Executive function during and after acute moderate aerobic exercise in adolescents

Keishi Soga a,1, Takayuki Shishido b, *, Ryoichi Nagatomi c,2

a Graduate School of Sport Sciences, Waseda University, 2-579-15, Mikajima, Tokorozawa, Saitama 359-1192, Japan
b Faculty of Education, Osaka Kyoiku University Tennoji Campus, 4-88 Minami Kawahoricho, Tennoji, Osaka 543-0054, Japan
c Division of Biomedical Engineering for Health & Welfare, Tohoku University Graduate School of Biomedical Engineering, 2-1 Seiryomachi, Aoba-ku, Sendai 980-8575, Japan

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ABSTRACT

Objectives: In two experiments, we investigated the effects of acute moderate-intensity exercise on aspects of executive function in adolescents.

Design: An experimental design was used.

Methods: Fifty-five Japanese adolescents (Experiment 1: N = 28; Experiment 2: N = 27) performed a modified flanker task and a modified n-back task to assess inhibitory control and working memory before, during, and after walking on a treadmill at moderate intensity (Experiment 1: 60% maximal heart rate; Experiment 2: 70% maximal heart rate). In a separate session, the same testing sequence was administered while participants sat in a chair.

Result: The results revealed that reaction time for working memory increased during exercise in both experiments, while response accuracy decreased during exercise only at 70% maximal heart rate. Moderate intensity exercise had no substantial effect on inhibition control. Following cessation of the exercise, no effects were observed for either executive function assessment.

Conclusion: These results indicate that moderate intensity exercise selectively affects executive function in adolescents. Further, during physical activity, adolescents maintain inhibitory control, but their working memory declines. Further research is required to reveal the mechanisms underlying this phenomenon and to expand beyond the laboratory setting to the areas of sports and physical activities of daily living.

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The past decade has seen growing interest in the effects of exercise on cognitive function. Evidence is accumulating that exercise induces plasticity and protection in the nervous system (Zigmond & Smythe, 2010), improves memory acquisition (Winter et al., 2007) and motor cortex plasticity (Cirillo, Lavender, Ridding, & Semmler, 2009), and prevents age-related forms of cognitive dysfunction, such as dementia (Etgen et al., 2010; Podewils et al., 2005).

Of the cognitive functions, cognitive processes (e.g., updating information, planning a schedule, and orchestrating thought) have been described as executive functions, an umbrella term for processes necessary for goal-directed behavior and for coping with changing situations (Huizenga, Dolan, & van der Molen, 2006). These functions include selective attention, decision-making, voluntary response inhibition, working memory, and cognitive flexibility, which are responsible for filtering out unimportant information and holding other information in memory to carry out functions in the short term (Blakemore & Choudhury, 2006).

Research to date has provided insights on improving executive function after moderate-intensity exercise in participants from preadolescents to young adults (Alves et al., 2012; Hillman et al., 2009; Kamijo, Nishihira, Higashiura, & Kuroiwa, 2007; Kashihiara, Maruyama, Murota, & Nakahara, 2009; Sibley & Beilock, 2007). Using a modified flanker task, Drollette, Shishido, Pontifex, and Hillman (2012) observed that approximately 15 min of moderate-intensity walking at 60% maximal heart rate (HRmax) improved inhibitory control relative to a seated state in preadolescents aged 9–11 years. The flanker task has been widely used to assess inhibitory control (Eriksen & Eriksen, 1974). The modified flanker task consists of congruent (e.g., <<<<< or >>>>>>) and incongruent...
trials (>>>< or <<<<)). Participants are required to respond according to the target direction presented centrally, without diverting their attention to irrelevant information. Budde, Voelcker-Rehage, Pietrabyk-Kendziorska, Ribeiro, and Tidow, 2008 used the d2 test to demonstrate that 10 min of acute physical exercise enhanced the attentional aspect of executive function in adolescents aged 13–16 years. The d2 test is a psychodiagnostic instrument for measuring concentration and selective attention. It consists of 14 lines of 47 randomly mixed letters, either “d” or “p”, with each letter followed by one, two, or more dashes. Participants are instructed to mark all the “d” letters with two dashes within 20 s, ignoring “p” letters with one or two dashes, and “d” with more than two dashes. Based on these findings, there seems to be a consensus that moderate exercise has benefits for executive function in young participants across a range of ages (Verburgh, Konigs, Scherder, & Oosterlaan, 2013).

