Effect of sustained high-intensity exercise on executive function

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Abstract Exercise-induced changes in executive function affect the control of action in a dynamic environment. This study aimed to examine the effect of sustained high-intensity exercise on executive function. Nine healthy male and female participants (age, 21-28 years) completed an exercise session with 65-min treadmill running at 75% VO2max. Executive function was assessed before and after exercise with the Stroop Color and Word Test that included congruent and incongruent conditions. The reaction time and response accuracy of the test were measured, and the task difficulty was controlled by adjusting the stimulus duration so that each participant could maintain at least 80% response accuracy to exclude the effect of a speed–accuracy trade-off. The levels of plasma norepinephrine and adrenocorticotropic hormone were examined. A significant interaction with the reaction time was found (condition × time, P = 0.024), in which the reaction time significantly increased after exercise only in the incongruent condition (P = 0.019). The response accuracy was not significantly different between before and after exercise in both conditions, which indicated that the response accuracy was controlled as intended. The levels of plasma norepinephrine and adrenocorticotropic hormone were significantly increased after exercise (P < 0.05). These results demonstrated that the reaction time in the incongruent condition increased after sustained high-intensity exercise with a cognitive function test with the response accuracy controlled, indicating a decline in executive function. Increased levels of plasma norepinephrine and adrenocorticotropic hormone may contribute, at least in part, to such decline in executive function.

Keywords: sustained high-intensity exercise, executive function, Stroop Color and Word Test

Introduction

Executive function, the cognitive process responsible for the synthesis of external stimuli and the development of goals and strategies, plays an important role in the control of action in situations that require changing and updating goal-directed strategies in a dynamic environment1-4. Executive function can be affected by acute exercise, which induces changes in modulators of cognitive function such as arousal and the levels of some brain neurotransmitters that are influenced by stress hormones including catecholamines and glucocorticoids5-8). When exercise is continued, the arousal level changes and the levels of stress hormones increase, which presumably deteriorate the processing of executive function9-11). Such exercise-induced changes in executive function would affect the control of action in dynamic situations that require a sustained moderate- to high-intensity exercise, such as sports activities. Therefore, the effect of sustained high-intensity exercise on executive function needs to be investigated.

There have been consistent findings showing that exercise of a short to moderate duration (≤30 min)12) and moderate intensity (40-70% VO2max)12) improves executive function13-17), however, when the exercise duration exceeds 60 min or when the intensity is >70% VO2max, the findings on the effect of exercise on executive function have been controversial. Dietrich et al.18) reported that executive function was impaired during approximately 62 min of running at 75% maximal heart rate, whereas Hogervorst et al.19) demonstrated that executive function was enhanced (based on a shorter time to finish the Stroop interference task) after 60 min of cycling at 75% maximal work capacity. Research investigating the effect of a sustained high-intensity exercise on executive function is lacking11), and whether such exercise can enhance or deter-
riorate executive function remains unclear.

A trade-off between speed and accuracy could be a reason for such inconsistent findings about the effect of a sustained high-intensity exercise on executive function. When cognitive function tests that measure speed and accuracy (e.g., flanker task and Stroop Color and Word Test [Stroop test]) are administered, the results could be influenced by the speed–accuracy tradeoff\(^\text{20}\), as shown by Fitts\(^\text{21}\). As the reaction time to the task can be shortened at the cost of making more errors, it cannot be concluded that a shortened reaction time indicates an improvement in cognitive function if the response accuracy becomes worse. Either the reaction time or the response accuracy needs to be controlled to exclude the speed–accuracy tradeoff. The response accuracy of cognitive tasks can be easily controlled by practice, relative to the reaction time. A change in the reaction time would reflect a change in cognitive function more precisely when the response accuracy of the test is controlled\(^\text{17}\). In fact, a previous study showed that the effect of fatigue on tennis skills was counteracted by a speed–accuracy tradeoff after heavy exercise\(^\text{22}\). Thus, the effect of high-intensity exercise on executive function should be examined under the condition in which the response accuracy is controlled, to exclude a speed–accuracy tradeoff.

