Effect of Exercise Intensity and Duration on Postexercise Executive Function

HAYATO TSUKAMOTO[1,2], SAKI TAKENAKA[1], TADASHI SUGA[1], DAICHI TANAKA[1], TATSUYA TAKEUCHI[1], TAKAFUMI HAMAOKA[3], TADAO ISAKA[1], and TAKESHI HASHIMOTO[1]

[1]Graduate School of Sport and Health Science, Ritsumeikan University, Shiga, JAPAN; [2]Research fellow of the Japan Society for the Promotion of Science, Tokyo, JAPAN; and [3]School of Medicine, Tokyo Medical University, Tokyo, JAPAN

ABSTRACT

TSUKAMOTO, H., S. TAKENAKA, T. SUGA, D. TANAKA, T. TAKEUCHI, T. HAMAOKA, T. ISAKA, and T. HASHIMOTO. Effect of Exercise Intensity and Duration on Postexercise Executive Function. *Med. Sci. Sports Exerc.*, Vol. 49, No. 4, pp. 774–784, 2017. **Purpose**: The effect of exercise volume represented by exercise intensity and duration on postexercise executive function (EF) improvement remains unclear. In the present study, involving two volume-controlled evaluations, we aimed to compare acute exercise protocols with differing intensities and durations to establish an effective exercise protocol for improving EF. **Methods**: In study 1, 12 healthy male subjects performed cycle ergometer exercise, based on a low-intensity (LI) protocol for 20 min (LI_{20}), moderate-intensity (MI) protocol for 20 min (MI_{20}), and MI_{20} volume-matched LI protocol for 40 min (LI_{40}). The exercise intensities for the LI and MI were set at 30% and 60% of peak oxygen consumption, respectively. In study 2, 15 healthy male subjects performed MI exercise for 10 min (MI_{10}), MI_{20}, and 40 min (MI_{40}). To evaluate the EF, the color–word Stroop task was administrated before exercise, immediately after exercise, and during the 30-min postexercise recovery. **Results**: In study 1, postexercise EF improvement was sustained for a longer duration after MI_{20} than after LI_{40} and was sustained for a longer duration after LI_{40} than after LI_{20}. In study 2, although there was no significant difference in post-MI exercise EF improvement, the magnitude of difference in the EF between preexercise and 30-min postexercise recovery period was moderately larger in MI_{40}, but not in MI_{10} and MI_{20}, indicating that the EF improvement during postexercise recovery could be sustained after MI_{40}. **Conclusion**: The present findings showed that postexercise EF improvement could be prolonged after MI exercise with a moderate duration compared with volume-matched LI exercise with a longer duration. In addition, MI exercise with a relatively long duration may slightly prolong the postexercise EF improvement. **Key Words:** BRAIN HEALTH, COGNITION, AEROBIC EXERCISE, POSTEXERCISE RECOVERY, AROUSAL SYSTEM, STROOP TEST

Emerging researches have suggested that executive function (EF) is facilitated by acute aerobic exemrcise (4,5,20,26). In previous studies, Byun et al. (3) reported that even low-volume exercise, comprising low-intensity (LI) exercise (30% of peak oxygen consumption [$\dot{V}O_{2peak}$]) and a short duration (10 min), could improve EF, as evaluated by the Stroop test at least 5 min after the exercise. Moreover, Lucas et al. (17) reported that low-volume exercise, comprising LI exercise (30% of HR reserve [HRR]) and a short duration (8 min), could improve the Stroop test–measured EF. In addition, the authors indicated that an increased exercise volume, with a higher intensity (70% HRR) and a longer duration (16 min), could further improve EF (17). Thus, they suggested that although the underlying effects of exercise intensity and duration were unclear, exercise volume may be an important factor for EF improvement. Nevertheless, the application of vigorous intensity (e.g., >80% HRR) could negatively affect EF, as evaluated by the Wisconsin card sorting test (29). In addition, an exercise protocol including a very long duration (e.g., >3 h) at moderate-intensity (MI) for 60% $\dot{V}O_{2peak}$ also impaired exercise-induced improvement of cognitive performance, as evaluated by the map recognition task (12). Thus, markedly high exercise volume may diminish the positive effects of exercise on EF. To elucidate exercise protocols for effectively improving EF, the effect of exercise volume on exercise-induced EF improvement should be determined, particularly the contribution of the exercise volume components (i.e., exercise intensity and duration), in a volume-controlled study. However, to our knowledge, such studies have not yet been performed. In the present study, we aimed to directly compare acute exercise protocols with differing intensities and durations to establish an effective exercise protocol for improving EF.

To achieve our goal, we designed two volume-controlled studies. In the first study (study 1), we aimed to evaluate the effect of exercise intensity and duration on EF using moderate-volume exercises. In a meta-analysis, Chang et al. (5) stated that when a cognitive task was administered immediately after exercise, lighter intensity exercise appears to have a beneficial

---

Address for correspondence: Tadashi Suga, Ph.D., Faculty of Sport and Health Science, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan; E-mail: t-suga@fc.ritsumei.ac.jp.
Submitted for publication April 2016.
Accepted for publication November 2016.

0195-9131/17/4904-0774/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000001155

effect on the results. However, when cognitive tasks were administered after a delay after exercise, it was found that exercises with greater intensity elicited the strongest positive effects. In fact, we recently determined that the EF improvement during postexercise recovery was sustained for a longer period in high-intensity interval exercise (HIIE) than in volume-matched MI exercise (26). On the basis of these findings, we sought to examine the effect of exercise volume on EF during postexercise recovery to determine the effect of exercise intensity. In study 1, we hypothesized that the postexercise EF improvement would be more effective in exercise protocols with a higher volume (i.e., 30% $\dot{V}O_{2peak}$ for 40 min and/or 60% $\dot{V}O_{2peak}$ for 20 min) than in exercise protocols with a lower volume (i.e., 30% $\dot{V}O_{2peak}$ for 20 min). Moreover, we hypothesized that, compared with volume-matched LI exercise (i.e., 30% $\dot{V}O_{2peak}$ for 40 min), the application of MI exercise (i.e., 60% $\dot{V}O_{2peak}$ for 20 min) would elicit stronger positive effects on EF. Furthermore, we expected that the endurance of postexercise recovery would still exhibit stronger positive effects in cases of MI exercise compared with that of LI exercise.

In the second study (study 2), we aimed to evaluate the effect of different exercise volumes, based on exercise duration with the same intensity, on postexercise EF. Recently, Chang et al. (4) reported that the effect of exercise on the Stroop test–measured cognitive function immediately after MI exercise (65% HRR) was strongest for 20-min exercise duration compared with that for 10- or 45-min exercise duration. Nevertheless, the authors only examined the cognitive function immediately after exercise, and hence, the effect of exercise duration on the endurance of EF improvement during postexercise recovery remains unknown. In the present study, we attempted to extend this observation to postexercise recovery.

METHODS

Subjects. Twelve healthy male subjects (age = 23.2 ± 0.5 yr, height = 172.2 ± 1.5 cm, weight = 66.6 ± 2.2 kg, $\dot{V}O_{2peak}$ = 45.9 ± 2.0 mL·kg^{-1}·min^{-1}) participated in study 1, and 15 healthy male subjects (age = 22.6 ± 0.4 yr, height = 171.3 ± 1.4 cm, weight = 65.3 ± 2.1 kg, $\dot{V}O_{2peak}$ = 47.3 ± 1.8 mL·kg^{-1}·min^{-1}) participated in study 2. The subjects were informed of the experimental procedures and potential risks and provided written consent to participate in the study. All subjects were right-hand dominant; free of any known neurological, cardiovascular, and pulmonary disorders; and free from color blindness or abnormal vision. All procedures were approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2014-028). Subjects were instructed to avoid strenuous physical activity in the 24 h before each experimental session. Each subject also abstained from food (overnight fasting), caffeine, and alcohol for 12 h before each experiment.

Experimental conditions. A schematic representation of the exercise protocols used in studies 1 and 2 are presented in Figure 1. All subjects completed cycle ergometer exercise based on either exercise protocols in a randomized and counterbalanced order in both studies. These protocols were separated by at least 72 h. All protocols were performed after a warm-up at 50 W for 5 min and instructed to maintain a cadence of 60 rpm, which was carefully checked by examiners. In study 1, experimental protocols consisted of low-volume LI exercise for 20 min (LI_{20}), high-volume LI for 40 min (LI_{40}), and LI_{40}-volume-matched MI exercise for 20 min (MI_{20}). To exclude the effect of the time interval between preexercise and postexercise, LI_{20} and MI_{20} used a rest period of 20 min in the sitting position after color–word Stroop task (CWST) measurement before exercise. The exercise intensities in LI and MI were set at 30% and 60% of $\dot{V}O_{2peak}$, respectively. The exercise volumes in LI_{20}, MI_{20}, and LI_{40} were 95 ± 3, 183 ± 7, and 189 ± 6 kJ, respectively. In study 2, experimental protocols consisted of MI for 10 min (MI_{10}), MI_{20}, and 40 min (MI_{40}). In the aforementioned manner, after CWST measurement before exercise, MI_{10} and MI_{20} protocols used a rest period of 30 and 20 min in the sitting position, respectively. The exercise volumes in MI_{10}, MI_{20}, and MI_{40} were 89 ± 3, 179 ± 5, and 358 ± 10 kJ, respectively.