However, acute exercise and activities that demand executive function do not typically occur in sequence. Sports performance and many activities of daily life (e.g., conversation while walking, attending to pedestrians and cars while bicycling, and planning the next actions while housecleaning) require that executive function be exerted at the same time as the physical effort. Particularly in the domain of sports, large amount of information has been accumulated rapidly. McMorris and Graydon (1996) demonstrated that experienced players show significantly greater processing speed in decision-making performance during moderate and vigorous exercise, suggesting that sports players efficiently perform cognitive functions under situations of stress from physical demands. Accordingly, a successful performer needs to constantly assess the situation and plan decisions, which requires the ability to simultaneously process cognitive and physical demands. Given that executive functions are associated with successful sports performance (Vestberg, Gustafson, Maurex, Ingvary, & Petrovic, 2012), investigation of the impact of simultaneous exercise on executive function may contribute to the understanding of the influence of physical demand on executive function.

Studies of the executive function of young participants during acute moderate-intensity exercise have so far produced inconsistent results. Although some have found that simultaneous exercise during a cognitive task facilitates executive function (Davranche, Hall, & McMorris, 2009; Schaefer, Lövden, Wiekhorst, & Lindenberger, 2010; Schmidt-Kassow, Kulga, Gunter, Rothermich, & Kotz, 2010), other studies have reported no significant positive effects of exercise on executive function, and some have even found adverse effects (Davranche & McMorris, 2009; Del Giorno, Hall, O’Leary, Bixby, & Miller, 2010). For example, Pontifex and Hillman (2007) showed that moderate exercise (60% HRmax) interfered with executive function, resulting in impaired inhibitory control, in young adults 18–24 years of age.

Much of the research on changes in executive function during exercise has focused on young adults. Studies of children suggest a different pattern of results. For example, Drollette et al. (2012) studied preadolescents 9–11 years of age and observed that inhibitory control and working memory did not change during moderate intensity walking (60% HRmax). Little is known about the relationship between acute moderate-intensity exercise and executive function in adolescents. Further investigation is therefore needed to determine whether such effects are found in adolescent participants.

Furthermore, there may be methodological problems concerning the effect of simultaneous exercise on executive function, depending on the type of exercise. Meta-analytical research revealed that cognitive function of young adults deteriorated during running, whereas cycling was related to improvements of cognitive function (Lambourne & Tomporowski, 2010). The inconsistent results might be attributable to differences in the physical effort required for running and cycling. Treadmill exercise requires more attention allocation to bodily movements than cycling. For example, running and walking require control of the balance of body posture, compared to cycling. According to the transient hypofrontality hypothesis (Dietrich, 2003), conflict of attentional resources between physical demand and cognition may result in deterioration of cognitive function associated with the prefrontal cortex (Dietrich, 2006). Del Giorno et al. (2010) showed increased false alarms in a contingent continuous performance task and increased unique errors in the Wisconsin card sorting test during exercise. The results support the transient hypofrontality hypothesis in that simultaneous physical demand was associated with decrements in executive function. These declines in executive function with simultaneous exercise were observed in young adults (Del Giorno et al., 2010; Pontifex & Hillman, 2007). Given that the adolescent population, with maturing brains, perform similarly to young adults in tests of executive function, such as inhibitory control (Ordaz, Foran, Velanova, & Luna, 2013) and working memory (Satterthwaite et al., 2013), exercise-induced deterioration of executive function may occur in adolescents as well as young adults.

