

Aftereffects of Cognitively Demanding Acute Aerobic Exercise on Working Memory

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ABSTRACT

KAMIJO, K., and R. ABE. Aftereffects of Cognitively Demanding Acute Aerobic Exercise on Working Memory. *Med. Sci. Sports Exerc.*, Vol. 51, No. 1, pp. 153–159, 2019. **Purpose:** This study examined the aftereffects of cognitively demanding acute aerobic exercise on working memory in middle-age individuals. **Methods:** In a within-participants design, middle-age males ($n = 28$) performed a two-back task to assess working memory before, immediately after, and 30 min after the following three interventions: 1) a rest-cognition intervention, in which they performed a cognitive task on a cycle ergometer without exercising; 2) an exercise-cognition intervention, in which they simultaneously exercised on a cycle ergometer and performed a cognitive task; and 3) an exercise-only intervention, in which they only exercised on a cycle ergometer. **Results:** The exercise-only intervention resulted in increased hit rate and decreased reaction times and intraindividual variability on correct rejection trials, suggesting that simple aerobic exercise had a beneficial impact on working memory. By contrast, the exercise-cognition intervention resulted in increased intraindividual variability on correct rejection trials, which is suggestive of cognitive fatigue resulting from the additional cognitive demands. Such a decline was not observed even in the rest-cognition condition. **Conclusions:** Cognitive fatigue caused by additional cognitive demands during aerobic exercise may cancel beneficial postexercise effects on working memory. Cognitively demanding acute aerobic exercise appears to be less effective than simple aerobic exercise in improving executive function. **Key Words:** SINGLE BOUT OF EXERCISE, EXECUTIVE FUNCTION, COGNITIVE FUNCTION, COGNITIVE FATIGUE, MIDDLE AGE

A considerable number of studies published over the last two decades have provided evidence that chronic regular exercise improves cognitive function across the lifespan, and this beneficial effect is disproportionately greater for higher-order cognitive function (i.e., executive function), such as inhibition, working memory, and cognitive flexibility (1,2). More recently, researchers have attempted to shed light on the types of exercise that are more effective for improving cognitive function. Some have found that cognitively demanding *chronic* exercise (e.g., exergaming) has a greater impact on cognitive function than simple exercise (e.g., running) (3,4). It is possible that this *chronic* effect is attributable to the increased beneficial effects of *acute*

exercise on cognitive function given by cognitively demanding exercise than simpler exercise because the habitual repetitions of acute exercise result in chronic effects. Several studies have indeed found that cognitively demanding acute exercise had a greater positive impact than simpler exercise on postexercise cognitive performance in children (5,6) and older adults (7). However, other research has suggested that sustained cognitive effort during exercise may not enhance cognitive function. Berman et al. (8) found that working memory performance improved after walking in nature, but not after walking in urban areas. Based on attention restoration theory (9), Berman et al. suggested that walking in nature, which modestly captures bottom-up attention, can provide the opportunity to replenish cognitive abilities. Stated differently, urban environments, which require sustained top-down attention, may induce cognitive fatigue, resulting in inferior working memory performance. Several other studies also found cognitively demanding exercise to be less effective than simpler exercise in enhancing cognitive function in children (10,11) and young adults (12).

Because these acute exercise studies were conducted in a variety of settings, including exergaming (5,7,12), game-based exercise (6), and classrooms (10,11), factors besides cognitive demands that could have influenced postexercise cognitive function, such as motor control demands, social interaction, and enjoyment, were likely to have differed between the exercise conditions. Differences in experimental

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design (i.e., between-participants vs within-participants) may have also led to different effects on cognitive performance. In acute exercise studies, a within-participants design is generally considered to be more appropriate than a between-participants design in preventing effects of individual differences or other personality attributes. A relatively small number of studies have used a within-participants design to examine the after-effects of cognitively demanding acute exercise. Studies using a within-participants design showed a smaller improvement in postexercise cognitive performance for cognitively demanding exercise relative to simpler exercise (11,12). Thus, further empirical research is needed to elucidate the aftereffects of cognitively demanding acute exercise on cognitive function in a well-controlled laboratory setting. The present study examined the aftereffects of such exercise on working memory, which is one of the key aspects of executive function.