Experimental procedure. Before the experimental days, subjects were familiarized with the CWST on their first visit to our laboratory. The CWST was practiced until the subject achieved consistent scores. Subsequently, $\dot{V}O_{2peak}$ was measured to calculate the exercise intensity required for the exercise protocols.

On the experiment days, subjects practiced the CWST before CWST measurement before exercise to prevent the learning effect. Next, the subjects rested for 5 min before undergoing measurements of cardiovascular and psychological parameters and fingertip blood sampling to collect preexercise data, which concluded within 5 min. Ten minutes after the practice CWST was conducted, the subjects performed the CWST measurement before exercise. Subsequently, the subjects carried out either of the exercise protocols. During the exercise sessions, HR and mean arterial pressure (MAP) were measured to evaluate cardiovascular responses. Fingertip blood samples were collected to determine glucose and lactate levels. In study 1, these cardiovascular parameters and blood metabolites were obtained before exercise, immediately after exercise, and during postexercise recovery (three times with 10-min intervals). In study 2, to assess the differences in the levels of blood metabolites depending on exercise duration, the blood metabolites in all protocols were obtained before exercise, during exercise (five times with 10-min intervals), immediately after exercise, and during the 30-min postexercise recovery (three times with 10-min intervals). The RPE was recorded to evaluate psychological response during exercise. After exercise was completed, the CWST measurement was performed as soon as possible. Moreover, CWST measurement was performed during the postexercise recovery for 30 min with three times with 10-min intervals (26). To evaluate the psychological condition for CWST measurement, the felt arousal scale (FAS) (24) and the visual analog scale (VAS) (26,27) were measured immediately after measurements of CWST. In a

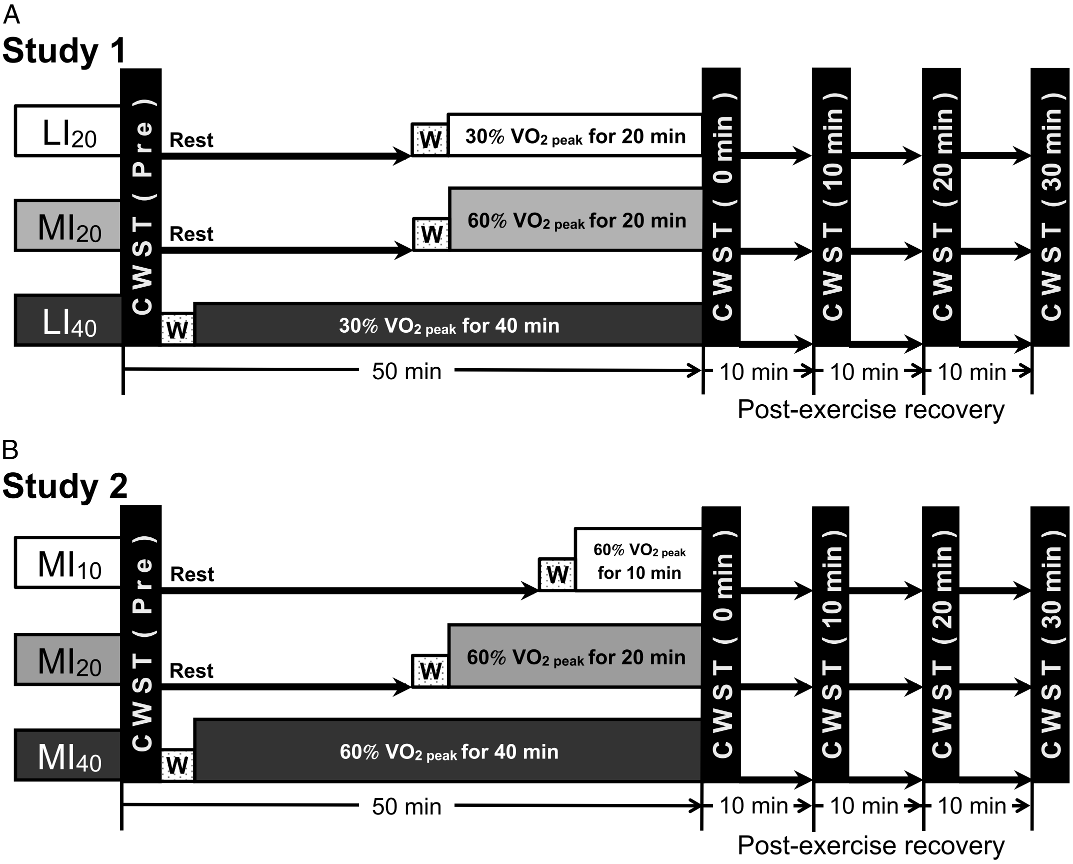

FIGURE 1—A schematic representation of the experimental protocols in Study 1 (A) and Study 2 (B). The experimental protocols in study 1 comprised LI exercise for 20 min (LI_{20}), MI exercise for 20 min (MI_{20}), and MI_{20} volume-matched LI for 40 min (LI_{40}). The experimental protocols in study 2 comprised MI for 10 min (MI_{10}), MI_{20}, and 40 min (MI_{40}). The evaluation of EF in both studies was performed using the CWST. All protocols were performed after a warm-up (W) at 50 W for 5 min. The CWST-derived EF was measured before exercise, immediately after exercise, and during the 30-min postexercise recovery.

preliminary study, we examined the effect of staying in a resting condition for 40 min in the sitting position on postexercise EF in eight health male subjects (age = 22.6 ± 0.2 yr, height = 172.0 ± 2.1 cm, weight = 67.7 ± 2.9 kg). According to the order of CWST measurements in studies 1 and 2, the CWST measurements were performed before the condition, immediately after the condition, and during the 30-min postcondition (three times with 10-min intervals). In the results, the CWST-measured EF did not significantly differ among the five time points (data not shown).

Ramp incremental test. At the first visit, all subjects performed a maximal incremental exercise test to determine $\dot{V}O_{2peak}$ on a cycle ergometer. Initially, subjects performed 3 min of baseline cycling at 30 W, after which the workload was increased at a rate of 30 $W{\cdot}min^{-1}$ until the limit of tolerance. The subjects were asked to maintain a cadence of 60 rpm. During the incremental test, breath-by-breath pulmonary gas-exchange data were collected and averaged every 10 s (AE-310S; Minato Medical Science, Osaka, Japan). HR was measured continuously via telemetry (RS 400; Polar Electro Japan, Tokyo, Japan). The $\dot{V}O_{2peak}$ was determined as the highest 30-s mean value attained before exhaustion. Exhaustion was assessed to be the maximum when three of the following criteria were obtained: 1) a plateau in the $\dot{V}O_2$ despite increasing workload, 2) a respiratory exchange ratio higher than 1.10, 3) an HR higher than 90% of the age-predicted maximum [208 − 0.7 × age], and 4) a task failure of the pedaling rate of at least 55 rpm for 5 s despite maximal effort (26,27).

Cardiovascular parameters. HR was measured continuously via telemetry during a ramp incremental test. Systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured via a mercury manometer (FC-110ST; Focal, Chiba, Japan). MAP was calculated as [(SBP − DBP)/3 + DBP].

Blood glucose and lactate levels. A fingertip blood sample was collected from the nondominant hand (i.e., left hand) into a capillary tube to determine the glucose and lactate levels, to exclude the influence on CWST. The blood glucose levels were measured using a glucose analyzer (Glutest Neo Alpha; Sanwa Kagaku Kenkyusho, Nagoya, Japan). The blood lactate levels were measured using a lactate analyzer (Lactate Pro 2; Arkray, Kyoto, Japan).

Psychological parameters. RPE—The RPE was measured to assess the effort expended during exercise. This scale ranges from 6 (no exertion) to 20 (maximal exertion) (2).

FAS—The FAS was measured to assess arousal level; this scale ranges from 1 (low arousal) to 6 (high arousal). For example, a high arousal level is “excitement,” and a low arousal level is “relaxation” (24).

VAS—The VAS for the CWST consisted of questions of three psychological types that assess mental fatigue, ability to concentrate, and motivation. Each VAS was labeled from 0 mm (i.e., not at all) to 100 mm (i.e., extremely). The subjects drew lines to indicate their response (26,27).

