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Effects of a Single Bout of Exercise-Induced Fatigue on Executive Function in Male College Students

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Abstract: Objective: To investigate the effects of a single bout of exercise-induced fatigue on executive function in male college students, so as to provide theoretical support for the physical and mental health development of college students and the improvement of their learning outcomes. Methods: A within-subject pre-/post-fatigue design was adopted. Thirty male college students were recruited. Fatigue was induced on a treadmill while participants wore a Polar H9 heart rate strap for real-time heart rate monitoring. The Stroop task, 2-back task and More-odd shifting task were used to measure the reaction time and accuracy of the three sub-functions of executive function (inhibition, updating and shifting) before and after fatigue. Results: After a single bout of exercise-induced fatigue, the reaction times of inhibition and updating in male college students decreased significantly ($P<0.05$) and their accuracy increased significantly ($P<0.05$), whereas the reaction time of shifting decreased significantly ($P<0.05$) with no difference in accuracy ($P>0.05$). After fatigue, the standardized negative increments in reaction time differed significantly among the three sub-functions ($F=1.342$, $P<0.05$), while the increments in accuracy did not ($F=0.141$, $P>0.05$). Post hoc multiple comparisons showed that the standardized negative increment in reaction time for updating was significantly greater than that for shifting ($P<0.05$) and inhibition ($P<0.05$). Conclusion: A single bout of exercise-induced fatigue can improve the level of executive function in male college students, simultaneously enhancing both the processing speed and processing quality of inhibition and updating, while enhancing only the processing speed of shifting. In addition, the improvement in the processing speed of updating induced by a single bout of exercise-induced fatigue is greater than that of inhibition and shifting.

Keywords: Fatigue; Executive Function; Male College Students

1. Introduction

Executive function is a higher-order cognitive ability, referring to the cognitive processes that consciously control thoughts and behaviors[1], and mainly comprises three components: inhibition, updating and shifting. Inhibition is the ability of an individual to ignore irrelevant stimuli while pursuing a cognitively represented goal[2]; updating is a limited-capacity system for temporarily processing and storing information[3]; and shifting means that an individual can flexibly adjust his or her thinking to meet the demands of new problems or situations[3]. In fact, executive function plays a key role in the learning process of college students, and a high level of executive function is usually positively correlated with good learning outcomes[4].

With the deepening of modern health concepts, the promoting effect of exercise interventions on cognitive function has become a research hotspot at the intersection of exercise science and cognitive neuroscience. Executive function, as a core component of human higher-order cognitive abilities, plays a key role in complex cognitive activities such as goal-directed behavior, emotion regulation and problem solving. Of particular note, college students in early adulthood are going through a critical stage of brain development, and the myelination of their prefrontal cortex is not yet fully mature, which gives research on the plasticity of executive function in this population special academic value and practical significance. In recent years, researchers have begun to focus on the immediate effects of acute exercise on cognitive function; however, many research gaps remain regarding the relationship between single bout exercise-induced fatigue and executive function, which urgently need further exploration.

Early research on exercise and cognition mostly focused on the cumulative effects of long-term regular exercise. Long-term aerobic exercise can significantly improve executive function in older adults, especially inhibitory control and task-switching abilities. With advances in experimental techniques, researchers have gradually turned to the immediate effects of a single exercise session. Moderate-intensity acute exercise can improve working memory performance within 60 minutes after exercise, whereas high-intensity exercise may have negative effects on cognitive function due to accumulated fatigue. This finding has prompted in-depth discussion of the "exercise intensity threshold"; however, existing studies have mostly focused on children or older adults, and insufficient attention has been paid to young college students, who are at a special stage of brain development.

In recent years, universities have fully implemented the National Fitness Program, and studying after exercise-induced fatigue has become a common healthy lifestyle phenomenon among college students who balance work and rest. Exercise-induced fatigue is a protective response mechanism of the human body during exercise training[5], and is also a basic requirement for producing training effects. Previous studies have mostly explored the effects of exercise on executive function in terms of exercise type, duration and intensity[6, 7], and few studies have examined the effects on college students' executive function from the perspective of exercise-induced fatigue. Running is the simplest and most effective form of exercise for college students, and it is also the most frequently chosen exercise in their self-directed workouts[8]. Therefore, this study fully simulated the actual situation of college students' daily exercise and study, designed a treadmill model to induce fatigue in male college students, and explored the effects of a single bout of exercise-induced fatigue on their executive function, so as to provide theoretical support for the physical and mental health development of college students and the improvement of their learning outcomes.