The majority of acute exercise studies have focused on children, young adults, or older adults (13), and thus little is known about the effects of acute exercise on cognitive function in middle-age individuals. Spartano et al. (14) indicated that midlife aerobic fitness was associated with brain volume nearly 20 yr later, suggesting that aerobic exercise in middle age may be beneficial for healthy brain aging. The secondary purpose of this study was to examine whether middle-age individuals experience effects of aerobic exercise on working memory that are similar to those found in other age groups. Middle-age individuals are in their most productive years, and working memory plays a critical role in supporting them in various aspects of complex everyday cognitive activities (15) including business performance (16). Therefore, an association between aerobic exercise and working memory could encourage middle-age individuals to exercise during working hours.

The present study used a within-participants design in which middle-age participants performed a two-back task, which required updating working memory information before, immediately after, and 30 min after three interventions: 1) a rest-cognition intervention, in which participants performed a cognitive task on a cycle ergometer without exercising; 2) an exercise-cognition intervention, in which participants simultaneously performed a cycling exercise and a cognitive task; and 3) an exercise-only intervention, in which participants only exercised on a cycle ergometer without performing a cognitive task. The exercise-cognition condition and the exercise-only condition were identical in every way except for cognitive demands during the cycling exercise, and the rest-cognition condition served as a rest control condition. Given that a number of studies have shown beneficial effects of acute aerobic exercise on postexercise executive function (13,17), we predicted that working memory performance, as reflected in response accuracy and reaction times (RT), would improve after the interventions in both exercise conditions, but not in the rest-cognition condition. Because of the contradictory findings noted above, we could not make a firm prediction regarding the beneficial effects of acute exercise on working memory in the exercise-cognition versus exercise-only conditions.

METHOD

Participants

Thirty-six middle-age men were recruited from Shimano Inc., Osaka, Japan. All participants reported being free of neurological disorders, cardiovascular disease, and any medications that influenced central nervous system function, and all were nonsmokers with normal or corrected-to-normal vision. The study was approved by the Ethics Committee on Human Research of Waseda University, and all participants provided written informed consent. Data from eight participants were discarded because they did not complete all experimental conditions (six participants) or performed below chance (i.e., <50%) on the two-back task used to assess working memory (two participants). Thus, data from 28 participants were analyzed. Table 1 presents demographic data for this sample. A sensitivity analysis performed based on this sample with 80% power and alpha of 0.05 demonstrated sufficient sensitivity to detect repeated measures effects exceeding $f = 0.247$ (assuming correlation between repeated measures ≥ 0.5) and t -test differences exceeding $d = 0.549$ (with a two-tailed alpha), as computed using G*Power 3.1.9.2 (18).

Laboratory Procedure

On the first day, participants completed the informed consent form, the Physical Activity Readiness Questionnaire (19) to screen for possible medical risks that could be exacerbated by exercise, and the Global Physical Activity Questionnaire (20) to assess their physical activity levels, and had their height and weight measured. They were then given task instructions for the two-back and switch tasks, which were performed in subsequent experimental conditions on different days, and they engaged in practice trials until they reached the criterion of 70% accuracy.

Figure 1 illustrates the experimental protocol. A within-participants repeated-measures design was used. Three experimental conditions were investigated: the rest-cognition condition, the exercise-cognition condition, and the exercise-only condition. Participants performed a two-back task before (pretest), immediately after (post 1), and 30 min after (post 2) each intervention while sitting on a chair. Between post 1 and post 2, they sat on the chair and quietly read a newspaper. Each condition was conducted at the same time on a different day (mean days apart = 10.1 d, SD = 2.8), and the condition order was randomized and counterbalanced across participants. Before the start of each experimental session, participants were fitted with an HR monitor (Garmin Forerunner 735XT, Garmin, Olathe, KS) to measure HR throughout the test.

TABLE 1. Mean (SD) values for demographic data.

