Effects of Moderate-to-Vigorous Acute Exercise on Visual Consciousness

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Research Article

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Abstract

Background

the effect of acute exercise on cognition covers almost all stages of information processing, but few studies have focused on visual awareness. Subjective reports on the appearance of faint speed-changes in the perception of stimuli were used as an index for visual consciousness. Visual consciousness was assessed after exercise or rest. Aside from subjective index, objective speed-change discrimination was added as an index for the level of consciousness. Results: the results showed that subjective reports on the appearance of faint speed-changes in the perception of stimuli were affected by acute aerobic exercise. The hit rate for speed-change detection was marginally significantly higher after exercise than sedentary condition. Furthermore, the d' index was higher after exercise. Analysis of the results obtained for the objective discrimination task showed that discrimination speed was boosted only when subjects were aware of the speed-change. Conclusions: these results suggest that acute exercise enhances visual consciousness.

1. Background

The evolutionary mechanism allowing fleeing prey to more easily detect predators in environments rich in irrelevant stimuli may ensure species survival. In these life-threatening situations, typically associated with high arousal level (threat and exercise), the early and more accurate identification of predators' motion information is essential for prey in the process of fleeing [1]. In modern society, people feel more effective when they perform mental activities during or following exercise. For instance, athletes' experience tells us that after warming-up, their response to the start signal is improved. Such phenomena are not confined to people's observations. Some well-designed experiments have confirmed such an enhancing effect of exercise on cognitive processing (for review, [2]. In a meta-analysis review, the differential effects of differing intensities of acute exercise on speed and on the accuracy of cognition were examined. A comparison between speed and accuracy as dependent variables showed that speed accounted for most of the effect of exercise on cognition [3].

The enhancing effect of acute exercise has been observed in a series of cognitive tasks, such as the critical flicker fusion task (sensory) [4], the perception task (perception) [5], the simple reaction time/choice reaction time task (motor) [6, 7], the visual attention task (attention) [8], and the decision-making problem (decision-making) [9]. Notably, in recent years, research interests have been increasingly focused on prefrontal cortex-dependent cognitive tasks, including the Stroop task, the Eriksen Flanker task, and the Simon task [10]. Additional studies revealed that higher-order cognitive domains such as cognitive flexibility, inhibitory control, and working memory benefit more from acute exercise-elicited cognitive benefits [11], although detrimental effects of acute in-task exercise on executive function are also frequently observed [1].

The effect of acute exercise on cognition covers almost all stages of information processing, such as sensation, perception, motor, attention, and higher-order domains (inhibition, decision-making, and working memory). However, few of these studies touch on consciousness. The subjectivity of consciousness makes it one of the most attractive topics in psychology. Therefore, in current research, combinations of subjective and objective indicators are adopted to verify if acute exercise affects visual consciousness. In addition, under the framework of signal detection theory [12], two main parameters (d' , indicates the strength of the signal relative to noise; C , reflects the subject's response strategy) can help us to explore the source of changes in subjective awareness, due to changes in discrimination or subjective criteria, or both. The identification and understanding of motion information in the environment is critical; motion is therefore understood at the conscious level. In their meta-analysis review, moderate-intensity exercise demonstrated a significantly larger mean effect size than observed for low- or high-intensity exercise, and there was no significant difference between the mean effect size for arousal when testing took place post-exercise, compared to during exercise, for speed; however, accuracy studies demonstrated a significantly larger mean effect size after exercise [3]. Therefore, in the current study, we tested visual consciousness shortly after exercise (moderate-intensity cycling) or rest (control).