Sustained high-intensity exercise induces plasma norepinephrine (NE) and adrenocorticotropic hormone (ACTH) release\(^\text{6,9,14,23}\), which would selectively decrease the performance of central executive tasks since high levels of plasma NE and ACTH have been reported to result in a decline in executive function\(^\text{11,24}\). Central executive task performance can be tested using incongruent tasks of Stroop test\(^\text{25}\), in which increased reaction time indicates decreased performance. Thus, reaction time in the incongruent Stroop test would increase after sustained high intensity exercise when the speed–accuracy tradeoff was excluded, indicating a decline in executive function. However, to the best of our knowledge, there are no studies that examined the effect of sustained high-intensity exercise on executive function under the condition in which the speed–accuracy tradeoff was excluded.

The purpose of this study was to examine the effect of sustained high-intensity exercise on executive function under the condition in which the response accuracy is controlled. We hypothesized that an increased reaction time in the incongruent condition would be observed after sustained high-intensity exercise.

### Materials and Methods

#### Participants

Nine young healthy participants (five males and four females; mean age, 24 ± 2 years; body mass, 64.1 ± 4.0 kg; height, 170.9 ± 4.8 cm; and VO\(_{2}\text{max}\), 43.8 ± 8.7 ml·kg\(^{-1}\)·min\(^{-1}\)) participated in this study. None of the participants had a history of mental or somatic disorder. This study was performed in compliance with the Declaration of Helsinki. The study protocol was approved by the Ethics Review Board of Ritsumeikan University Biwako-Kusatsu Campus (BKC-IRB-2014-034). Each participant received an explanation of the nature and purpose of the study, and gave written informed consent for participation. The sample size of this study was determined from the preliminary results of the changes in the reaction time of the incongruent Stroop test after a sustained high-intensity exercise, which was the primary outcome measure of this study. On the basis of the means and variances of those data, eight participants were needed to detect the changes in the reaction time to achieve a power of \((1 − β) = 0.80\) at \(P < 0.05\).

#### Maximal graded exercise test

The participants underwent a maximal exercise test to determine their exercise intensity at least 5 days before the experiment. Oxygen uptake was measured with a breath-by-breath gas and volume analyzer (AE-310S; Minato Medical Science, Osaka, Japan) during running on a treadmill (Life Fitness, Tokyo, Japan). The participants ran at a constant inclination of 1% and the speed was increased by 0.9 km/h every 1 min from 6.0 km/h. Heart rate was recorded continuously during the exercise test by using a heart rate monitor (Polar RS800CX; Polar Electro Oy, Kempele, Finland). VO\(_{2}\text{max}\) was considered to be valid when at least two of the following three criteria were met: a plateau in VO\(_{2}\) despite an increase in workload, a respiratory exchange ratio of \(≥1.10\), and attainment of at least 90% of age-predicted maximal heart rate (220 − age)\(^\text{26}\).

#### Experimental protocol

Participants were familiarized with the experimental protocols prior to the exercise sessions. For female participants, the experiment was conducted during the follicular phase of the menstrual cycle. On the day before the experiment, the participants were instructed to eat dinner by 22:00 and to not consume anything other than water after the meal. On the following morning, the participants came to the laboratory and consumed breakfast at 8:20. The breakfast provided 485 kcal (18.8 g protein, 10.1 g fat, and 75.6 g carbohydrate).