It is important to note that the individual’s level of physical fitness is potentially involved in the interference of physical demand on executive function. Previous findings have suggested that higher levels of fitness are positively associated with better executive function, compared to lower levels. Participants with higher levels of fitness utilized effective encoding and retrieval and executive control aspects of memory function (Chaddock, Hillman, Buck, & Cohen, 2011). Similarly, higher levels of aerobic fitness benefited recall during an initial learning period of a relatively difficult memory task (Raine et al., 2013). An event-related brain potential (ERP) study suggested that high-fit people showed greater allocation of attention resources toward cognitive assessment tasks, as measured by greater amplitude of P3, relative to low-fit individuals (Hillman, Castelli, & Buck, 2005). Moreover, increased aerobic fitness has been shown to lead to positive effects on executive function during the development of younger individuals (Buck, Hillman, & Castelli, 2008). Luque-Casado, Zabala, Morales, Mateo-March, and Sanabria (2013) showed that high-fit participants had faster reaction times in a psychomotor vigilance task, with greater heart rate variability parameters, compared to lower-fit people. This result suggests that benefits for executive function may derive from a high fitness level. Based on these findings, it is likely that a high fitness level is positively involved in the relation between exercise and executive function.

The primary purpose of this study was to investigate the relationship between acute moderate-intensity aerobic exercise and executive function in adolescents. We administered a modified flanker task and a modified spatial n-back task to 15- to 16-year-old participants in order to assess inhibitory control and working memory, respectively. These executive assessment tasks have been successfully established in previous studies of the relation between acute exercise and executive function, but with a main focus on inhibitory control in adolescents (Budde et al., 2008; Hogan et al., 2013; Stroth et al., 2009). The relationship between acute exercise and working memory in adolescents therefore remains an open question. In the current study, we manipulated working memory using a modified spatial n-back task in order to assess working memory during and after exercise (Drollette et al., 2012). The n-back tasks are experimental paradigms to assess working memory ability (Owen, McMillan, Laid, & Bullmore, 2005). According to Owen et al.’s review (2005), neuroimaging studies conducted during an n-back task suggest that prefrontal cortex significantly contributes to aspects of working memory. In the modified spatial
n-back task that we employed, participants were required to respond as quickly and accurately as possible while holding and retrieving information about spatial locations of targets. To the best of our knowledge, this is the first investigation of the effect of exercise on working memory associated with functioning of the frontal brain area in an adolescent population.

This present study used two experimental designs to examine the effect of acute exercise on executive function. The first experiment investigated the effect of aerobic exercise (60% HRmax) on executive function in 15- to 16-year-old participants. Second, because the effects of exercise on executive function differed with exercise intensity, the second experiment demonstrated the influence of exercise intensity (70% HRmax) on executive function in adolescent participants. We hypothesized that executive function would improve after cessation of a single bout of moderate-intensity exercise. Because inhibitory control declined during simultaneous exercise for young adults, possibly due to the transient hypofrontality, we also predicted that simultaneous moderate-intensity exercise would interfere with executive function in our adolescent participants.

**Experimental Procedure**

**Participants**

Twenty-eight adolescent participants (24 male and 4 female) 15–16 years of age (15.6 ± .5 yr), were recruited from Sendai National College of Technology, Miyagi, Japan. Before taking part in the experiment, all participants were fully informed about the experimental protocol and provided written consent. The Ethics Committee of the Sendai National College of Technology approved this study. The average aerobic fitness levels of the participants were assessed by 20 m shuttle run test that was administered approximately 6 months prior to this experiment. Because all the participants were not involved in sports activities or physical training sessions after the 20 m shuttle run assessment until the experiment, we consider there were no significant changes in their fitness levels. According to the established method of maximal 20-m shuttle run test, “participants ran from one marker to another marker set 20 m apart, while keeping pace with a prerecorded cadence. The cadence is set to music and increased every minute. Participants were instructed to keep up with the cadence for as long as possible. The test was terminated when a participant failed to reach the appropriate marker in the allotted time twice or could no longer maintain the pace. The number of laps completed was recorded” (Mahar, Guerieri, Hanna, & Kemble, 2011). The average aerobic fitness levels of participants as assessed by 20 m shuttle run test (Table 1) were estimated as 49.9 ± 5.8 ml/min/kg VO2peak for male, and 42.5 ± 2.2 ml/min/kg for female in experiment 1 and 50.7 ± 4.4 ml/min/kg VO2peak for male, and 42.4 ± 6.9 ml/min/kg for female in experiment 2 (Matsuzaka et al., 2004; VO2peak = 61.1 – 2.20gender – 0.462age – 0.862BMI + 0.192 TL, where gender = 0 if male or 1 if female, age (years), body mass index (BMI: kg·m⁻²), TL(total laps); R² = .80), apparently lower than the national average of the same generation both for men and women.