2. Materials And Methods

2.1. Participants

Twenty volunteers with normal or corrected-to-normal vision participated in the study. Participants were instructed to: (1) avoid vigorous exercise during the 24-hr period before the experiment; (2) avoid caffeine intake on the day of the study; (3) sleep for a sufficient number of hours on the night preceding the experiment. All had normal color vision, as assessed by the Ishihara color vision test. No participant had a history of physical disability or mental illness. Data from two subjects were discarded, due to an excessively high false-alarm rate (false alarm rate = 80%) in one case and due to a lack of convergence at the specified threshold testing stage (staircase method) in the other case. The final cohort included eight men and ten women, all right-handed, with mean [$\pm$ standard deviation (SD)] age of 23.33 ± 1.41 yr (range, 20–27 years), mean height of 168.61 ± 9.10 cm (range, 150–187 cm), and mean weight of 63.89 ± 19.54 kg (range, 45–116 kg). Mean body mass index (BMI) was 22.20 ± 5.16 kg/m² (range, 17.36–37.86). The short form of the International Physical Activity Questionnaire (Lee, Macfarlane, & Stewart, 2011) was employed to assess habitual physical activity. The mean metabolic equivalent of task-hours per week among the study population was 1488.68 ± 935.77 (METs/wk). Aerobic fitness was tested by estimating the maximum rate of oxygen consumption ($\text{VO}_{2\text{max}}$) using a Bruce protocol (maximal graded exercise test, GXT) [13], where participants wore the Cosmed K4b2 (Cosmed Srl, Rome, Italy), a portable indirect calorimetry system, while running on a motor-driven treadmill until participants met one of the following criteria : (1) a plateau in oxygen consumption (an increase of <2 mL/kg/min despite an increase in workload); (2) peak heart rate (HR) ≥ 185 beats per minute (bpm) and an HR plateau; (3) respiratory exchange ratio ≥ 1.0 [14]. Mean maximal oxygen uptake per kilogram bodyweight ($\text{VO}_{2\text{max}}/\text{kg}$) was 33.81 ± 6.31 mL/kg/min (range, 24.4–45.9 mL/kg/min). Participants signed their informed written

consent and were paid for their participation. The study followed the ethical guidelines of the Declaration of Helsinki and was approved by the local ethics committee at Shanghai University of Sports in China.

2.2. Acute Exercise Manipulation

Acute exercise consisted of 5 min of warm-up and 20 min of moderate- to vigorous-intensity cycling on a Monark Ergonomic 839E bicycle. Moderate- to vigorous-intensity exercise was defined as 70% based on American College of Sports Medicine (ACSM) exercise guidelines[15] Target HR was determined using the Karvonen formula [16] $[\text{Target HR} = (\text{HR reserve} \times 70\%) + \text{resting HR}]$. HR reserve was calculated as “maximal HR – resting HR”, with “maximal HR” estimated with the following formula: $208 - 0.7 \times \text{age}$ [17]. Resting HR was measured after participants had been seated, wearing an HR monitor, for 15 min. To further verify exercise intensity, ratings of perceived exertion (RPE) were assessed every 30 sec using the Borg scale [18], which ranges from a score of 0, “not tired at all”, to 10, “very, very tired”.

2.3. Cognitive task stimuli

Stimuli were presented on a calibrated computer screen (resolution, 1024×768 pixels, refresh rate, 60 Hz), positioned 110 cm from the subject’s eyes. Stimulus presentation was controlled by the Psychtoolbox package for Matlab [19, 20]. All displays used a black background. The central focus of the screen was a white dot with a degree of visual angle (dva) of 0.15° . The target consisted of a set of red dots and a set of green dots. Each set comprised 50 dots, and all targets were in an annulus 1–3 dva from fixation. One colored population rotated clockwise; the other rotated counterclockwise (randomly assigned). The luminance of the red dots was fixed (1.57 cd/m^2). The luminance of green circles was set individually for each subject (using the heterochromatic flicker method) at perceptual equiluminance with red [21].

2.4. Task and procedure

Each participant was tested in the laboratory on two separate occasions within a 5-d period. Each participant was tested at the same time on both days to avoid potential disturbances of physiological rhythm. Exercise vs. rest (exercise, 5-min warm-up + 25 min cycling; control, 25 min reading) was designed as a within-subject factor, completed separately on two occasions. The order of exercise and control treatments was randomly assigned and counterbalanced between subjects. During each session, a cognitive task (visual consciousness task) always followed immediately after cessation (within 5 min) of exercise or the sedentary condition. After the control session, participants were assessed for GXT. The cognitive task comprised 4 sessions (mean duration, 5 min/session). Each session consisted of 44 trials (40 speed change-present trials, 4 speed change-absent trials).

During each trial, subjects were exposed to a 600-ms fixation screen, and the colored dots were shown rotating for 900 ms. During 74% of trials, one of the two dot populations either sped up or slowed down at an acceleration/deceleration rate determined by a prior one-up-one-down staircase procedure that identified a target 50% detection rate for each participant (see below). On the remaining 26% of trials, the dots rotated at their original uniform velocity (6 dva/s). Participants were then presented successively

with two response screens for a maximum of 3 s. The first screen was a task of two-alternative forced-choice speed-change discrimination: subjects were asked to determine whether there was an acceleration or deceleration of the target stimuli (Question 1). Subjects were then asked whether they thought variable-speed motion was “present” or “absent” in a single dot population (Question 2). Based on subjects' answers to the second question, the subject's response to each stimulus was classified as “aware” (subject perceived the speed change by answering “present”) or unaware (speed change was not perceived, and the subject answered “absent”). Participants were instructed to answer quickly and accurately and were explicitly told to make a choice even if they were not sure of their response. During the inter-stimulus interval (2–3 s), a black background was displayed.