Measures	Mean (SD)	Range
Age (yr)	44.1 (3.6)	40.1–52.1
Height (cm)	172.7 (5.0)	158.2–182.5
Weight (kg)	70.4 (7.4)	58.5–87.4
Body mass index ($\text{kg}\cdot\text{m}^{-2}$)	23.6 (2.4)	20.6–28.9
GPAQ total score ($\text{kcal}\cdot\text{wk}^{-1}$)	1615.0 (1185.0)	0–4320

GPAQ, Global Physical Activity Questionnaire.

5, which were enclosed within a solid or dashed square. This task asked participants to press one of two buttons with their index fingers corresponding to whether the digit was lower (left button) or higher (right) than 5 for the digit surrounded by a solid square, or whether the digit was odd (left) or even (right) for the digit surrounded by a dashed square. Seventy-two stimuli were presented, and the first trial was discarded, leaving 71 trials to be analyzed. The task (i.e., low/high or odd/even) changed predictably every two trials (i.e., AABBA...), resulting in 36 nonswitch and 35 switch trials. All eight digits were pseudorandomly presented with equal probability. Each stimulus was presented for 200 ms with a fixed stimulus onset asynchrony of 2500 ms, and thus the task duration was 3 min. Participants performed four blocks of this 3-min switch task during the interventions in both cognition conditions. Outcome variables for the switch task included response accuracy, RT, and SDRT on nonswitch and switch trials. Data from one participant were lost due to experimenter error, and analyses for the switch task performance were thus conducted for 27 participants.

Statistical Analysis

Data were analyzed using SPSS (SPSS v. 25, Chicago, IL). For the two-back task, response accuracy, RT, and SDRT on hit and correct rejection trials were separately analyzed using a 3 (Condition: rest-cognition, exercise-cognition, exercise-only) \times 3 (Time: pretest, post 1, post 2) repeated-measures ANOVA. For the switch task, response accuracy, RT, and SDRT were analyzed using a 2 (Condition: rest-cognition, exercise-cognition) \times 2 (Trial: switch, nonswitch) repeated-measures ANOVA. HR was analyzed using a 3 (Condition: rest-cognition, exercise-cognition, exercise-only) \times 4 (Time: pretest, during, post 1, post 2) repeated-measures ANOVA. RPE was analyzed using a paired *t*-test between the exercise-cognition and exercise-only conditions. Analyses with three or more within-participants levels used the Greenhouse-Geisser statistic if the sphericity assumption was violated. *Post hoc* analyses were conducted using univariate ANOVA and Bonferroni-corrected *t*-tests. Effect sizes are presented as partial eta-squared and Cohen's *d* for ANOVA and *t*-tests, respectively. All statistical analyses were conducted using a significance level of $P = 0.05$ before Bonferroni correction.

RESULTS

Intervention

Analysis of HR revealed significant main effects of Condition ($F(2, 54) = 129.3, P < 0.001, \eta^2_p = 0.83$), and Time, ($F(3, 81) = 499.1, P < 0.001, \eta^2_p = 0.95$), which were qualified by a Condition-Time interaction ($F(6, 162) = 171.6, P < 0.001, \eta^2_p = 0.87$), as shown in Figure 2. No differences emerged at pretest, ($F(2, 54) = 0.5, P = 0.6, \eta^2_p = 0.02$), whereas significant differences were observed during intervention and at post 1 and post 2 ($F(2, 54) \geq 8.5, P \leq 0.002, \eta^2_p \geq 0.24$). Bonferroni-corrected *post hoc t*-tests ($P < 0.017$) indicated

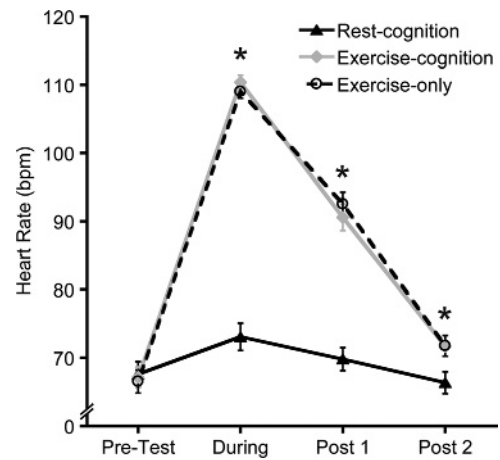


FIGURE 2—Mean heart rate for each experimental condition. Error bars indicate SE. * $P < 0.017$ (Bonferroni correction) between rest-cognition condition and both exercise conditions.