The exercise session started 3 hours after breakfast. The participants ran for 5 min at a workload corresponding to 40% VO\(_{2}\text{max}\) as a warm-up, followed by 65 mins of running at 75% VO\(_{2}\text{max}\) on a treadmill, in a temperature-controlled room (mean temperature, 21°C). The cognitive function test was administered before (pre-exercise) and immediately after (post-exercise: within 2 mins after) the exercise session, similar to previous studies\(^\text{10,19,27}\). Immediately before each cognitive function test, subjective perceptions of fatigue and arousal were assessed and a blood sample was taken. The rating of perceived exertion (RPE) was measured with the Borg 15-point scale. Perceptual fatigue and arousal were assessed by using a scale ranging from 1 (not at all) to 20 (maximal)\(^\text{28}\).
Cognitive function test. The cognitive function test was performed at pre-exercise and post-exercise in a seated position. The modified Stroop test\(^{29}\) was administered to assess the cognitive function of the participants. In the present study, the test included congruent and incongruent conditions. A computer screen that displayed different words with different colors was placed at eye level 1 m in front of the participants in a sitting position. The words presented at the center of the screen were 9.5 cm high and 10.0 cm wide. For the congruent condition, the word “BLUE,” “GREEN,” or “RED” in Japanese was displayed in the congruent ink color. For the incongruent condition, the word was displayed in a different ink color (e.g., BLUE printed in green ink). The participants were asked to identify the color of the displayed word by pressing the appropriate key on the keyboard, with the index, middle, and fourth fingers of their right hand (the dominant hand of all participants). The participants were instructed to press the key in accordance with the color of the ink and ignore the semantic meaning as accurately and quickly as possible. A white fixation cross (+) on a black background appeared for 750 ms followed by word stimulus presentation with a duration adjusted for each participant, and a blank black screen for 750 ms. The task difficulty was controlled by adjusting the stimulus duration from 650 to 1000 ms to minimize the learning effects. The stimulus duration was decreased by 50 ms in a stepwise manner from 1000 ms until the participant reached the response accuracy above 80%\(^{30-32}\), while maintaining a Coefficient of variation of the reaction time of less than 5% during a practice session held before the experiment.

The test consisted of six blocks of 25 trials each, for a total of 150 trials. The trial conditions (congruent and incongruent) were set in a random order. Software (E-Prime 2.0: Psychology Software Tools, Sharpsburg, PA, USA) was used to present the stimuli and measure the reaction time. The reaction time and response accuracy were averaged for each trial condition. The trials in which the reaction time was recorded to be <120 ms were excluded from the calculation.

Blood analysis. The levels of plasma NE and ACTH were analyzed. An indwelling needle was inserted into a median cubital vein. A 12-ml venous blood sample was taken at each time point. All samples were centrifuged at 3000 rpm for 15 min at 4°C. The levels of NE and ACTH were analyzed by means of reverse-phase isocratic high-performance liquid chromatography at a clinical laboratory (Kinkiyoken KK, Otsu, Japan).

Statistical analyses. The outcome measures were the reaction time of the Stroop test, blood levels of hormones, and subjective perceptions at pre-exercise and post-exercise. A two-way repeated-measures ANOVA, with condition (congruent and incongruent condition) and time (pre-exercise and post-exercise) as factors, was used to examine the main and interaction effects on the reaction time and response accuracy. When significant interactions were found, Bonferroni post hoc test was performed to detect the sources of the significant differences. A paired Student’s t test was performed to assess differences in the blood levels of hormones and the subjective perceptions between pre-exercise and post-exercise. The Spearman rank correlation coefficient was calculated to assess the correlations between the change in the reaction time of the Stroop test and the change in the plasma levels of hormones. In all analyses, \(P < 0.05\) was used to indicate statistical significance. The data were analyzed with SPSS (version 19.0; SPSS Inc., Tokyo, Japan).

Results

Cognitive function. The results of the reaction time and the response accuracy in the congruent and the incongruent conditions of the Stroop test are shown in Fig. 1. A significant interaction with the reaction time (condition \(\times\) time, \(F_{[1,8]} = 7.654, P = 0.024, \eta^2_p = 0.489\)) was observed, in which the reaction time significantly increased from pre-exercise to post-exercise only in the incongruent condition \((P = 0.019)\) (Fig. 1A). A significant main effect of condition on the reaction time was observed \((F_{[1,8]} = 38.724, P < 0.001, \eta^2_p = 0.829\). The reaction time in the congruent condition showed a higher value compared to the incongruent condition at pre-exercise and post-exercise \((P < 0.01)\). There was no significant time effect on the reaction time \((F_{[1,8]} = 1.763, P = 0.221, \eta^2_p = 0.181)\). No significant main effects of time or interaction on the response accuracy were observed \((P > 0.1)\) (Fig. 1B). A significant main effect of condition on the response accuracy was observed \((F_{[1,8]} = 29.391, P = 0.001, \eta^2_p = 0.786)\). The response accuracy in the congruent condition showed a higher value than in the incongruent condition at pre-exercise and post-exercise \((P < 0.01)\). The change in reaction time without a significant change in response accuracy between pre-exercise and post-exercise in the incongruent condition indicated that there was no speed-accuracy tradeoff.