**Method**

**Participants**

Of the participants was 1.2 ± 0.5 yr), were recruited from Sendai National College of Technology, Miyagi, Japan. Before taking part in the experiment, all participants were fully informed about the experimental protocol and provided written consent. The Ethics Committee of the Sendai National College of Technology approved this study. The average aerobic fitness levels of the participants were assessed by 20 m shuttle run test that was administered approximately 6 months prior to this experiment. Because all the participants were not involved in sports activities or physical training sessions after the 20 m shuttle run assessment until the experiment, we consider there were no significant changes in their fitness levels. According to the established method of maximal 20-m shuttle run test, “participants ran from one marker to another marker set 20 m apart, while keeping pace with a prerecorded cadence. The cadence is set to music and increased every minute. Participants were instructed to keep up with the cadence for as long as possible. The test was terminated when a participant failed to reach the appropriate marker in the allotted time twice or could no longer maintain the pace. The number of laps completed was recorded” (Mahar, Guerieri, Hanna, & Kemble, 2011).

**Procedure**

The protocol used a within-participants, repeated-measures design. Both experiments were divided into three sessions separated by at least 24 h. In the first session, the participants completed questionnaires and practiced the cognitive tasks. In the second session, the participants were randomly assigned to either a rest session or an exercise session; in the third session, they were assigned to the other session (cross-over design). All procedures were conducted by five experimenters in accordance with guidelines established through consensus of all experimenters. Because participants of the study were students, we had to respect their study times and class hours. Consequently, the experiments were performed on weekdays in the afternoon between 2:15 PM and 8:15 PM, and on weekends between 9:00 AM and 5:30 PM. In order to minimize the potential circadian effect on cognitive functions, we carefully allocated sessions 2 and 3 of each participant on different days, but at similar times. The average inter-individual difference in the time of the day between session 2 and 3 among the participants was 1.2 ± 1.8 h (experiment 1 and 2). Participants were told not to be involved in vigorous physical activities such as sports the day before the experimental sessions they were assigned. They were also told to report before the experimental sessions, in case they happened to be involved in vigorous physical activities or to have experienced serious mental distress, so that their sessions could be postponed or canceled and allocated on other days without mental and physical load that might affect cognitive functions.

**Session 1** During the first session, the participants completed questionnaires concerning their health histories and demographic information, and their height and weight were measured. Next, they practiced each of the cognitive tasks (60 trials of the flanker task and 20 trials of each of the three conditions of the n (0, 1, 2)-back task until their accuracy rates reached 70%. All practice tests were performed under two conditions: while walking on a motor-driven treadmill at 60% (Experiment 1) of age-predicted maximal heart rate (HRmax; 208 – .7 × age; Machado & Denadai, 2011;...
was attached to the handlebars of the treadmill for responding with 60% of participants’ maximal heart rate. The treadmill was equipped with ergonomically-designed, bicycle-like handlebars, with computer mouse response buttons positioned at thumb locations for both hands. Two computer mouse devices were attached to the handlebars of the treadmill for responding during the cognitive tasks. HR Monitor (Polar, RS400™, Finland) was fitted to participants while walking on the treadmill.