EF measurements. To assess EF, in the present study, we used the CWST. EF concerned with working memory, reasoning, task flexibility, and problem solving (19). The CWST is a well-known paradigm for investigating aspects of a higher cognition that depend on EF (23). Specifically, it pays selective attention to specific information and the inhibition of prepotent response during decision-making tasks involving stimuli and responses (18). This CWST was programmed by modifying an Excel Visual Basic for Applications from our previous studies (20,26,27). We measured both the reaction time and the response accuracy by using the CWST. The following instructions were given to the subjects: “You must perform as accurately and quickly as possible.” The stimulus words included the names of four colors (“RED,” “YELLOW,” “GREEN,” and “BLUE”), which were presented in a font size of 48 points, on a 98-inch display, at a visual angle of 180°, and at a viewing distance of 2 m, as previously described (20). The stimuli were presented until a response was made. All words were written in Japanese. We prepared a color-labeled 10-key board: number 1 key was labeled red, number 2 key was labeled yellow, number 3 key was labeled green, and number 4 key was labeled blue. The subjects were required to press the color-labeled key that corresponds to the text meaning of the stimulus word. The subjects performed three types of CWST. The congruent task, which is a facilitated task, displayed the color names presented in the same-colored text. The neutral task, which is a control task, displayed the color names presented in black text. The incongruent task, which is an interference task, displayed the color names presented in a different-colored text. The words for each type of task were presented in a random order. One trial of each task consisted of 24 stimulus words and was repeated for three trials. The reaction time and response accuracy recorded per one trial of each task and the values for three trials of each task were averaged. To evaluate the EF, a reverse-Stroop interference score was calculated as [(reaction time of incongruent task − reaction time of neutral task)/reaction time of neutral task × 100] (14,26,27).

Statistical analysis. The data are expressed as the mean ± SEM. The RPE immediately before exercise completion was analyzed by using one-way (only the condition) repeated-measures ANOVA after normal data distribution was confirmed. The physiological and psychological parameters and the CWST-measured interference score during the experimental session were analyzed by using a two-way (time–condition) repeated-measures ANOVA after normal data distribution was confirmed. The CWST-measured reaction time and the response accuracy during the experimental session were analyzed by using a three-way (type of CWST–time–condition) repeated-measures ANOVA after normal data distribution was confirmed. If the sphericity assumption was not met, Greenhouse–Geisser corrections were used. Partial eta squared (η_p^2) values were determined as a measure of the effect size for all the main effects and interactions. The *post hoc* comparisons involved paired *t*-tests with the Bonferroni correction. In a statistical manner, the Bonferroni-corrected *P* values for the type of CWST, time, and condition were set at 0.017, 0.01, and 0.017, respectively. The magnitude of the differences in the interference scores at each time point among the exercise conditions in Study 2 was assessed using Cohen's effect size, which is usually used to evaluate the strength of the effect sizes as follows: weak ($d < 0.40$), moderate ($0.40 \leq d < 0.80$), and strong ($d \geq 0.80$) (6,7). All statistical analyses were conducted using IBM SPSS software (version 19.0; International Business Machines Corp., Armonk, NY).

RESULTS

Study 1. The levels of cardiovascular parameters and blood metabolites before exercise were similar among all protocols (Table 1). HR analysis revealed a significant time–condition interaction ($F_{8,\ 88} = 102.73$, $P < 0.01$, $\eta_p^2 = 0.90$). This significant interaction indicates that the HR for MI_{20} was higher than that for LI_{20} and LI_{40} during postexercise recovery for 30 min. MAP analysis revealed a significant time–condition interaction ($F_{4.20,\ 46.24} = 7.37$, $P < 0.01$, $\eta_p^2 = 0.40$). This significant interaction indicates that the MAP immediately after MI_{20} was significantly higher than that immediately after LI_{20} and LI_{40} ($t_{11} = 5.22$, $P < 0.017$ and $t_{11} = 4.70$, $P < 0.017$ for both). Blood glucose level analysis revealed a significant time–condition interaction ($F_{8,\ 88} = 2.62$, $P < 0.01$, $\eta_p^2 = 0.19$). This significant interaction indicates that blood glucose level immediately after MI_{20} was significantly lower than that immediately after LI_{40} ($t_{11} = 3.39$, $P < 0.017$). Blood lactate level analysis revealed a significant time–condition interaction ($F_{2.16,\ 23.73} = 56.41$, $P < 0.01$, $\eta_p^2 = 0.84$). This significant interaction indicates that blood lactate level immediately after MI_{20} was significantly higher than that immediately after LI_{20} and LI_{40} ($t_{11} = 8.56$, $P < 0.017$ and $t_{11} = 9.75$, $P < 0.017$ for both). These differences remained significant for blood lactate level during the 20-min postexercise recovery period. The RPE immediately before exercise completion was a significant main effect ($F_{2,\ 22} = 59.85$, $P < 0.01$, $\eta_p^2 = 0.85$) and was significantly higher for MI_{20} (14.4 ± 0.3) than for LI_{20} and LI_{40} (10.8 ± 0.3; $t_{11} = 10.01$, $P < 0.017$ and 9.9 ± 0.5; $t_{11} = 8.28$, $P < 0.017$ for both).

The values of reaction time and response accuracy of each CWST before exercise were similar among all protocols (Table 2). In the reaction time values, there were significant main effects for type of CWST ($F_{2,\ 22} = 141.43$, $P < 0.01$, $\eta_p^2 = 0.93$), time ($F_{2.05,\ 22.51} = 15.24$, $P < 0.01$, $\eta_p^2 = 0.58$), and

TABLE 1. Changes in the cardiovascular responses and blood metabolites levels during the experimental session in studies 1 and 2.

		Postexercise Recovery			
	Preexercise	**0 min**	**10 min**	**20 min**	**30 min**
Study 1					
HR (bpm)					
LI_{20}	68.3 ± 2.5	$102.7 \pm 2.3^{*}$	$67.3 \pm 2.5^{**}$	$64.8 \pm 2.2^{*,**}$	$63.1 \pm 1.7^{**}$
MI_{20}	68.0 ± 2.3	$149.4 \pm 8.4^{*,a}$	$84.4 \pm 3.1^{*,**,a}$	$77.1 \pm 2.7^{*,**,***,a}$	$70.5 \pm 2.3^{**,***,****,a}$
LI_{40}	65.1 ± 2.1	$106.4 \pm 2.6^{*,b}$	$68.1 \pm 2.6^{**,b}$	$65.6 \pm 2.1^{**,b}$	$64.3 \pm 2.1^{**,b}$
MAP (mm Hg)					
LI_{20}	90.0 ± 2.4	$95.4 \pm 2.7^{*}$	90.5 ± 2.0	$88.9 \pm 2.6^{**}$	90.4 ± 2.3
MI_{20}	90.4 ± 2.1	$107.1 \pm 1.7^{*,a}$	$91.6 \pm 2.6^{**}$	$90.4 \pm 2.4^{**}$	$88.4 \pm 2.2^{**}$
LI_{40}	92.3 ± 2.0	$97.4 \pm 1.7^{*,b}$	$89.2 \pm 2.2^{*,**}$	$89.1 \pm 2.1^{*,**}$	$90.2 \pm 2.1^{**}$
Blood glucose ($\mathrm{mg \cdot dL^{-1}}$)					
LI_{20}	90.6 ± 2.3	85.1 ± 2.1	87.3 ± 2.9	$91.9 \pm 2.9^{**}$	$90.4 \pm 2.1^{**}$
MI_{20}	89.0 ± 1.5	$81.2 \pm 2.3^{*}$	$87.7 \pm 1.9^{**}$	$90.3 \pm 1.7^{**}$	$88.6 \pm 1.7^{**}$
LI_{40}	89.1 ± 1.7	88.8 ± 2.0^{b}	90.3 ± 1.8	90.7 ± 1.4	89.0 ± 2.0
Blood lactate ($\mathrm{mmol \cdot L^{-1}}$)					
LI_{20}	0.9 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	1.0 ± 0.1	1.0 ± 0.1
MI_{20}	1.0 ± 0.1	$3.3 \pm 0.3^{*,a}$	$1.9 \pm 0.2^{*,**,a}$	$1.3 \pm 0.2^{**,***,a}$	$1.2 \pm 0.1^{**,***}$
LI_{40}	1.0 ± 0.1	1.0 ± 0.1^{b}	0.9 ± 0.1^{b}	0.8 ± 0.1^{b}	0.9 ± 0.1
Study 2					
HR (bpm)					
MI_{10}	67.6 ± 2.5	$141.5 \pm 3.3^{*}$	$77.8 \pm 2.9^{*,**}$	$74.1 \pm 2.3^{*,**}$	$71.3 \pm 2.2^{**,***}$
MI_{20}	67.9 ± 2.5	$152.5 \pm 3.5^{*,c}$	$87.1 \pm 2.1^{*,**,c}$	$79.9 \pm 1.9^{*,**,***,c}$	$74.3 \pm 1.7^{**,***,****}$
MI_{40}	69.7 ± 2.7	$159.1 \pm 3.7^{*,c}$	$91.3 \pm 2.3^{*,**,***,c}$	$85.1 \pm 2.8^{*,**,***,c}$	$83.3 \pm 2.7^{*,**,***,c,d}$
MAP (mm Hg)^{e,f,g,h,i}					
MI_{10}	94.3 ± 1.7	109.6 ± 2.4	96.0 ± 1.6	95.2 ± 1.9	95.1 ± 1.6
MI_{20}	96.4 ± 2.2	107.1 ± 2.9	95.8 ± 2.4	95.0 ± 2.4	93.8 ± 2.1
MI_{40}	94.4 ± 1.4	107.3 ± 2.1	97.1 ± 2.2	93.1 ± 2.2	92.7 ± 1.7
Blood glucose ($\mathrm{mg \cdot dL^{-1}}$)^{e,f,g,h}					
MI_{10}	92.6 ± 1.0	86.5 ± 1.5	90.7 ± 0.7	90.3 ± 0.9	91.5 ± 1.2
MI_{20}	93.0 ± 1.6	86.8 ± 1.7	91.1 ± 1.7	93.4 ± 2.0	92.2 ± 1.8
MI_{40}	92.5 ± 1.4	85.5 ± 2.6	93.7 ± 3.1	94.0 ± 2.4	93.9 ± 2.1
Blood lactate ($\mathrm{mmol \cdot L^{-1}}$)					
MI_{10}	1.0 ± 0.1	$3.3 \pm 0.2^{*}$	$1.9 \pm 0.1^{*,**}$	$1.3 \pm 0.1^{*,**,***}$	$1.1 \pm 0.1^{**,***,****}$
MI_{20}	1.0 ± 0.1	$3.3 \pm 0.2^{*}$	$1.8 \pm 0.1^{*,**}$	$1.3 \pm 0.1^{*,**,***}$	$1.1 \pm 0.1^{**,***,****}$
MI_{40}	1.0 ± 0.1	$2.5 \pm 0.2^{*,c,d}$	$1.5 \pm 0.1^{*,**,c}$	$1.2 \pm 0.1^{*,**,***}$	$1.2 \pm 0.1^{**,***}$