that HR was higher for both exercise conditions relative to the rest-cognition condition during intervention and at post 1 and post 2, t 's (27) $\geq 3.0, P$'s $\leq 0.006, d$'s ≥ 0.56). Although participants had higher HR even at post 2 for both exercise conditions, as expected, mean HR were within 10% of preexercise levels (7.3% and 8.8% for exercise-cognition and exercise-only, respectively), the criterion used in previous studies to examine the aftereffects of acute aerobic exercise on cognition (25,26). More importantly, changes in HR were nearly identical in the two exercise conditions. Analysis of RPE revealed no difference between the exercise-cognition (mean = 11.9, SD = 1.0) and exercise-only (mean = 11.8, SD = 0.9) conditions, t (27) = 1.8, $P = 0.2, d = 0.22$.

Two-Back Task Performance

Analysis of hit accuracy revealed a significant Condition-Time interaction ($F(4, 108) = 2.6, P = 0.04, \eta^2_p = 0.09$), as shown in Figure 3A. No time difference was observed for the rest-cognition and exercise-cognition conditions ($F(2, 54) \leq 1.7, P \geq 0.2, \eta^2_{ps} \leq 0.06$), whereas a significant time difference emerged in the exercise-only condition ($F(2, 54) = 4.2, P = 0.02, \eta^2_p = 0.13$). Bonferroni-corrected *post hoc t*-tests ($P < 0.017$) indicated that hit accuracy increased at post 2 relative to pretest for the exercise-only condition (t (27) = 3.1, $P = 0.005, d = 0.58$). Analysis of correct rejection accuracy revealed a significant Time main effect ($F(2, 54) = 8.8, P = 0.001, \eta^2_p = 0.25$), which demonstrated decreased correct rejection accuracy at post 1 relative to pretest and post 2 across conditions (t 's (27) $\geq 3.4, P$'s $\leq 0.002, d$'s ≥ 0.64 , as shown in Fig. 3B).

Analysis of hit RT revealed no significant main effects or interaction (P 's ≥ 0.3 ; Fig. 3C). Analysis of correct rejection RT revealed a significant main effect of Time ($F(2, 54) = 9.6, P < 0.001, \eta^2_p = 0.26$), which was qualified by a Condition-Time interaction ($F(4, 108) = 3.5, P = 0.01, \eta^2_p = 0.11$), as shown in Fig. 3D. No time difference was found for the exercise-cognition condition ($F(2, 54) = 0.8, P = 0.5, \eta^2_p = 0.03$),