In this study, "single bout of exercise-induced fatigue" is defined as a temporary state of physical and mental fatigue induced by a single structured exercise protocol, operationally defined as a post-exercise heart rate reserve (HRR) of 75%–85% and a rating of perceived exertion (RPE) score ≥16 (Borg, 1982). Executive function was measured multidimensionally based on the three-component model of Miyake et al. (2000), using the Stroop task (inhibition), the 2-back task (updating) and the More-odd shifting task (shifting).

2. Participants and Methods

2.1 Participants

G*Power 3.1 software was used to calculate the required sample size. With ANOVA as the statistical method and parameters set at =0.3, α=0.05,, calculation according to the formula indicated that at least 28 participants were required. From April to July 2024, 30 male undergraduate students with exercise habits were recruited at Guangxi Normal University in Guilin as participants, aged (21.18±3.21) years. Inclusion criteria: in good health; normal uncorrected or corrected vision; no color blindness or color weakness; no acute or chronic diseases, and no history of upper- or lower-limb injuries or medication within the past year; and exercising 3–5 times per week. Before the experiment, participants avoided strenuous exercise, staying up late and excessive drinking, and maintained good physical condition. The study was approved by the Human Ethics Committee of Guangxi Normal University (approval No.: 20240422001). All participants signed written informed consent before participation.

Table 1. Participant Characteristics

Number (n)	Age (y)	Height (m)	Body mass (kg)
30	21.18±3.21	1.74±6.32	70.43±7.26

2.2 Experimental Instruments

2.2.1 Executive Function Tests

A within-subject pre-/post-fatigue controlled design was adopted. The test tasks for inhibitory control, cognitive flexibility and working memory updating were programmed with E-Prime 2.0 software, which automatically recorded reaction time and accuracy. A double-blind crossover design was used to eliminate learning effects. Fatigue was induced on a treadmill while participants wore a Polar H9 heart rate strap for real-time heart rate monitoring, and the Stroop task, 2-back task and More-odd shifting task were used to measure the reaction time and accuracy of the three sub-functions of executive function (inhibition, updating and shifting) before and after fatigue.

2.2.1.1 Stroop Task (Inhibition)

The Stroop task is widely used to measure inhibition; it is simple and easy to understand, and its results are accurate and reliable[9]. First, the participant sat in front of the test computer with both hands on the keyboard, and a "+" fixation cue appeared at the center of the screen before the test began. Then, in the formal test, four stimulus images appeared irregularly at the center of the screen every 1000–1500 ms: the word "red" in red, the word "green" in red, the word "red" in green, and the word "green" in green. After each stimulus image, a blank image appeared randomly within 1000–2000 ms. When the ink color and the word meaning on the screen were inconsistent, the participant pressed the "J" key; when they were consistent, the participant pressed the "F" key. The test consisted of 15 practice trials and 80 formal trials. The procedure is shown in Figure 1.

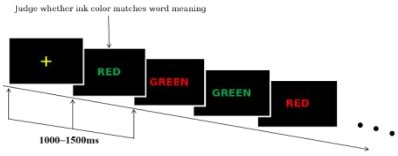

Figure 1. Inhibition Test: Stroop Task

2.2.1.2 More-odd Shifting Task (Shifting)

The More-odd shifting task is a mainstream paradigm for testing cognitive flexibility[10]. In this test phase, a digit from 1 to 9 (excluding 5) appeared randomly and individually at the center of the computer screen every 2000 ms, and participants were required to make magnitude, parity or mixed judgments on the digits and press the key as quickly as possible. According to the content, the test was divided into parts A, B and C, corresponding to magnitude judgment, parity judgment and mixed magnitude–parity judgment, respectively. In part A, red digits appeared: participants pressed "J" for digits greater than 5 and "F" for digits less than 5. In part B, green digits appeared: participants pressed "J" for even digits and "F" for odd digits. In part C, red or green digits appeared randomly: a parity judgment was made for green digits and a magnitude judgment for red digits. The test followed the ABCCBA sequence, with 16 trials each for A and B and 32 trials for C. The practice test included 8 trials each for parts A and B and 80 trials for part C. The procedure is shown in Figure 2.

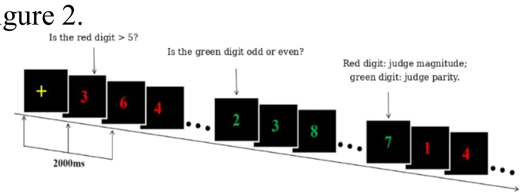

Figure 2. Shifting: More-Odd Shifting Task

2.2.1.3 2-back Task (Updating)

The 2-back task is a highly reliable experimental paradigm[11] and is currently widely used to study updating and its cognitive neural mechanisms[12]. In this test phase, digit images from 1 to 9 appeared randomly and individually at the center of the computer screen every 1500 ms. Starting from the third digit image, participants judged whether the current digit was the same as the digit presented two positions earlier, pressing "J" if different and "F" if the same, and so on. The test consisted of 15 practice trials and 80 formal trials. The procedure is shown in Figure 3.