Values are presented as mean ± SEM.

Significant time–condition interaction is as follows: $^{*}P < 0.01$ vs preexercise, $^{**}P < 0.01$ vs 0-min postexercise recovery, $^{***}P < 0.01$ vs 10-min postexercise recovery, $^{****}P < 0.01$ vs 20-min postexercise recovery, $^{a}P < 0.017$ vs LI_{20} in study 1, $^{b}P < 0.017$ vs MI_{20} in study 1, $^{c}P < 0.017$ vs MI_{10} in study 2, $^{d}P < 0.017$ vs MI_{20} in study 2. Significant main effect for time is as follows: $^{e}P < 0.01$ preexercise vs 0-min postexercise recovery, $^{f}P < 0.01$ 0-min postexercise recovery vs 10-min postexercise recovery, $^{g}P < 0.01$ 0-min postexercise recovery vs 20-min postexercise recovery, $^{h}P < 0.01$ 0-min postexercise recovery vs 30-min postexercise recovery, $^{i}P < 0.01$ 10-min postexercise recovery vs 30-min postexercise recovery.

type of CWST–time interaction ($F_{3.21,\ 35.33} = 2.69$, $P < 0.05$, $\eta_p^2 = 0.20$). However, there were no significant main effects for the other factors, including the main effect of the response accuracy values. Follow-up *post hoc* comparisons for the type of CWST–time interaction indicated that the reaction time values of the congruent task and neutral task were shorter than those of the incongruent task during postexercise recovery for 30 min, and that the reaction time values of the congruent task were shorter than those of the neutral task during postexercise recovery. In the congruent task, the reaction time values immediately after exercise were significantly shorter than those during the 20- and 30-min postexercise recovery periods ($t_{35} = 2.71$, $P < 0.01$ and $t_{35} = 4.63$, $P < 0.01$ for both). Moreover, the reaction time values during the 10-min postexercise recovery period were also significantly shorter than those before exercise and during the 20- and 30-min postexercise recovery periods ($t_{35} = 2.81$, $P < 0.01$; $t_{35} = 3.44$, $P < 0.01$; and $t_{35} = 4.92$, $P < 0.01$, respectively). In the neutral task, the reaction time values immediately after exercise and during the 10-min postexercise recovery period were significantly shorter than those during the 30-min postexercise recovery period ($t_{35} = 3.56$, $P < 0.01$ and $t_{35} = 3.56$, $P < 0.01$). In the incongruent task, the reaction time values immediately after exercise and during the 10- and 20-min postexercise recovery periods were significantly shorter than those before exercise ($t_{35} = 5.42$, $P < 0.01$; $t_{35} = 5.16$, $P < 0.01$; and $t_{35} = 2.81$, $P < 0.01$, respectively) and during the 30-min postexercise recovery period ($t_{35} = 6.74$, $P < 0.01$; $t_{35} = 6.91$, $P < 0.01$; $t_{35} = 4.02$, $P < 0.01$, respectively). Moreover, the reaction time values during the 20-min postexercise recovery period were significantly slower than those immediately after exercise and during the 10-min postexercise recovery period ($t_{35} = 3.61$, $P < 0.01$ and $t_{35} = 3.33$, $P < 0.01$ for both).

The interference score before exercise was similar among all protocols (Fig. 2A). There were significant main effects for time ($F_{4,\ 44} = 24.14$, $P < 0.01$, $\eta_p^2 = 0.69$) and condition ($F_{2,\ 22} = 5.93$, $P < 0.01$, $\eta_p^2 = 0.35$); however, only a trend toward a significant main effect was noted at time–condition interaction ($F_{8,\ 88} = 1.80$, $P = 0.087$, $\eta_p^2 = 0.14$). Follow-up *post hoc* comparisons for time indicated that the interference score immediately after exercise was significantly greater than that before exercise ($t_{35} = 7.07$, $P < 0.01$). These improvements remained significant for interference score during the 20-min postexercise recovery period. Follow-up *post hoc* comparisons for condition indicated that the interference scores for MI_{20} were higher than LI_{20} and LI_{40} ($t_{59} = 4.10$, $P < 0.017$ and $t_{59} = 3.49$, $P < 0.017$ for both). In addition, follow-up

TABLE 2. Changes in reaction time and response accuracy of the CWST obtained in study 1.

		Postexercise Recovery			
	Preexercise^{b,c}	0 min^{a,b,c}	10 min^{a,b,c}	20 min^{a,b,c}	30 min^{a,b,c}
Reaction time (ms)					
Congruent task**,****,*****,******,*******					
LI_{20}	9956 ± 621	9587 ± 409	9525 ± 475	9823 ± 451	10,203 ± 431
MI_{20}	9917 ± 462	9324 ± 376	9180 ± 444	9728 ± 428	9701 ± 431
LI_{40}	9744 ± 495	9216 ± 415	9259 ± 335	9743 ± 383	10,059 ± 404
Neutral task*****,*******					
LI_{20}	10,306 ± 479	10,197 ± 504	10,257 ± 525	10,338 ± 481	10,441 ± 444
MI_{20}	10,119 ± 381	9643 ± 392	9828 ± 411	9931 ± 345	10,295 ± 433
LI_{40}	10,053 ± 400	9822 ± 447	9626 ± 322	10,086 ± 368	10,245 ± 310
Incongruent task*,**,***,****,*****,******,*******,********					
LI_{20}	11,655 ± 615	11,137 ± 534	11,304 ± 584	11,527 ± 611	11,783 ± 558
MI_{20}	11,497 ± 481	10,229 ± 431	10,427 ± 467	10,712 ± 396	11,463 ± 517
LI_{40}	11,290 ± 481	10,729 ± 548	10,443 ± 421	11,181 ± 470	11,546 ± 416
Response accuracy (%)					
Congruent task					
LI_{20}	98.6 ± 0.5	97.7 ± 1.0	97.5 ± 0.7	97.4 ± 0.6	96.9 ± 0.7
MI_{20}	98.9 ± 0.5	97.0 ± 0.9	98.8 ± 0.3	98.8 ± 0.5	98.7 ± 0.4
LI_{40}	98.5 ± 0.6	98.2 ± 0.5	97.5 ± 0.9	97.6 ± 0.8	97.1 ± 0.8
Neutral task					
LI_{20}	99.0 ± 0.4	98.2 ± 0.5	98.3 ± 0.5	98.7 ± 0.6	98.4 ± 0.4
MI_{20}	98.3 ± 0.5	98.5 ± 0.6	99.2 ± 0.3	98.0 ± 0.8	98.1 ± 0.6
LI_{40}	98.5 ± 0.7	99.1 ± 0.4	98.3 ± 0.8	98.5 ± 0.5	97.6 ± 1.1
Incongruent task					
LI_{20}	97.3 ± 0.8	98.1 ± 0.5	97.7 ± 0.6	97.0 ± 1.2	98.5 ± 0.6
MI_{20}	98.7 ± 0.5	98.7 ± 0.5	99.1 ± 0.4	99.2 ± 0.4	98.0 ± 0.6
LI_{40}	98.0 ± 0.6	97.6 ± 0.6	98.6 ± 0.5	98.3 ± 0.5	98.8 ± 0.4

Values are presented as mean ± SEM.