Before the first treatment (exercise or control), an equiluminance procedure and a staircase procedure were performed to determine parameters for subsequent cognitive tasks (similar to [22]). The perceptual equiluminance of the two colors (red, green) was determined for each subject individually using a heterochromatic flicker method to minimize perceptual differences between red and green. Once the two colors were set at perceptual equiluminance, the acceleration or deceleration at which subjects could detect 50% of any speed-change was determined using a “one-up-one-down” staircase procedure. Trials were identical to those described above, except that acceleration or deceleration was varied from trial to trial, depending on whether the speed-change had been perceived in the previous trial of the same type. Acceleration and deceleration staircases were calibrated separately. This portion of the procedure required approximately 20 min. Before the second session, only a staircase procedure was run for the sake of verification. The acceleration/deceleration rate used in the cognitive task following cycling exercise or reading was exactly the same and was measured before the first intervention.

3. Results

3.1. Exercise intensity check

HR was measured during exercise and sedentary conditions to assess the effectiveness of exercise manipulation. Paired t-tests revealed significant differences between acute exercise (146.17 ± 5.51 bpm) and the control condition (76.69 ± 8.09 bpm; $t_{17} = 46.07$, $p < 0.001$). The average rating of perceived exertion, using an 11-point Borg scale, was 3.01 ± 0.73 , indicating that average subjective perceived intensity was moderate [18].

3.2. Cognitive performance

To examine the effects of acute exercise (exercise, control) on visual awareness, we first conducted paired t-tests on subjects' performance on speed change-present and speed change-absent trials, respectively (based on their responses to Question 2). Subjects were more likely to report the existence of speed changes during cognitive tasks completed after exercise (hit rate, mean $\pm$ SEM = $67.7 \pm 4.5\%$), compared with cognitive tasks completed after reading (hit rate, mean $\pm$ SEM = $59.1 \pm 4.8\%$) (paired t-test, $t_{17} = -2.00$, $p = 0.062$, marginally significant). For speed change-absent trials, there was no significant

difference in false alarm rate between experimental conditions (exercise, mean $\pm$ SEM = $30.6 \pm 4.9\%$; control, mean $\pm$ SEM = $31.7 \pm 5.3\%$; paired t-test, $t_{17} = 0.29$, $p = 0.78$). On this basis, according to signal detection theory, we calculated d' (the most important measure of signal detection theory sensitivity) and β , the likelihood ratio, an index of response bias. The results showed that d' was significantly higher for cognitive tasks completed after exercise, compared with cognitive tasks completed after reading (exercise, mean $\pm$ SEM = 1.23 ± 0.17 ; control, mean $\pm$ SEM = 0.87 ± 0.16 ; paired t-test, $t_{17} = -2.57$, $p = 0.020$). However, no such difference was found for likelihood ratio (β) (exercise, mean $\pm$ SEM = 1.82 ± 0.53 ; control, mean $\pm$ SEM = 1.67 ± 0.39 ; paired t-test, $t_{17} = -0.37$, $p = 0.72$).

Secondly, repeated-measures t-tests comparing exercise and control conditions were run on speed-change discrimination rate and reaction time. Analysis was conducted separately for “aware” and “unaware” trials. In order to minimize the influence of outliers on reaction time, we abandoned trials with reaction time < 50 ms or > 2500 ms. Data beyond 3 SDs from the mean were rejected. For “aware” trials, reaction time for speed-change discrimination was significantly shorter in the exercise condition than in the control condition (aware: exercise, mean $\pm$ SEM = 794.19 ± 49.0 ms; control, mean $\pm$ SEM = 890.62 ± 42.41 ms; paired t-test, $t_{17} = 3.26$, $p = 0.005$). There was no such difference between conditions when subjects were unaware of the speed-change (unaware: exercise, mean $\pm$ SEM = 979.20 ± 68.74 ms; control, mean $\pm$ SEM = 1048.42 ± 52.2 ms; $t_{17} = 1.41$, paired t-test, $p = 0.18$). The discrimination rate for aware trials (exercise, mean $\pm$ SEM = $88.64 \pm 2.18\%$; control, mean $\pm$ SEM = $88.69 \pm 1.53\%$) was much higher than that for unaware trials (exercise, mean $\pm$ SEM = $59.09 \pm 3.57\%$; control, mean $\pm$ SEM = $58.22 \pm 3.66\%$), without any significant exercise-related differences (aware, paired t-test, $t_{17} = 0.042$, $p = 0.97$; unaware, paired t-test, $t_{17} = -0.16$, $p = 0.88$).