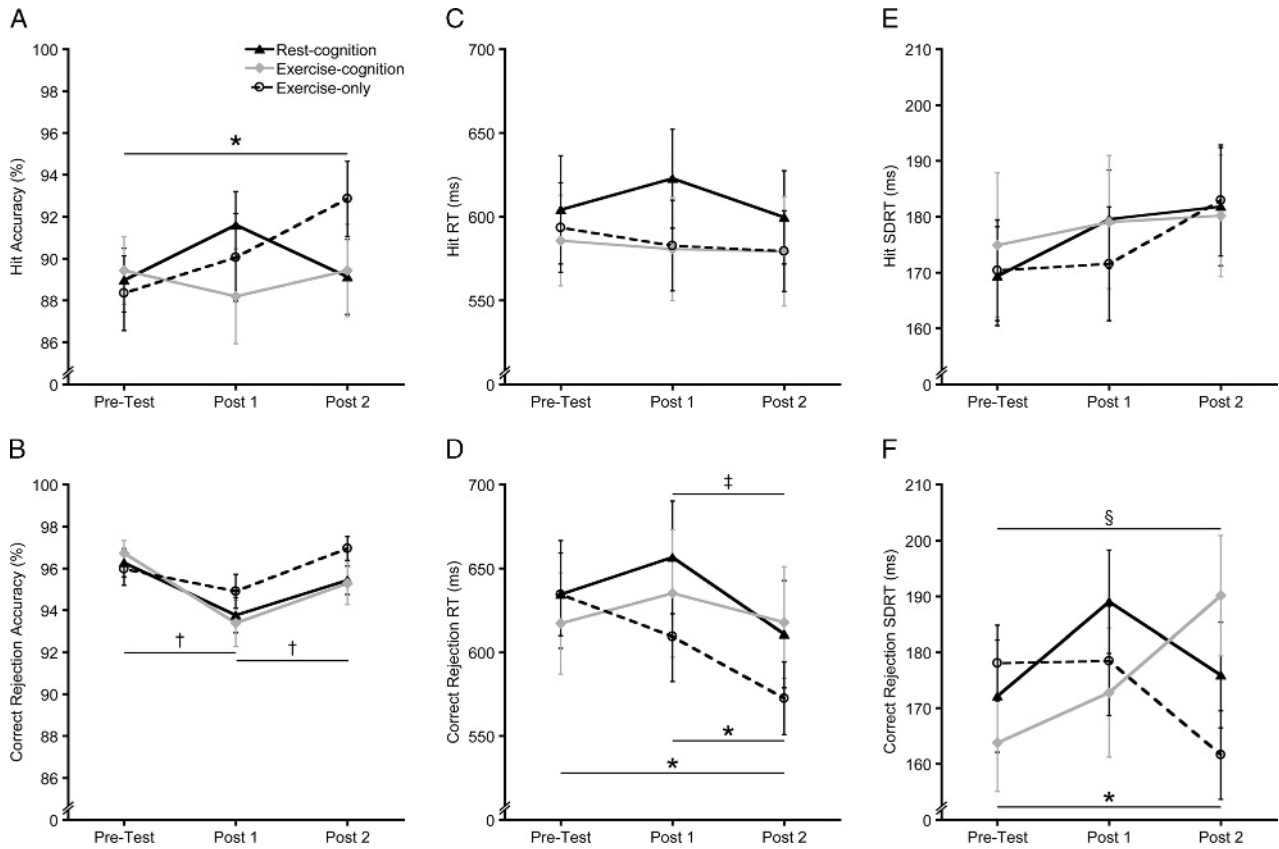


FIGURE 3—Mean response accuracy (A, B), RT (C, D), and SDRT (E, F) on hit and correct rejection trials during two-back task for each experimental condition. Error bars indicate SE. * $P < 0.017$ (Bonferroni correction) for exercise-only condition, † $P < 0.017$ across conditions, ‡ $P < 0.017$ for rest-cognition condition, § $P < 0.017$ for exercise-cognition condition.

but significant time differences were observed for the rest-cognition and exercise-only conditions (F 's(2, 54) ≥ 5.5 , P 's ≤ 0.007 , $\eta^2_{ps} \geq 0.17$). Bonferroni-corrected *post hoc t*-tests ($P < 0.017$) indicated that correct rejection RT decreased at post 2 relative to post 1 in the rest-cognition condition ($t(27) = 4.1$, $P < 0.001$, $d = 0.78$) and relative to pretest and post 1 for the exercise-only condition (t 's (27) ≥ 3.2 , P 's ≤ 0.004 , d 's ≥ 0.60).

Analysis of hit SDRT revealed no significant main effect or interaction (P 's ≥ 0.4 ; Fig. 3E). Analysis of correct rejection SDRT revealed a significant Condition–Time interaction, $F(4, 108) = 4.0$, $P = 0.004$, $\eta^2_p = 0.13$, as illustrated in Fig. 3F. Significant time differences were observed for the exercise-cognition and exercise-only conditions (F 's(2, 54) ≥ 3.7 , P 's ≤ 0.03 , $\eta^2_{ps} \geq 0.12$), but not for the rest-cognition condition ($F(2, 54) = 2.0$, $P = 0.1$, $\eta^2_p = 0.07$). Bonferroni-corrected *post hoc t*-tests ($P < 0.017$) indicated that correct rejection SDRT increased at post 2 relative to pretest in the exercise-cognition condition ($t(27) = 2.7$, $P = 0.01$, $d = 0.52$), but decreased at post 2 relative to pretest in the exercise-only condition ($t(27) = 2.6$, $P = 0.016$, $d = 0.49$).