In the reaction time, significant type of CWST–time interaction is as follows: *$P < 0.01$ preexercise vs 0-min postexercise recovery, **$P < 0.01$ preexercise vs 10-min postexercise recovery, ***$P < 0.01$ preexercise vs 20-min postexercise recovery, ****$P < 0.01$ 0-min postexercise recovery vs 20-min postexercise recovery, *****$P < 0.01$ 0-min postexercise recovery vs 30-min postexercise recovery, ******$P < 0.01$ 10-min postexercise recovery vs 20-min postexercise recovery, *******$P < 0.01$ 10-min postexercise recovery vs 30-min postexercise recovery, ********$P < 0.01$ 20-min postexercise recovery vs 30-min postexercise recovery, $^{a}P < 0.017$ congruent task vs neutral task, $^{b}P < 0.017$ congruent task vs incongruent task, $^{c}P < 0.017$ neutral task vs incongruent task.

LI_{20}, LI for 20 min; MI_{20}, MI for 20 min; LI_{40}, LI for 40 min.

post hoc analyses comparing the condition effect within each period revealed that the improvements of interference score during the 10-min postexercise recovery period was significantly greater in MI_{20} than in LI_{20} ($t_{11} = 4.50$, $P < 0.017$). The interference score improvement during the 20-min postexercise recovery period was significantly greater in MI_{20} than in LI_{40} ($t_{11} = 3.38$, $P < 0.017$). Moreover, only a trend toward a significant improvement in the interference score in MI_{20} compared with that in LI_{20} was observed during the 20-min postexercise recovery period ($t_{11} = 2.52$, $P = 0.029$). *Post hoc* analyses comparing the time effect within each condition revealed that the interference score immediately after exercise was significantly greater than that before exercise in all protocols (LI_{20}: $t_{11} = 3.28$, $P < 0.01$; MI_{20}: $t_{35} = 5.23$, $P < 0.01$; LI_{40}: $t_{35} = 5.10$, $P < 0.01$). The improvement of interference score in LI_{40} remained significant during the 10-min postexercise recovery period, but not in LI_{20}. Moreover, the improvement in MI_{20} was still observed during the 20-min postexercise recovery period.

The FAS-measured arousal level and VAS-measured psychological conditions before exercise were similar among all protocols (Figs. 2B and 2C). The arousal level analysis revealed a significant time–condition interaction ($F_{3.84,\ 42.27} = 3.73$, $P < 0.05$, $\eta_p^2 = 0.25$). *Post hoc* analyses comparing the condition effect within each period revealed that the increased arousal level immediately after exercise was significantly higher in MI_{20} than in LI_{20} and LI_{40} ($t_{11} = 4.84$, $P < 0.017$ and $t_{11} = 5.00$, $P < 0.017$ for both). *Post hoc* analyses comparing the time effect within each condition revealed that the arousal level immediately after exercise was significantly higher than that before exercise in all protocols (LI_{20}: $t_{11} = 4.73$, $P < 0.01$; MI_{20}: $t_{11} = 5.82$, $P < 0.01$; LI_{40}: $t_{11} = 4.69$, $P < 0.01$). Moreover, the increase of the arousal level in LI_{20} was sustained during the 20-min postexercise recovery period, whereas the increase of the arousal levels in MI_{20} and LI_{40} were sustained during the 10-min postexercise recovery period. The VAS-measured mental fatigue for CWST analysis revealed a significant time–condition interaction ($F_{3.65,\ 40.13} = 3.34$, $P < 0.05$, $\eta_p^2 = 0.23$). *Post hoc* analyses comparing the condition effect within each period revealed that the increased mental fatigue during the immediately after exercise, 10-, and 20-min postexercise recovery periods were significantly higher after MI_{20} than LI_{20} ($t_{11} = 3.93$, $P < 0.017$; $t_{11} = 3.59$, $P < 0.017$; and $t_{11} = 3.74$, $P < 0.017$, respectively). Moreover, mental fatigue during the 10- and 20-min postexercise recovery periods was significantly higher after MI_{20} than LI_{40} ($t_{11} = 2.90$, $P < 0.017$ and $t_{11} = 2.97$, $P < 0.017$ for both). *Post hoc* analyses comparing the time effect within each condition revealed that the mental fatigue immediately after exercise was significantly higher than that before exercise in all condition (LI_{20}: $t_{11} = 4.04$, $P < 0.01$; MI_{20}: $t_{11} = 5.09$, $P < 0.01$; LI_{40}: $t_{11} = 3.34$, $P < 0.01$). There were no significant main effects for other factors, including main effects of ability to concentrate and motivation for CWST.

Study 2. The levels of cardiovascular parameters and blood metabolites before exercise were similar among all

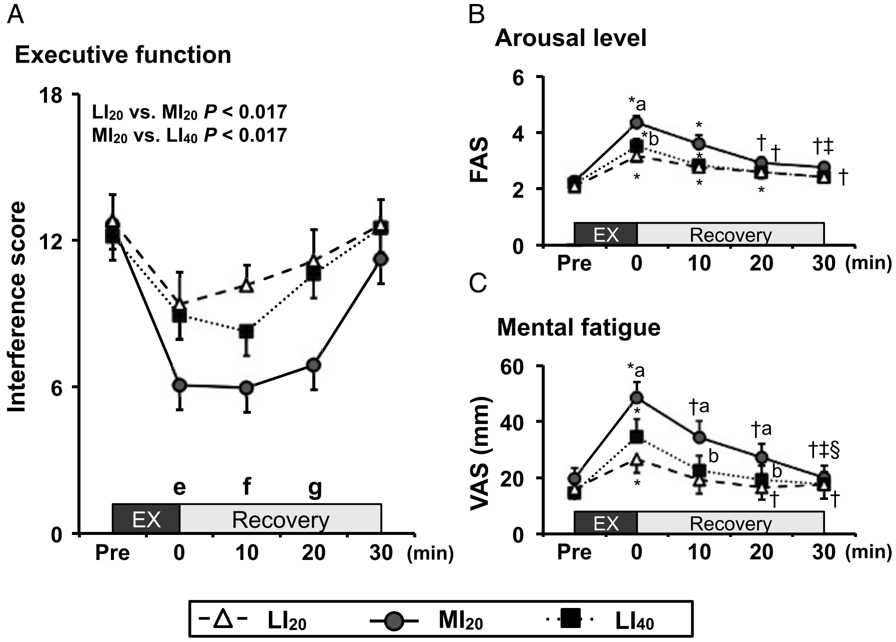

FIGURE 2—Changes in EF and psychological conditions for the CWST during the experimental session in study 1. The changes in the interference score (A), FAS-measured arousal level (B), and VAS-measured mental fatigue (C) in study 1 are presented using *open triangles* for LI_{20}, *gray circles* for MI_{20}, and *black squares* for LI_{40}. Values are presented as mean ± SEM. Significant time–condition interaction is as follows: $^aP < 0.017$ vs LI_{20}; $^bP < 0.017$ vs MI_{20}; $*P < 0.01$ vs preexercise; $†P < 0.01$ vs postexercise for 0 min (i.e., immediately after exercise); $‡P < 0.01$ vs postexercise for 10 min; $§P < 0.01$ vs postexercise for 20 min. Significant main effect for time is as follows: $^eP < 0.01$ preexercise vs 0-min postexercise recovery, $^fP < 0.01$ 0-min postexercise recovery vs 10-min postexercise recovery, $^gP < 0.01$ 0-min postexercise recovery vs 20-min postexercise recovery.

protocols (Table 1). HR analysis revealed a significant time–condition interaction ($F_{1.66,\ 23.19} = 721.80$, $P < 0.01$, $\eta_p^2 = 0.98$). This significant interaction indicates that the HR for MI_{20} and MI_{40} were significantly higher than MI_{10} during postexercise recovery for 30 min, except the 30-min post-MI_{20} recovery period. MAP analysis also revealed a significant main effect for time ($F_{1.97,\ 27.51} = 58.93$, $P < 0.01$, $\eta_p^2 = 0.81$); however, there were no significant main effects for condition ($F_{2,\ 28} = 0.35$, $P > 0.05$, $\eta_p^2 = 0.62$) and time–condition interaction ($F_{8,\ 112} = 0.89$, $P > 0.05$, $\eta_p^2 = 0.06$). Blood glucose level analysis revealed a significant main effect for time ($F_{2.39,\ 33.44} = 12.98$, $P < 0.01$, $\eta_p^2 = 0.48$); however, there were no significant main effects for condition ($F_{2,\ 28} = 0.54$, $P > 0.05$, $\eta_p^2 = 0.08$) and time–condition interaction ($F_{8,\ 112} = 1.24$, $P > 0.05$, $\eta_p^2 = 0.08$). Blood lactate level analysis revealed a significant time–condition interaction ($F_{2.73,\ 38.26} = 7.86$, $P < 0.01$, $\eta_p^2 = 0.36$). This significant interaction indicates that blood lactate level immediately after exercise was significantly lower after MI_{40} than MI_{10} and MI_{20} ($t_{14} = 3.39$, $P < 0.017$ and $t_{14} = 4.98$, $P < 0.017$ for both). The RPE immediately before exercise completion was a significant main effect ($F_{2,\ 28} = 27.36$, $P < 0.01$, $\eta_p^2 = 0.66$) and was significantly higher for MI_{20} (13.9 ± 0.4) and MI_{40} (14.7 ± 0.4) than for MI_{10} (12.4 ± 0.4; $t_{14} = 4.22$, $P < 0.017$ and $t_{14} = 6.86$, $P < 0.017$ for both) and was also significantly higher for MI_{40} than for MI_{20} ($t_{14} = 3.21$, $P < 0.017$).