Blood analysis. Table 1 shows the concentrations of blood hormones at pre-exercise and post-exercise. The plasma ACTH concentration significantly increased after exercise \((P = 0.004, d = 2.238)\). The plasma NE concentration was significantly higher at post-exercise than at pre-exercise \((P = 0.005, d = 1.562)\). In the congruent condition, the Spearman rank correlation coefficient revealed no significant correlation in the changes between the plasma levels of hormones and the reaction time \((r_s = 0.167, P = 0.693, \text{for ACTH}; r_s = -0.100, P = 0.798, \text{for NE})\). In the incongruent condition, there was no significant correlation in the changes between the plasma level of ACTH and the reaction time \((r_s = -0.048, P = 0.911)\), while the plasma level of NE positively correlated with the reaction
Perceptual assessments. The mean RPE was 7 ± 2 and 17 ± 2 at pre-exercise and post-exercise, respectively. The RPE was significantly increased after exercise (P < 0.001, \( d = 5.042 \)). The perceptual fatigue was significantly larger at post-exercise than at pre-exercise (17 ± 3 vs. 5 ± 4, \( P < 0.001, d = 3.367 \)). The perceptual arousal did not change from pre-exercise to post-exercise (13 ± 3 vs. 11 ± 4, \( P = 0.100 \)).

Discussion

The present study examined the effect of sustained high-intensity exercise on executive function. A significant interaction (condition × time) was found with the reaction time of the Stroop test, in which the reaction time significantly increased after sustained high-intensity exercise in the incongruent condition, although no significant difference was found between pre- and post-exercise in the congruent condition. Increased levels of plasma NE and ACTH were observed after the exercise. These results suggest that sustained high-intensity exercise induced a decline in executive function, which could be attributed to the increased levels of plasma NE and ACTH.

A significant increase in reaction time was observed after exercise in the incongruent condition, whereas no such increase was observed in the congruent condition. The congruent and incongruent tasks are known to assess different aspects of cognitive function, which seems to be a cause for such a condition-dependent difference. The incongruent task in the Stroop test has been used to assess an aspect of executive function, such as the capacity of the participants to inhibit or override a dominant response\(^2,25\), whereas the congruent task is known to mainly measure selective attention and concentration\(^33\). Our results suggest that sustained high-intensity exercise induced a decline in executive function, observed as an

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**Table 1. Blood levels of hormones.**

<table>
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<tr>
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<th>Pre-exercise</th>
<th>Post-exercise</th>
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<tbody>
<tr>
<td>Plasm ACTH concentration</td>
<td>20.4 ± 11.5</td>
<td>102.1 ± 50.3*</td>
</tr>
<tr>
<td>Plasm NE concentration</td>
<td>0.45 ± 0.23</td>
<td>1.98 ± 1.37*</td>
</tr>
</tbody>
</table>

Data are expressed as means ± SD. ACTH: adrenocorticotropic hormone, NE: norepinephrine. *\( P < 0.05 \) vs Pre-exercise.
increase in the reaction time in the incongruent condition, while selective attention and concentration were not affected by the exercise. This was determined by the fact that no exercise-induced changes in reaction time in the congruent condition were seen.

No significant differences were observed in the response accuracy between pre- and post-exercise, indicating that the response accuracy was controlled as intended. When cognitive function tests that measure speed and accuracy are administered, the results could be influenced by the speed–accuracy tradeoff, which could be one of the reasons for the inconsistent findings of the previous studies investigating the effect of high-intensity exercise on response time. As the response accuracy was controlled in this study, the effect of such trade-off appears to be excluded, which may have contributed to the detection of exercise-induced changes in executive function.