Switch Task Performance

Table 2 presents switch task performance for the rest-cognition and exercise-cognition conditions. Analysis of response accuracy revealed a significant main effect of Trial

($F(1, 26) = 21.2$, $P < 0.001$, $\eta^2_p = 0.45$, with higher response accuracy for nonswitch relative to switch trials across conditions. Analysis of RT also revealed a significant main effect of Trial, $F(1, 26) = 49.3$, $P < 0.001$, $\eta^2_p = 0.66$, with shorter RT for nonswitch relative to switch trials across conditions. The Trial main effect was also significant in the analysis of SDRT ($F(1, 26) = 7.2$, $P < 0.01$, $\eta^2_p = 0.22$), with smaller SDRT for nonswitch relative to switch trials across conditions. No main effects or interactions involving the factor were significant for any switch task performance measures. These results demonstrate the typical switch effect, with no difference in cognitive performance between the rest-cognition and exercise-cognition conditions.

DISCUSSION

In the exercise-only condition, working memory performance improved after moderate aerobic exercise, as indicated

TABLE 2. Mean (SD) values for switch task performance.

Measures	Rest-Cognition	Exercise-Cognition
Nonswitch accuracy (%)*	95.5 (3.5)	96.3 (2.6)
Switch accuracy (%)	93.8 (5.4)	93.3 (4.7)
Nonswitch RT (ms)*	627.1 (129.8)	646.0 (146.6)
Switch RT (ms)	696.0 (140.7)	718.4 (157.6)
Nonswitch SDRT (ms)*	177.0 (40.7)	185.9 (45.7)
Switch SDRT (ms)	194.2 (42.9)	202.6 (43.7)

* $P < 0.05$ between nonswitch and switch trials across conditions.

by greater hit accuracy and shorter correct rejection RT. This result supports existing evidence that simple aerobic exercise has a beneficial impact on the working memory aspect of executive function (13,17). Furthermore, the positive effects of simple exercise were observed 30 min after, but not immediately following, acute aerobic exercise. This result is consistent with the conclusions of a meta-analysis, which reported that the effects of moderate intensity exercise were more significant after a delay than immediately following the exercise (17). In addition, intraindividual variability on correct rejection trials decreased 30 min after cycling exercise relative to pretest in the exercise-only condition. Intraindividual variability is considered to reflect the ability to monitor and maintain the consistency of task performance during acute cognitive effort (27). Thus, the decreased intraindividual variability following aerobic exercise observed in the exercise-only condition is likely to be indicative of upregulation of executive control to maintain task performance over the entire course of the working memory task.

Contrary to our hypothesis, no such improvement was observed for the exercise-cognition condition. Based on attention restoration theory (8), we suggest that beneficial postexercise effects on working memory may have been nullified because of cognitive fatigue from additional cognitive demands during the cycling exercise. The results of correct rejection SDRT support this assertion. The intraindividual variability on correct rejection trials increased 30 min after cycling exercise relative to pretest for the exercise-cognition condition, which is opposite to the exercise-only condition. Wang et al. (24) examined changes in cognitive performance during a prolonged (3 h) executive function task and found that intraindividual variability increased linearly over time and tended to change more over time than response accuracy and RT. From these findings, they suggested that change in intraindividual variability over time is a key performance measure of cognitive fatigue. Accordingly, the increased intraindividual variability after the present cycling exercise in the exercise-cognition condition is suggestive of cognitive fatigue resulting from the additional cognitive demands during exercise. Thus, the present evidence suggests that cognitively demanding acute aerobic exercise is less effective than simple aerobic exercise in improving postexercise executive function, consistent with prior research using a within-participants design (11,12).