The values of reaction time and response accuracy of each CWST before exercise were similar among all protocols (Table 3). In the reaction time values, there were significant main effects for type of CWST ($F_{1.37,\ 19.15} = 79.27$, $P < 0.01$, $\eta_p^2 = 0.85$), time ($F_{2.01,\ 28.20} = 15.50$, $P < 0.01$, $\eta_p^2 = 0.53$), and type of CWST–time interaction (reaction time $F_{2.71,\ 37.96} = 5.85$, $P < 0.01$, $\eta_p^2 = 0.30$). However, there were no significant main effects for the other factors, including main effect of the response accuracy values. Follow-up *post hoc* comparisons for the type of CWST–time interaction indicated that the reaction time values of congruent task and neutral task were shorter than incongruent task during all the periods, and the reaction time values of congruent task was shorter than neutral task during postexercise recovery for 30 min. In the congruent task, the reaction time values immediately after exercise were significantly shorter than those during all the periods (preexercise; $t_{44} = 5.31$, $P < 0.01$; 10-min postexercise recovery period; $t_{44} = 3.96$, $P < 0.01$; 20-min recovery postexercise period; $t_{44} = 3.34$, $P < 0.01$; 30-min recovery postexercise period: $t_{44} = 3.05$, $P < 0.01$). In the neutral task, the reaction time values immediately after exercise were significantly shorter than those during all the periods (preexercise: $t_{44} = 6.14$, $P < 0.01$; 10-min postexercise recovery period: $t_{44} = 3.41$, $P < 0.01$; 20-min postexercise recovery period: $t_{44} = 3.85$, $P < 0.01$; 30-min recovery postexercise period: $t_{44} = 3.68$, $P < 0.01$). In the incongruent task, the reaction time values during all the postexercise recovery periods were significantly shorter than those before exercise (0-min postexercise recovery period: $t_{44} = 8.85$, $P < 0.01$; 10-min postexercise recovery period: $t_{44} = 5.91$, $P < 0.01$; 20-min postexercise recovery period: $t_{44} = 3.73$, $P < 0.01$; 30-min postexercise recovery period: $t_{44} = 3.19$, $P < 0.01$), whereas those immediately after exercise were significantly shorter than those during postexercise

TABLE 3. Changes in reaction time and response accuracy of the CWST obtained in study 2.

		Postexercise Recovery			
	Preexercise^{a,b,c}	**0 min**^{a,b,c}	**10 min**^{a,b,c}	**20 min**^{a,b,c}	**30 min**^{a,b,c}
Reaction time (ms)					
Congruent task *,*****,******,*******					
MI$_{10}$	9941 ± 480	9241 ± 331	9498 ± 356	9272 ± 449	9274 ± 381
MI$_{20}$	9653 ± 510	8971 ± 386	9323 ± 464	9524 ± 494	9525 ± 423
MI$_{40}$	9951 ± 386	8743 ± 312	9245 ± 364	9456 ± 363	9275 ± 332
Neutral task *,*****,******,*******					
MI$_{10}$	10,280 ± 457	9642 ± 402	10,008 ± 408	9983 ± 438	10,025 ± 408
MI$_{20}$	10,322 ± 482	9450 ± 357	10,256 ± 522	9955 ± 392	10,288 ± 443
MI$_{40}$	10,241 ± 447	9663 ± 347	9805 ± 307	10,001 ± 353	9802 ± 335
Incongruent task *,**,***,****,*****,******,*******,********					
MI$_{10}$	11,752 ± 572	10,554 ± 480	10,885 ± 491	11,002 ± 546	11,257 ± 528
MI$_{20}$	11,914 ± 737	10,217 ± 484	11,003 ± 637	11,109 ± 550	11,553 ± 586
MI$_{40}$	11,809 ± 684	10,404 ± 441	10,376 ± 352	10,803 ± 420	10,793 ± 416
Response accuracy (%)					
Congruent task					
MI$_{10}$	98.1 ± 0.6	98.1 ± 0.6	97.8 ± 0.6	97.9 ± 0.6	97.8 ± 0.4
MI$_{20}$	97.5 ± 0.7	96.9 ± 0.9	97.3 ± 0.8	98.1 ± 0.6	98.8 ± 0.4
MI$_{40}$	97.1 ± 0.6	97.5 ± 0.8	97.6 ± 0.6	95.7 ± 2.0	97.4 ± 0.8
Neutral task					
MI$_{10}$	98.0 ± 0.8	98.8 ± 0.3	98.4 ± 0.4	97.9 ± 0.6	97.4 ± 0.6
MI$_{20}$	98.4 ± 0.4	98.0 ± 0.6	97.5 ± 0.6	97.9 ± 0.6	97.9 ± 0.7
MI$_{40}$	97.3 ± 0.7	98.2 ± 0.7	98.5 ± 0.4	95.3 ± 1.9	98.0 ± 0.5
Incongruent task					
MI$_{10}$	98.3 ± 0.5	98.5 ± 0.3	98.1 ± 0.6	97.3 ± 0.9	98.4 ± 0.5
MI$_{20}$	97.3 ± 0.9	98.4 ± 0.4	97.7 ± 0.5	97.6 ± 0.8	98.3 ± 0.5
MI$_{40}$	98.1 ± 0.6	97.1 ± 0.8	98.0 ± 0.8	97.6 ± 0.6	97.1 ± 0.6

Values are presented as mean ± SEM.

In the reaction time, significant type of CWST–time interaction is as follows: *$P < 0.01$ preexercise vs 0-min postexercise recovery, **$P < 0.01$ preexercise vs 10-min postexercise recovery, ***$P < 0.01$ preexercise vs 20-min postexercise recovery, ****$P < 0.01$ preexercise vs 30-min postexercise recovery, *****$P < 0.01$ 0-min postexercise recovery vs 10-min postexercise recovery, ******$P < 0.01$ 0-min postexercise recovery vs 20-min postexercise recovery, *******$P < 0.01$ 0-min postexercise recovery vs 30-min postexercise recovery, ********$P < 0.01$ 10-min postexercise recovery vs 30-min postexercise recovery, $^{a}P < 0.017$ congruent task vs neutral task, $^{b}P < 0.017$ congruent task vs incongruent task, $^{c}P < 0.017$ neutral task vs incongruent task.

recovery for 30 min (10-min postexercise recovery period: $t_{44} = 2.82$, $P < 0.01$; 20-min postexercise recovery period: $t_{44} = 3.96$, $P < 0.01$; 30-min recovery postexercise: $t_{44} = 5.70$, $P < 0.01$). Moreover, the reaction time values during the 10-min postexercise recovery period were significantly shorter than those during the 30-min postexercise recovery period ($t_{44} = 4.15$, $P < 0.01$).

The interference score before exercise was similar among all protocols (Fig. 3A). There was significant main effect for time ($F_{1.79,\ 25.04} = 17.45$, $P < 0.01$, $\eta_p^2 = 0.56$). However, there were no significant main effects for the other factors. Follow-up *post hoc* comparisons for the time effect indicated that the interference scores immediately after exercise were significantly greater than that before exercise ($t_{44} = 4.15$, $P < 0.01$). Although the improvement in the interference scores after exercise remained significant during the 30-min postexercise recovery period ($t_{44} = 3.34$, $P < 0.01P < 0.05$), that immediately after exercise and during the 10- and 20-min postexercise recovery periods were greater than that during the 30-min postexercise recovery period (0-min postexercise recovery period: $t_{44} = 3.73$, $P < 0.01$; 10-min postexercise recovery period: $t_{44} = 6.54$, $P < 0.01$; 20-min postexercise recovery period: $t_{44} = 4.87$, $P < 0.01$). The interference scores during postexercise recovery for 30 min did not exhibit a significant difference in the main effect for condition, whereas follow-up *post hoc* comparisons for condition indicated that the interference scores for MI$_{40}$ were slightly higher than those for MI$_{10}$ ($t_{74} = 2.14$, $P = 0.036$). In addition, the magnitude of the differences between preexercise and 30-min postexercise recovery period, which was evaluated using Cohen's effect size, was moderately larger in MI$_{40}$ (Cohen's $d = 0.68$), but not in MI$_{10}$ and MI$_{20}$ (Cohen's $d = 0.30$ and 0.31 for both).