Sessions 2 and 3. Each of these two sessions consisted of three successive periods during which the cognitive tasks were performed (i.e., before walking or sitting, during walking or sitting, after walking or sitting). The participants were assigned randomly to either walking on a motor-driven treadmill or sitting in a chair on the stationary treadmill during the second session and then to the other condition during the third session, in a within-participants crossover design. Each participant walked on the treadmill at an intensity of 60% (Experiment 1) of maximal heart rate (HRmax; 208 ± .7 × age; Machado & Denadai, 2011; Mahon et al., 2010). In the exercise condition, experimenter changed walking speed and grade of treadmill for approximately 5 min until steady-state walking occurred that corresponding with 60% of participants’ maximal heart rate. The participants wore an HR monitoring chest band, and the HR was monitored on the wrist type receiver attached on the side bar of the treadmill. Within the initial warm-up session of 5 min, the participants ran on the treadmill, the grade and speed of which was adjusted so that the HR reached the target range (target HR ±5%). The initial grade was 0%. In the first 2 min, the speed was increased by 2.5 km/h/min. When the HR of the participants did not reach the target range, the treadmill speed was increased by 5 km/h/min in the next minute. When the HR had not reached the target range at this point, the grade was increased within the next 2 min at 5%/min. In case, the HR exceeded the target range, the grade of the treadmill was decreased by 2.5%/min, so that the participants ran at the target HR range after 5 min of warm-up (see Table 1). During the exercise session, the first 5 min consisted of a warm-up period during which HR was raised to reach a target level of 60% (Experiment 1) of HRmax. During exercise, the average speed and grade was provided at Table 1. The post-activity assessment period began after the HR returned to within 10% of its pre-activity value. All assessment periods in Experiment 1 (durations: exercise session, 13.3 ± 2.0 min; rest session, 13.0 ± 2.0 min) were separated by approximately 5 min of break.

The break time was determined by the time at which HR returned to within 10% of its pre-activity value in the exercise session. Each participant was fitted with a Polar HR monitor before each session (sessions 2 and 3) until the end of the session, approximately 1 h, and HR was recorded average HR of 15 s using Polar HR monitor before and after each task (e.g., flanker task and n(0, 1, 2)−back task).

Cognitive tasks

Behavior recording and stimulus presentation were controlled with Presentation software (NeuroBehavioralSystems, Inc., USA). Stimuli were presented on a computer screen positioned at the front of the treadmill.

Flanker task. This task requires interference control and has been linked to the ability to inhibit task-irrelevant information in a stimulating environment. Participants were instructed to attend to the center (i.e., target) arrow while ignoring flanking arrows, and to respond as quickly and accurately as possible by pressing the right button with their right forefinger if the center arrow was pointing to the right and the left button with their left forefinger if the center arrow was pointing to the left. This task contained 100 randomized trials with equiprobable directionality and congruency within congruent (i.e., >>>>> or <<<<<) and incongruent (i.e., <<<<< or >>>>>>) arrays of 3 cm-tall white arrows on a black background screen. Each array was presented for 200 ms with a fixed interstimulus interval of 1500 ms. We assessed reaction time (RT) and response accuracy for the flanker task.

Spatial n-back. The n-back task is an empirical method of evaluating working memory. In this modified version, six white-framed boxes appeared on a green background screen. These boxes were 4 × 4 cm square and were arranged hexagonally 9.5 cm from the center of the screen. On each trial, a photograph of a black and white cow appeared pseudorandomly inside one of the six boxes. The participants were instructed to indicate in which box a cow had appeared n (0, 1, 2) items previously as quickly and accurately as possible. For the 0-back task, the participants were instructed to press the right button with their right forefinger when the cow appeared in the upper right box and the left button with their left forefinger when the cow appeared inside any of the remaining five boxes. For the 1-back task, the participants were instructed to press the right button with their right forefinger if the cow appeared in the same box as it had one trial previously and the left button with their left forefinger if the cow appeared in any of the remaining five boxes. Similarly, for the 2-back task, the participants were instructed to press the right button if the cow appeared in the same box as it had two trials previously and the left button if the cow appeared in any of the remaining five boxes. On all trials, each target was displayed for 250 ms, with a fixed interstimulus interval of 2500 ms. The 0-back task consisted of 45 trials with 15 targets, and the 1- and 2-back tasks comprised 72 trials with 24 targets, with a 33.3% probability of the target appearing on each trial for all tasks. We assessed reaction time (RT) and response accuracy for the n-back task.