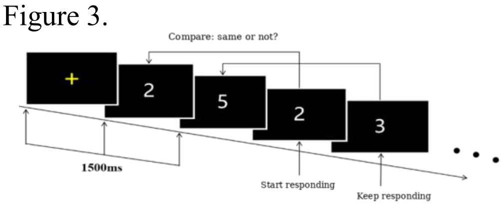

Figure 3. Updating Test: 2-Back Task

2.2.2 Fatigue Induction and Definition

A treadmill (Phantom X1, Zhejiang Merach Technology Co., Ltd., China) and a heart rate monitor chest strap (H9, Polar, Finland) were used to implement the fatigue induction protocol and monitor the exercise load. The treadmill fatigue model designed by Gordon was adopted: the initial incline was 0 and the speed was 5 km/h; the incline was then increased by 2% every 2 minutes until it reached 14%, after which it was no longer increased, with the speed kept constant during this period. The speed was then increased by 0.5 km/h every minute until the participant was exhausted and could no longer maintain the current speed[13]. Fatigue was defined using heart rate and the rating of perceived exertion scale, and was determined when the participant met either of the following conditions: 1) RPE reached level 17 (very hard) or above[14]; 2) heart rate reached 85% of the maximum heart rate (220 − age)[15].

2.3 Statistical Methods

SPSS 27.0 software was used for statistical analysis. Measurement data were tested with Bartlett's test for homogeneity of variance and the Kolmogorov–Smirnov test for normality; all were confirmed to be normally distributed with homogeneous variances and are expressed as mean ± standard deviation ($\bar{x}$±s). Paired-samples t-tests were performed on the differences in reaction time and accuracy of inhibition, updating and shifting before and after fatigue, and one-way ANOVA was used to analyze the differences in the increments of each sub-function before and after fatigue. The level of statistical significance was set at α=0.05. The increments in reaction time and accuracy of each sub-function before and after fatigue were standardized using the following formula:

$$\frac{\text{Standardized RT/}}{\text{accuracy increment}} = \frac{\text{Post} - \text{fatigue} - \text{Pre} - \text{fatigue}}{\text{Pre} - \text{fatigue}}$$

3. Results

3.1 Changes in Executive Function Before and After Fatigue

Paired-samples t-tests (Table 2) showed that, after fatigue, the reaction times of inhibition and updating were shorter than before fatigue (t=-2.214, P=0.046; t=-4.435, P<0.001), and their accuracy was higher than before fatigue (t=2.311, P=0.031; t=4.029, P<0.001). The reaction time of shifting after fatigue was shorter than before fatigue (t=-3.498, P=0.004), but, differently, there was no difference in accuracy (t=0.533, P=0.589). These results indicate that a single bout of exercise-induced fatigue can simultaneously improve the processing speed and processing quality of inhibition and updating in male college students, while improving only the processing speed of shifting.

Table 2. Differences in Executive Function Before and After Fatigue ($\bar{x}$±s)

Pre/post fatigue	Inhibition reaction time (ms)	Inhibition accuracy (ms)	Updating reaction time (ms)	Updating accuracy (ms)	Shifting reaction time (ms)	Shifting accuracy (ms)
Pre-fatigue	679.470±49.512	0.918±0.052	889.611±148.744	0.879±0.042	731.597±111.698	0.891±0.076
Post-fatigue	649.224±68.116	0.946±0.041	773.571±157.623	0.906±0.031	686.331±99.041	0.908±0.129
T value	-2.213	2.311	-4.435	4.029	-3.498	0.533
P value	0.046	0.031	<0.001	<0.001	0.004	0.589

3.2 Comparison of Changes in Executive Function Before and After Fatigue

One-way ANOVA (Table 3) showed that the standardized negative increments in reaction time of inhibition, updating and shifting before and after fatigue differed significantly (F=1.341, P=0.025, η2=0.179), whereas the increments in accuracy did not (F=0.141, P=0.081, η2=0.126). Post hoc multiple comparisons showed that the standardized reaction time increment of updating before and after fatigue was significantly greater than that of shifting (P=0.03) and inhibition (P=0.01). These results indicate that a single bout of exercise-induced fatigue improves the processing speed of updating in male college students more than that of inhibition and shifting, while having no differential effect on processing quality among the sub-functions.