The FAS-measured arousal level and the VAS-measured psychological conditions before exercise were similar among all protocols (Figs. 3B and 3C). The arousal level analysis revealed a significant time–condition interaction ($F_{8,\ 112} = 4.10$, $P < 0.05$, $\eta_p^2 = 0.23$). *Post hoc* analyses comparing the condition effect within each period revealed that the increased arousal level immediately after exercise was significantly higher in MI$_{40}$ than in MI$_{10}$ ($t_{14} = 4.58$, $P < 0.017$). In addition, the arousal level of 10-min postexercise recovery period was significantly higher after MI$_{20}$ and MI$_{40}$ than MI$_{10}$ ($t_{14} = 2.82$, $P < 0.017$ and $t_{14} = 4.18$, $P < 0.017$ for both). *Post hoc* analyses comparing the time effect within each condition revealed that the arousal level immediately after exercise was significantly higher than that of preexercise in all protocols (MI$_{10}$: $t_{14} = 5.17$, $P < 0.01$; MI$_{20}$: $t_{14} = 7.25$, $P < 0.01$; MI$_{40}$: $t_{14} = 7.87$, $P < 0.01$). Moreover, the increase in arousal levels after MI$_{20}$ and MI$_{40}$, but not MI$_{10}$, remained significant during the 20-min postexercise recovery period. The VAS-measured mental fatigue for CWST analysis revealed a significant time–condition interaction ($F_{3.64,\ 51.01} = 3.69$, $P < 0.05$, $\eta_p^2 = 0.21$). *Post hoc* analyses comparing the condition effect within each period revealed that the increased mental fatigue level immediately after exercise was significantly higher after MI$_{40}$ than MI$_{10}$ and MI$_{20}$ ($t_{14} = 3.89$, $P < 0.017$ and $t_{14} = 3.14$, $P < 0.017$). *Post hoc* analyses comparing the time effect within each condition revealed that the mental fatigue immediately after exercise in all protocols was significantly higher

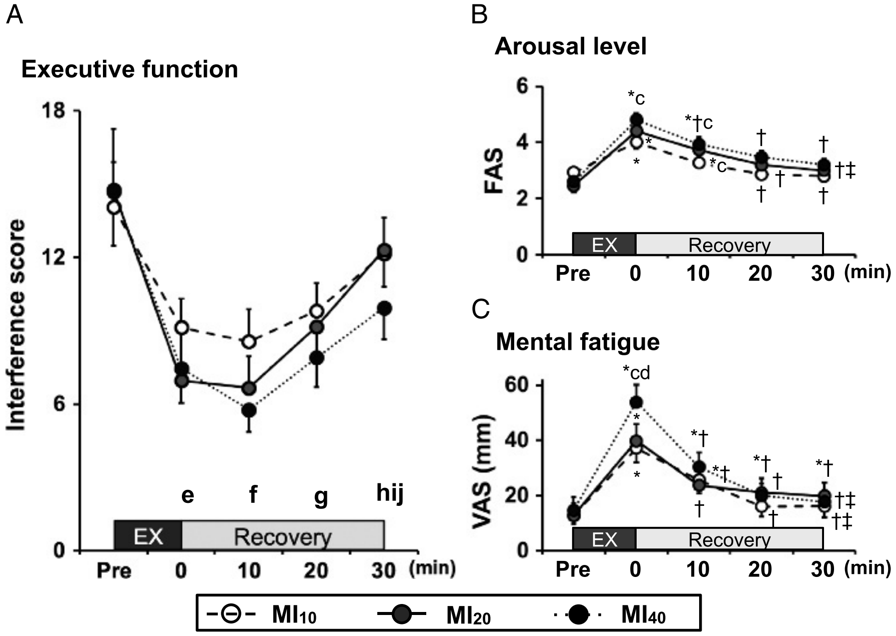

FIGURE 3—Changes in EF and psychological conditions for the CWST during the experimental session in study 2. The changes in the interference score (A), FAS-measured arousal level (B), and VAS-measured mental fatigue (C) in study 2 are presented using *open circles* for MI_{10}, *gray circles* for MI_{20}, and *black circles* for MI_{40}. Values are presented as mean ± SEM. Significant time–condition interaction is as follows: $^{c}P < 0.017$ vs MI_{10}; $^{d}P < 0.017$ vs MI_{20}; $*P < 0.01$ vs preexercise; $\dagger P < 0.01$ vs postexercise for 0 min (i.e., immediately after exercise); $\ddagger P < 0.01$ vs postexercise for 10 min. Significant main effect for time is as follows: $^{e}P < 0.01$ preexercise vs 0-min postexercise recovery, $^{f}P < 0.01$ 0-min preexercise recovery vs 10-min postexercise recovery, $^{g}P < 0.01$ 0-min preexercise recovery vs 20-min postexercise recovery, $^{h}P < 0.01$ 0-min postexercise recovery vs 30-min postexercise recovery, $^{i}P < 0.01$ 10-min postexercise recovery vs 30-min postexercise recovery, $^{j}P < 0.01$ 20-min postexercise recovery vs 30-min postexercise recovery.

than that before exercise (MI_{10} $t_{14} = 5.05$, $P < 0.01$; MI_{20} $t_{14} = 5.11$, $P < 0.01$; and MI_{40} $t_{14} = 6.98$, $P < 0.01$). Moreover, the increase in mental fatigue remained significant during the 10-min postexercise recovery period after MI_{10} and MI_{40}, and during the 30-min postexercise recovery period after MI_{20}. There were no significant main effects for other factors, including main effects of ability to concentrate and motivation.

DISCUSSION

In the present study, involving two volume-controlled evaluations, we assessed the effect of exercise volume on postexercise EF improvement to establish an effective exercise protocol. First, in study 1, we compared the effect of higher-volume exercises (MI_{20} and LI_{40}) and lower-volume exercise (LI_{20}) on postexercise EF, within the range of moderate exercise volume, as per the recommended guidelines (1,10,13). The findings showed that the postexercise EF was improved to a greater extent after MI_{20} than after LI_{20} and LI_{40}. Moreover, we observed a slight trend toward statistical significance with regard to postexercise EF improvement among the different exercise conditions with time, as analyzed using two-way ANOVA; this result showed that the postexercise EF improvement could be sustained for a longer duration after LI_{40} than after LI_{20}. Hence, we suggest that, within the range of moderate exercise volume, higher-volume exercise, particularly with the application of MI rather than LI, could effectively prolong postexercise EF as compared with lower-volume exercise. On the basis of the results of study 1, in study 2, we examined the effect of the exercise duration of MI exercise on postexercise EF. Chang et al. (4) reported that the effect of exercise duration on the Stroop test–measured cognitive function immediately after MI exercise was greater after 20 min than after 10 or 45 min of exercise. However, the protocol for prolonging EF improvement during postexercise recovery was unclear. In the present study, we did not observe any significant difference in the postexercise EF improvement among exercise conditions with differing durations, as assessed via two- or three-way ANOVA. In addition to further statistical analysis, we assessed the magnitude of the differences in the interference scores at each time point among the different exercise conditions by using Cohen's effect size (6,7). These results showed that the magnitude of the differences between preexercise and 30-min postexercise recovery periods was moderately larger in MI_{40}, but not in MI_{10} and MI_{20}, indicating that EF improvement during postexercise recovery could be sustained after MI_{40}. Hence, we suggest that MI exercise with a relatively long duration could slightly prolong the postexercise EF improvement.

The mechanisms underlying the acute exercise-induced improvement in EF are poorly understood. Byun et al. (3) reported that acute exercise-induced EF improvement is mediated by the psychological arousal system, which is correlated with neural activation in the brain. In the present study, the FAS-measured arousal level immediately after exercise was significantly greater in exercise protocols with a higher intensity or a longer duration than that in exercise protocols with a lower intensity or a shorter or moderate duration. In particular, in study 1, MI_{20} markedly increased the arousal level immediately after exercise, as compared with LI_{40}, whereas the EF improvement immediately after exercise was similar between the volume-matched MI_{20} and LI_{40}. Thus, the extent of EF improvement immediately after exercise may not be explained only by the psychological arousal response. By contrast, Grego et al. (12) suggested that exercise with a markedly long duration (3 h) at 60% $\dot{V}O_{2max}$ compromised cognitive ability, probably by causing central nervous system fatigue. In study 2, the increase in VAS-measured mental fatigue immediately after exercise was significantly greater after MI_{40} than after MI_{10} and MI_{20}. However, no significant difference was observed in postexercise EF improvement among the exercise conditions with differing durations. Hence, postexercise EF improvement may be independent of the enhancement of psychological mental fatigue. Furthermore, psychological responses, such as arousal level and mental fatigue, may not be sufficient for explaining the sustained nature of EF improvement during the postexercise recovery.

In general, glucose and lactate are important energy sources in the human brain (28). Although the brain mainly relies on glucose at rest, the uptake of glucose markedly decreases during high-intensity exercise, along with an increase in blood lactate levels (15). Hence, because of the compensatory action of decreased glucose uptake, the main energy source in the brain during high-intensity exercise switches to lactate (28). Interestingly, Ferris et al. (9) reported that the increased blood lactate level induced by acute exercise correlated with blood brain-derived neurotrophic factor (BDNF) level, which is a major maker for cognitive function. Moreover, Schiffer et al. (22) determined that lactate infusion at rest increased the blood BDNF level, indicating that lactate is an important regulator for controlling the BDNF level. Recently, we reported that the EF improvement during the postexercise recovery was sustained for a longer period in HIIE than in volume-matched MI exercise, and that these EF responses were associated with the blood lactate response during the postexercise recovery (26). More recently, we showed that EF improvement during the postexercise recovery in HIIE was closely related to blood lactate levels (27). In study 1, the blood lactate levels after LI_{20} and LI_{40} did not increase to within the lactate threshold, whereas the blood lactate levels after MI_{20} were significantly greater compared with those before exercise. However, we did not obtain direct evidence linking brain lactate metabolism and postexercise EF improvement, and this relationship should be elucidated in future studies.