Randomized administration of the congruent and incongruent conditions may also have contributed to the detection of a decline in executive function. It has been reported that the reaction time in incongruent trials presented among congruent trials would have more Stroop interference than that of incongruent trials alone. The incongruent conditions randomly intermixed with the congruent conditions in our study may have increased the Stroop interference in the incongruent conditions, in which the exercise-induced change in the reaction time was more pronounced in incongruent conditions. Taken together, exercise-induced changes in reaction time could be sensitively detected under incongruent tasks intermixed with congruent tasks with the response accuracy controlled, increasing the Stroop interference and excluding the effect of the speed–accuracy tradeoff.

Increased plasma levels of NE and ACTH could be one of the possible reasons for the decline in executive function after sustained high-intensity exercise. Although the significance was marginal, the increase in plasma NE level correlated with the increase in the reaction time in the incongruent condition, indicating decreased performance in the central executive task. High levels of NE synthesis and release in the brain have been reported to disrupt neural processing in the prefrontal cortex, which plays a prominent role in the process involved in central executive tasks. Furthermore, it has been reported that peripheral NE induces NE synthesis and release in the brain through the vagus nerve. Therefore, an increased level of plasma NE concentration observed in this study might have resulted in a high level of NE release in the brain, decreasing the performance of central executive tasks. Although there was no significant correlation in the changes between the plasma ACTH level and the reaction time in the incongruent condition, an increased level of ACTH has also been reported to decrease the performance of the executive function task. Taken together, a decline in executive function might be attributed, at least in part, to the increased level of plasma NE and ACTH. Further studies are still needed to elucidate the underlying physiological mechanisms and other potential physiological factors that could deteriorate executive function.

The present study has several limitations. We found an exercise-induced increase in the reaction time when the cognitive function test was conducted immediately after the exercise; however, it is unclear whether such an increase would be observed when the test is performed during exercise. Nevertheless, when the cognitive function test is administered during treadmill running, the attention of participants would be allocated to the control of body movement (motor task) and the cognitive function tests (cognitive task); thereby, the intersubject variability of attentional allocation may obscure the exercise-induced change in the performance of cognitive function tests. Further studies are needed to determine whether the exercise-induced increase in reaction time would also be observed during exercise. Another limitation of this study is the lack of a non-exercise control condition. Reaction time performance might deteriorate over time even without exercise due to mental fatigue and/or reduced attention. The observed increase in the reaction time after exercise in the incongruent task may have also resulted from such time-dependent factors. However, considering that no significant change was observed after exercise in the reaction time in the congruent condition, time-dependent changes in the reaction time should be minimal. A loss of significance in the correlation between the reaction time and plasma level of NE in the incongruent condition might have been due to the small sample size. However, the sample size was determined from the preliminary results of the changes in the reaction time in the incongruent task after exercise, which was the primary outcome measure of this study. Although the sample size may not have been large enough to detect a significant correlation, it appeared to be large enough to detect changes in the reaction time, as a significant increase was observed after exercise in the incongruent task. It should also be noted that although we adopted a cognitive function test in which the response accuracy was controlled to exclude the effect of a speed–accuracy tradeoff, there are other methods to exclude the effect of the tradeoff, by using physiological indices such as electroencephalogram measurements. Further studies are needed to examine whether an exercise-induced decline in executive function could also be detected when such physiological indices are used as alternative methods.

In conclusion, the reaction time was found to increase after sustained high-intensity exercise in the incongruent condition, which indicates a decline in executive function. Increased plasma levels of NE and ACTH might have contributed to the decline in executive function. Such exercise-induced changes in reaction time could be sensitively detected under a condition in which incongruent tasks are intermixed with congruent tasks with the response accuracy controlled, increasing the Stroop
interference and excluding the effect of speed-accuracy tradeoff. These findings would be useful to assess the effect of intervention treatments on executive function in sustained high-intensity exercises.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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