It is notable that two-back performance in the rest-cognition condition after the intervention was mostly sustained relative to pretest, suggesting that the current intermittent switch task did not produce cognitive fatigue independently. Stated differently, the simultaneous combination of the switch task and aerobic exercise (i.e., cognitively demanding exercise) may have resulted in cognitive fatigue. It has been well established that the anterior cingulate cortex (ACC) plays a critical role in executive function (28), and ACC activity is likely to be sensitive to cognitive fatigue. For example, Lorist et al. (29) showed that ACC activity decreased during a prolonged executive function task with concomitant increases in RT and declines in performance adjustments after errors (i.e.,

disappearance of posterror slowing). This suggests that the reduced task performance caused by cognitive fatigue is partly due to deterioration in ACC functions such as action monitoring, the ability to monitor performance and adjust goal-directed behavior. ACC activity also seems to be associated with perception of effort during cycling exercise (30) and can influence exercise performance. Martin et al. (31) found that cognitive fatigue induced by a prolonged executive function task, which should have resulted in decreased ACC activity, impaired subsequent cycling performance. These findings suggest that ACC activity is important for maintaining both cognitive performance and exercise performance. In the present study, it is likely that the intermittent switch task alone and moderate aerobic exercise alone were not enough to induce fatigue in the ACC, whereas the simultaneous combination of the switch task and aerobic exercise (i.e., cognitively demanding exercise) triggered fatigue in the ACC. Given that the present study did not assess ACC activity, further neuroimaging studies are required to support this assertion.

Although we demonstrated that cognitively demanding acute aerobic exercise was less effective than simple exercise in improving executive function, some caution is warranted in interpreting the present results. First, we should emphasize that because we focused on *acute* exercise here, the present findings do not mean that cognitively demanding *chronic* exercise has a smaller effect than simpler exercise on executive function. Several studies have indicated that cognitively demanding *chronic* exercise is effective in improving cognitive function (3,4). It is possible that a greater amount of load on the brain is required for chronic improvements in cognitive function, as with the overload principle of strength training. Thus, the effects of acute exercise and chronic exercise should be considered separately. Second, because the current switch task, which was used to impose additional cognitive demands during cycling exercise, required extensive amounts of top-down cognitive control (23), cognitive fatigue was likely to have been produced after cognitively demanding exercise. This fatigue in turn may have underlain the observed impaired working memory performance. Further research should examine whether the effects of cognitively demanding exercise on executive function differ depending on the amount of cognitive demand during exercise. Third, as we only examined male participants here, our findings may not generalize to female populations. More importantly, the present study showed that the effects of acute simple aerobic exercise (i.e., the exercise-only intervention) on executive function in middle-age males, who have received little research attention, were similar to those on other age groups, as reported in a meta-analysis (13). Fourth, because the order of conditions was counterbalanced for all 36 participants, and data from eight participants were discarded from the analyses, the presentation order was not perfectly counterbalanced for the remaining 28 participants that were included in the current analyses. However, the order was randomized, and the six possible orders were equally distributed among the 28 participants with four to five participants for each order. Thus, it

is reasonable to assume that the order effect was negligible. Lastly, the rest-cognition condition in the present study was not a typical nonexercise control condition. Consequently, this difference might make it difficult to conduct a simple comparison between the current study and past studies. However, we believe that the rest-cognition condition was the appropriate control condition for the present study.

The present study has shown that additional cognitive demands during acute aerobic exercise (i.e., cognitively demanding exercise) can cancel beneficial postexercise effects on working memory. It is well documented that chronic changes in exercise behavior are difficult to sustain (32). Meanwhile, for example, if work efficiency can be improved after a single bout of acute aerobic exercise, people may try to find time to exercise during working hours. Thus, we believe that acute exercise

studies are important from a behavioral change perspective. Given that the effects are likely to differ between acute and chronic exercise, future studies are needed to link the relationship between the effects of these types of exercise on cognition.

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K. K. has no conflicts of interest to disclose. K. K. is now at Faculty of Engineering, Information and Systems, University of Tsukuba, Tsukuba, Ibaraki, Japan, and Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, Japan. R. A. is an employee of Shimano Inc. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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