The present study mainly focused on the EF response during postexercise recovery. Only a few previous studies have focused this topic (21,26,27). In the present study, we sought to elucidate the methods for effectively improving EF, which could then facilitate the establishment of an effective exercise protocol for improving human health. To promote and maintain health, the American College of Sports Medicine and American Heart Association recommend that healthy adults 18–65 yr of age need to perform exercise of sufficient volumes, such as MI exercise for at least 30 min (13). In addition, a previous meta-analysis indicated that the long-term exercise-induced improvement in cognitive function, including EF, was more effective after exercise interventions with a relatively long duration (>30 min) than after exercise interventions with a relatively short duration (<30 min) (8); these findings could be used to establish effective exercise protocol for improving human health, including the physical fitness level (10,11,13,16). Moreover, compared with habitual lower-intensity exercise, higher-intensity exercise can effectively improve cardiovascular and metabolic health (1,11,25). In the present study, the application of a higher-volume exercise (e.g., MI_{40}), within the range recommended by exercise guidelines, may yield prolonged EF improvement during postexercise recovery. In particular, in terms of exercise intensity, an increase from LI to MI might be potentially very effective for improving postexercise EF, although the effect of high-intensity exercise (such as >70% VO_{2peak}) was not examined in the present study. On the basis of these results, we propose that the increase in exercise volume within the range recommended by the exercise guidelines for human health improvement may be also effective for improving postexercise EF; however, it is unclear whether the acute effects of aerobic exercise on EF would also be observed in chronic exercise training. To obtain further evidence supporting this notion, further studies should examine the chronic effects of higher-volume exercise on EF.

The present study has several limitations. First, the present study included a relatively small number of subjects, as compared with previous studies. Chang et al. (4) recruited 26 subjects and examined the effects of the different exercise protocols on the Stroop test–measured cognitive performance. By contrast, studies 1 and 2 of the present study included 12 and 15 subjects, respectively. The lack of main effects for some parameters in the present study might be due to the relatively small sample power. Next, we concluded that higher-volume exercise within the range recommended by the exercise guideline from the American College of Sports Medicine and the American Heart Association is effective for improving postexercise EF, as compared with lower-volume exercise. Moreover, in a recent study, we showed that the EF improvement during postexercise recovery could be sustained for a longer period in HIIE than in volume-matched MI exercise (26). Importantly, the exercise volume of HIIE in the previous study is similar to that of MI_{40} in the present study, suggesting that HIIE represents an appropriate range of exercise volume for improving EF. By contrast, previous studies indicate that the improvement of cognitive performance during exercise is impaired by heavier-volume intensity exercise, such as an exercise protocol combining a high intensity with long duration (e.g., 40 min at 80% HRR) (29) or including a very long duration (e.g., 3 h) (12). Nevertheless, these protocols in previous studies might not specify the appropriate range of exercise volume, and further studies are needed to examine the optimal exercise volume on EF during postexercise recovery. Finally, we primarily recruited healthy young males for the present study. However, the improvement in EF may be more important for elderly individuals or those with various chronic diseases than for the healthy population. Hence, further studies are needed to examine the effect of exercise volume in elderly individuals and patients with chronic diseases such as Alzheimer's disease, type 2 diabetes, and chronic obstructive pulmonary disease.

In conclusion, the present study showed that higher-volume exercise could effectively prolong the exercise-induced improvement of EF, as compared with lower-volume exercise. In particular, we noted that the postexercise EF improvement was sustained for a longer period with MI exercise than with LI exercise, as compared with volume-matched exercises. Moreover, MI exercise with a relatively long duration may have a slightly ameliorative effect for prolonging the postexercise EF improvement, as compared with exercise with a relatively short duration. Therefore, we propose that the application of an optimized protocol based on exercise volume may be beneficial for improving cognition and can also be useful for developing effective exercise protocols for improving human health.

The authors appreciate the time and effort expended by the volunteer subjects. This study was supported by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Culture, Sports, Science, and Technology (no. 15J04023 to H. T.; no. 15K16497 to T. S.; no. 15H03077 to T. I.; nos. 26702029 and 15K12676 to T. H.).

Hayato Tsukamoto and Saki Takenaka contributed equally to this article.

The authors declare no conflict of interest. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. American College of Sports Medicine. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Med Sci Sports Exerc*. 1998;30(6):975–91.
2. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–81.
3. Byun K, Hyodo K, Suwabe K, et al. Positive effect of acute mild exercise on executive function via arousal-related prefrontal activations: an fNIRS study. *Neuroimage*. 2014;98:336–45.
4. Chang YK, Chu CH, Wang CC, et al. Dose–response relation between exercise duration and cognition. *Med Sci Sports Exerc*. 2015; 47(1):159–65.
5. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res*. 2012;1453:87–101.
6. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988. pp. 20–40.
7. Cohen J. A power primer. *Psychol Bull*. 1992;112(1):155–9.
8. Colcombe S, Kramer AF. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol Sci*. 2003;14(2): 125–30.
9. Ferris LT, Williams JS, Shen CL. The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. *Med Sci Sports Exerc*. 2007;39(4):728–34.
10. Garber CE, Blissmer B, Deschenes MR, et al. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Med Sci Sports Exerc*. 2011;43(7): 1334–59.
11. Gormley SE, Swain DP, High R, et al. Effect of intensity of aerobic training on VO_{2max}. *Med Sci Sports Exerc*. 2008;40(7): 1336–43.
12. Grego F, Vallier JM, Collardeau M, Rousseu C, Cremieux J, Brisswalter J. Influence of exercise duration and hydration status on cognitive function during prolonged cycling exercise. *Int J Sports Med*. 2005;26(1):27–33.
13. Haskell WL, Lee IM, Pate RR, et al. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med Sci Sports Exerc*. 2007;39(8):1423–34.
14. Ikeda Y, Hirata S, Okuzumi H, Kokubun M. Features of Stroop and reverse-Stroop interference: analysis by response modality and evaluation. *Percept Mot Skills*. 2010;110(2):654–60.
15. Kemppainen J, Aalto S, Fujimoto T, et al. High intensity exercise decreases global brain glucose uptake in humans. *J Physiol*. 2005;568:323–32.
16. Lee IM, Rexrode KM, Cook NR, Manson JE, Buring JE. Physical activity and coronary heart disease in women: is "no pain, no gain" passé? *JAMA*. 2001;285(11):1447–54.
17. Lucas SJ, Ainslie PN, Murrell CJ, Thomas KN, Franz EA, Cotter JD. Effect of age on exercise-induced alterations in cognitive executive function: relationship to cerebral perfusion. *Exp Gerontol*. 2012; 47(8):541–51.
18. MacLeod CM. Half a century of research on the Stroop effect: an integrative review. *Psychol Bull*. 1991;109(2):163–203.
19. Monsell S. Task switching. *Trends Cogn Sci*. 2003;7(3):134–40.
20. Ogoh S, Tsukamoto H, Hirasawa A, Hasegawa H, Hirose N, Hashimoto T. The effect of changes in cerebral blood flow on cognitive function during exercise. *Physiol Rep*. 2014;2(9):e12163.
21. Pontifex MB, Hillman CH, Fernhall B, Thompson KM, Valentini TA. The effect of acute aerobic and resistance exercise on working memory. *Med Sci Sports Exerc*. 2009; 41(4):927–34.
22. Schiffer T, Schulte S, Sperlich B, Achtzehn S, Fricke H, Strüder HK. Lactate infusion at rest increases BDNF blood concentration in humans. *Neurosci Lett*. 2011;488(3):234–7.
23. Stroop JR. Studies of interference in serial verbal reactions. *J Exp Psychol*. 1935;18(6):643–62.
24. Svebak S, Murgatroyd S. Metamotivational dominance: a multimethod validation of reversal theory constructs. *J Pers Soc Psychol*. 1985;48(1):107–16.
25. Swain DP, Franklin BA. Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. *Am J Cardiol*. 2006;97(1):141–7.
26. Tsukamoto H, Suga T, Takenaka S, et al. Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. *Physiol Behav*. 2016;155:224–30.
27. Tsukamoto H, Suga T, Takenaka S, et al. Repeated high-intensity interval exercise shortens the positive effect on executive function during post-exercise recovery in healthy young males. *Physiol Behav*. 2016;160:26–34.
28. van Hall G, Strømstad M, Rasmussen P, et al. Blood lactate is an important energy source for the human brain. *J Cereb Blood Flow Metab*. 2009;29:1121–9.
29. Wang CC, Chu CH, Chu IH, Chan KH, Chang YK. Executive function during acute exercise: the role of exercise intensity. *J Sport Exerc Psychol*. 2013;35(4):358–67.