Table 3. Changes in Executive Function Increments Before and After Fatigue ($\bar{x}$±s)

Executive function	Pre/post fatigue Negative increment in reaction time	Pre/post fatigue Increment in accuracy
Inhibition	0.041±0.018	0.032±0.011
Updating	0.132±0.029	0.034±0.010
Shifting	0.059±0.013*	0.030±0.009
F value	1.342	0.141
P value	0.025	0.081

Note: "*" indicates a significant difference between adjacent means (p<0.05), marked on the smaller value.

4. Analysis and Discussion

A single bout of exercise-induced fatigue can improve the processing speed and processing quality of inhibition and updating in male college students, while improving only the processing speed of shifting. In executive function, reaction time represents the processing speed with which an individual completes a task, i.e., the operating speed, and reflects the individual's level of attention. A shorter reaction time means that the individual can focus more intently, quickly notice key information and respond rapidly during task performance. Accuracy represents the precision with which an individual completes a task, i.e., the operating quality, and reflects the individual's thinking and judgment ability during task performance. Higher accuracy indicates that the individual maintains a high level of thinking during the task and avoids errors. Studies have found that exercise-induced fatigue triggers a stress response in the human body, causing sharp fluctuations in the concentrations of neurochemicals such as brain-derived neurotrophic factor, catecholamines and cortisol; when the levels of these substances rise within a certain range, they facilitate cognitive tasks[16]. In addition, the rise in body temperature after fatigue promotes blood circulation and oxygen delivery to the brain, which helps increase cerebral metabolic activity and neuronal activity, placing the brain in a more alert and active state and facilitating executive function tasks[17]. Ferris et al. found that inhibition improved in Stroop task tests performed by college students after exhaustive exercise[18]. Liu Jianju et al. found that after a single bout of exercise, the reaction time of updating in children and adolescents decreased and accuracy increased[19], which is consistent with the results of this study. However, some studies have found that a single bout of exercise has no obvious effect on the accuracy or reaction time of shifting[20]; the effect on reaction time differs from the results of this study. We believe the reason is that, unlike previous studies that used exercise intensity and duration as the intervention, this study used the onset of fatigue as the criterion for ending exercise, which may have affected updating to a different degree and led to inconsistent test results. The results of this study show that the accuracy of shifting was not affected after fatigue, possibly because fatigue has a limited effect on the thinking and judgment ability required when switching between different tasks. Although the results of this study show that a single bout of exercise-induced fatigue can improve inhibition, updating and shifting, some studies have shown that the effects of a single bout of exercise-induced fatigue on the body are not maintained indefinitely[21], suggesting that college students should exercise regularly in daily life to continuously improve executive function and thereby enhance learning outcomes. Furthermore, this study only examined the effects of fatigue reached through running, a common daily exercise, on the executive function of male college students, and the results were obtained from a single treadmill model of fatigue induction. Future studies could take into account college students' diverse exercise preferences and investigate the effects of fatigue induced by different types of exercise on executive function.

Although some progress has been made on the effects of exercise on cognitive function, significant disagreements remain in existing research. For example, regarding the cognitive effects of exercise intensity, high-intensity interval training (HIIT) can improve inhibitory control in adolescents, whereas the study by Lambourne et al. showed that excessive exercise load leads to a decline in executive function. This contradiction may stem from inconsistent criteria for assessing fatigue. In addition, most studies only measure cognitive changes within 30 minutes after exercise and lack continuous tracking during the fatigue recovery period. At the level of experimental design, existing studies mostly use a single cognitive task (e.g., the Stroop test), which makes it difficult to comprehensively reflect the multiple dimensions of executive function.

A single bout of exercise-induced fatigue improves the processing speed of updating in male college students more than that of inhibition and shifting, while having no differential effect on improving processing quality among the three sub-functions. Miyake et al. found that the shifting, inhibition and updating functions of the central executive can act independently yet are moderately correlated[22]. In terms of processing speed, Carelli, Forman and Mäntylä (2008) found that shifting requires fewer executive resources than updating and inhibition tasks[23]. Updating involves more automatic brain processing and a lower cognitive load, whereas inhibition and shifting involve suppressing interfering information, excluding irrelevant stimuli and switching between different tasks or mental sets, both of which require a higher cognitive load. Therefore, when cerebral metabolic activity and neuronal activity increase after fatigue, the improvement in processing speed of updating, a low-load cognitive task, is greater than that of inhibition and shifting, which are high-load cognitive tasks. In terms of processing quality, the three sub-functions show greater correlation with one another, so all improve after fatigue with no differences among them.

5. Conclusion

A single bout of exercise-induced fatigue can improve the level of executive function in male college students, simultaneously enhancing both the processing speed and processing quality of inhibition and updating, while enhancing only the processing speed of shifting. In addition, the improvement in the processing speed of updating induced by a single bout of exercise-induced fatigue is greater than that of inhibition and shifting.

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