Kurosawa et al., 1993), and these cholinergic modulations improve cognitive functions through enhanced task-related neural activity (Furey et al., 2000; Kukolja et al., 2009). Thus, it is also interesting to examine whether an acute bout of mild exercise leads to increased arousal levels, which may, in turn, mediate improved executive function. However, despite its likelihood, there has been no experimental evidence provided for the positive effects of an acute bout of mild exercise on cognitive and brain functions.

Executive function refers to higher cognitive functions related to adequate planning, judgment, decision-making, anticipation or reasoning, and plays a critical role in wellbeing (Funahashi, 2001). It has been found that exercise is effective in improving executive performance in various tasks, including decision-making tasks (McMorris et al., 1999) and inhibitory control tasks (Hyodo et al., 2012; Kamijo et al., 2004, 2007; Yanagisawa et al., 2010). Among various tasks, the color-word matching Stroop task (CWST) is widely used in experimental and clinical settings to measure executive brain functions localized in the prefrontal cortex (MacLeod, 1991; Stroop, 1935). The CWST requires subjects to shift cognitive attention onto the color in which the word appears, suppressing the automatic response of reading the meaning of the word. Behavioral performance in the Stroop task is usually measured by comparing the delayed reaction time that occurs when a subject names a color in the incongruent condition (e.g., the word “BLUE” printed in red ink) with that of the neutral condition (e.g., the word “XXXX” printed in blue ink), and this time delay is referred to as Stroop interference. Extending the findings of former studies, we postulated that an acute bout of mild exercise may also improve Stroop performance, reflecting improved executive functions.

In response to the Stroop interference effect, many neuroimaging studies with functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have reported specific brain activation in the anterior cingulate cortex (ACC) and lateral prefrontal cortex (LPFC) (Egner and Hirsch, 2005; Leung, 2000; MacDonald, 2000; Pardo et al., 1990; Taylor et al., 1997; Zysset et al., 2001). Although these apparatuses allow the investigation of deeper brain activation during a cognitive task, due to their constrained measuring environments they are not suitable for assessing transient exercise-induced cortical activation. In contrast, multichannel functional near-infrared spectroscopy (fNIRS) is easy to install and handle in a gym (Timinkul et al., 2008), allowing subjects to perform tasks in a natural and comfortable environment without considerable delay after exercising. Recent studies using fNIRS have revealed a neural substrate for acute moderate exercise induced improvement of cognitive function: cortical activation in the left dorsolateral PFC in young adults (Yanagisawa et al., 2010) and the right frontopolar area (FPA) in older adults (Hyodo et al., 2012) was associated with improved Stroop performance, representing executive functions of the brain.

Hence, in this study, we examined whether mild-exercise-induced cortical activation may have a critical role in improved executive performance by monitoring changes in LPFC activation in response to Stroop interference using event-related multichannel fNIRS. Moreover, we assessed the relationship among psychological state changes, acute mild exercise induced Stroop performance, and cortical activation. By examining these factors together, we aimed to explore the possible effects of an acute bout of mild exercise on executive function, and their neural substrate.

Materials and methods

Subjects

Twenty-five right-handed subjects participated in the study (mean age 20.6 ± 1 years [range 19 to 25 years]; 12 females). All subjects were Japanese native speakers, healthy, and naive to the experimental procedures for which they had volunteered. No subject reported a history of neurological or psychiatric disorders, or had a disease requiring medical care. All subjects had normal or corrected-to-normal vision and normal color vision. Written consent was obtained from all subjects. Ethical clearance for the study was obtained from the Institutional Ethics Committee of the University of Tsukuba. The study conformed to the ethical requirements of the latest version of the Helsinki Declaration.

Experimental procedure

The overall procedures consisted of three major steps. First, maximal oxygen uptake (VO_{2peak}) was measured to determine the appropriate individual intensity for mild exercise, which was defined as 30% of a subject's VO_{2peak} based on the classification of physical activity intensity of the American College of Sports Medicine (ACSM et al., 2010). Second, physiological signals derived from non-cortical regions were measured to determine the timing of fNIRS measurements to eliminate possible contaminations. Finally, two main sessions, control (Con) or exercise (Ex) were conducted with a counterbalanced measure design on different days. Details of the two preliminary steps are presented in the Supplementary material. All subjects attended Con and Ex experiments with the order being counterbalanced across subjects (Fig. 1A). In the Ex condition, subjects conducted the CWST before and 5 min after the

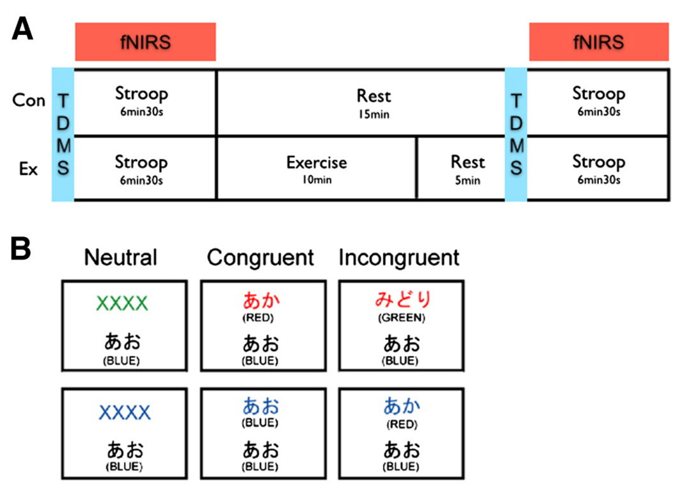

Fig. 1. (A) Experimental design, consisting of the exercise (Ex) and control (Con) conditions. Cortical hemodynamic changes were monitored with functional near-infrared spectroscopy (fNIRS) while subjects performed the Stroop task. (B) Illustration of the color-word matching Stroop task. Examples of single trials for the neutral, congruent, and incongruent conditions of the color-word matching Stroop task are exemplified. The presented letters were written in Japanese. Translations into English are denoted in parentheses.

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