4. Discussion

The current study employed cycling to explore the effect of acute exercise of moderate- to vigorous-intensity on visual consciousness. Subjective reports on the appearance of faint speed-changes in perceived stimuli were used as an index for visual consciousness. Objective speed-change discrimination was added as an index for the level of consciousness. The present study showed that subjective reports on the appearance of faint speed-changes in perceived stimuli were affected by acute moderate- to vigorous-intensity aerobic exercise. The hit rate of speed-change detection was marginally significantly higher after exercise, compared with the sedentary condition. The d' index, which is an indication of the strength of the signal relative to noise, was also higher after exercise than after the control condition. These results suggest that acute moderate- to vigorous-intensity aerobic exercise enhances visual consciousness. The results of the objective discrimination task showed that discrimination speed was boosted only when subjects were aware of the speed-change.

Among scientists who sought to explain the effect of acute exercise on cognition, Colin Davey first considered exercise as a stressor from the perspective of arousal [23], which can activate the autonomic nervous system and improve the level of physiological and psychological arousal. This explanation

seemed too general. In the current research results, after acute exercise, the responses of subjects were selectively enhanced. Moderate- to vigorous-intensity cycling increased the hit rate of speed-change detection, but there was no increase in the rate of false-positives in reports of changes in speed. The rate of speed-change discrimination increased only when subjects were aware of the speed-change. We sought to identify the physiological mechanism underlying this phenomenon. During exercise, the brain's metabolism is accelerated, and cerebral cortex blood flow is increased [24], which can further optimize the allocation of cognitive resources and improve the efficiency of cognitive processing [25]. This cognitive process may also affect visual awareness, as indicated by the results presented above.

Dietrich used the transient hypofrontality hypothesis to explain the negative effects of movement on cognitive performance during exercise [26, 27]. The theory holds that, during exercise, the motor and sensory integration system is continuously activated, which takes up the limited resources available for information processing. Meanwhile, the neural network unrelated to exercise is temporarily inhibited, as is the flow of blood and oxygen to the prefrontal cortex. Dietrich and Audiffren subsequently revised the transient hypofrontality hypothesis, proposing the "reticular activation and frontal lobe dysfunction model" (RAH) instead [28]. This model includes reticular activation and frontal lobe dysfunction. Although there is no way to exclude the influence of some factors closely related to visual consciousness (such as attention, which is closely related to the activation of reticular structure), these theories may structure our thinking about the neural mechanisms related to visual consciousness. Visual motor system integration is activated by exercise, which also inhibits frontal lobe activity. The enhancing effects of exercise on visual consciousness observed in the current study suggest that visual consciousness is closely related to neural activity in the posterior areas and less likely to be correlated with neural activity in the frontal areas, which are temporarily inhibited.

Declarations

Ethics approval and consent to participate: Participants provided informed written consent and were paid for their participation. The study followed ethical guidelines set forth by the Declaration of Helsinki and was approved by the local ethics committee at Shanghai University of Sport in China.

Consent for publication: agree to submit current manuscript to BMC Public Health.

Availability of data and materials: available upon demand.

Competing interests: the authors declare no competing financial interests.

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Authors' contributions: Y.L. and B.Z. designed experiments. X.M., Y.Y., Y.H., B.Z. and Y.L. conducted experiments and analyzed the data. Y.L. wrote the article.

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Figures

Figure 1

Experimental design. Two populations of dots, one red and one green, were shown on each trial. Each population was composed of 50 dots, and all targets were in an annulus 1–3 dva from fixation. One colored population rotated clockwise; the other rotated counterclockwise. Following a 600-ms fixation screen, the colored dots were shown rotating for 900 ms. On 74% of trials, one of the two dot populations either sped up or slowed down at an acceleration/deceleration rate determined by a prior one-up-one-down staircase procedure that identified a target 50% detection rate for each participant. On the remaining 26% of trials, the dots rotated at their original, uniform velocity (6 dva/s). Subjects were asked to answer two successive questions: first, whether there was an acceleration or deceleration of the target stimuli (two-alternative forced choice), and second, whether they thought one dot population moved at variable speed.