Statistical analysis. Repeated-measures analysis of variance (ANOVA) was performed on reaction time (RT) and response accuracy for each task using SPSS v. 19 (SPSS, Chicago, USA). The results of the flanker task were analyzed using mode (walking vs. sitting), trial type (congruent vs. incongruent), and time (before vs. during vs. after) as within-participant factors. The results of the n-back task were analyzed using mode (walking vs. sitting), target (0-back vs. 1-back vs. 2-back), and time (before vs. during vs. after) as within-participant factors. Greenhouse-Geisser adjustment was applied to each result for which the sphericity assumption was invalid. Post hoc univariate ANOVAs with Bonferroni corrected t tests were performed to decompose significant effects when appropriate. Estimated effect sizes were reported using partial eta-square (η²) values for the significant main effects and interactions. The level of significance was set to p < .05 for all analyses. All data for which either accuracy or RT differed by more than 3 SDs from the mean of all participants in more than two assessment periods across mode, trial type or target, and time were removed from the data set.

Results

Experiment 1

Flanker task

In the flanker task, accuracy or RT of two participants differed by more than three SDs from the mean of all participants, suggesting that they did not understand the task or that the level of the task
was not suitable for them. The data from these participants were excluded.

**Response accuracy.** The main effect of trial type was significant, $F(1, 25) = 31.5, p < .001, \eta^2 = .56$, with greater mean accuracy for congruent than for incongruent arrays, $t(25) = 5.6, p < .001$. The Mode × Time interaction was also significant, $F(2, 50) = 3.6, p = .035, \eta^2 = .126$. Decomposition of the two-way interaction by estimating the time effect within each mode revealed an effect of time for the exercise session, but not for the rest session. Post hoc analyses revealed that mean accuracy in the exercise session was significantly lower during walking (95.0% ± 4.4%) than after walking (96.8% ± 3.1%), $t(25) = 2.8, p = .01$ (Fig. 1A).

**Reaction time.** The main effect of trial type was significant, $F(1, 25) = 202.9, p < .001, \eta^2 = .89$, with shorter RT for congruent than for incongruent arrays, $t(25) = 14.2, p < .001$. Further analyses revealed no significant effects involving mode, $F$s ≤ 2.3, $p$s ≥ .144, $\eta^2$ = .083 (Fig. 1B).

**n-back task**

In the n-back task, no participant’s accuracy nor RT differed by more than three SDs from the mean of all participants, so all participants were included.

**Response accuracy.** The main effect of target was significant, $F(1, 38.1) = 24.88, p < .001, \eta^2 = .48$, with greater mean accuracy for 0-back than for 1-back and for 0-back and 1-back than for 2-back, $t$s(27) ≥ 3.2, $p$s < .001. The main effect of time was also significant, $F(2, 54) = 3.5, p = .04, \eta^2 = .116$, with lower mean accuracy during the test than after the test, $t(27) = 2.75, p = .011$. Further analyses revealed no significant effects involving mode, $F$s ≤ 1.2, $p$s ≥ .286, $\eta^2$ = .042 (Fig. 2A).

**Reaction time.** Significant main effects were found for target, $F(1, 33.5) = 53.6, p < .001, \eta^2 = .67$, and time, $F(2, 54) = 3.7, p = .031, \eta^2 = .12$, which was suppressed by a Target × Time interaction, $F(2.8, 74.3) = 9.3, p < .001, \eta^2 = .26$. The Mode × Time interaction was also significant, $F(2, 54) = 5.3, p = .008, \eta^2 = .16$. Decomposition of the within each mode revealed a time effect during the exercise session, but not before or after the test. Post hoc analyses indicated that n-back RT was longer in the exercise session (449.1 ± 72.2 ms) than in the rest session (406.8 ± 62.6 ms), $t(27) = 2.9, p = .007$. Furthermore, decomposition of the interaction by examining the effect of mode within each time revealed a mode effect during, but not before or after, the test. Post hoc analyses indicated that n-back RT was longer in the exercise session (449.1 ± 72.2 ms) than during walking (449.1 ± 62.6 ms), $t(27) = 2.9, p = .007$. Furthermore, decomposition of the interaction by examining the effect of mode within each time revealed a time effect for both exercise and rest sessions. Post hoc revealed that in the exercise session, mean RT was shorter after walking (418.2 ± 87.6 ms) than during walking (449.1 ± 62.6 ms), $t(27) = 2.9, p = .007$, whereas mean RT in the rest session was shorter during the test (406.8 ± 62.3 ms) than before the test (426.7 ± 61.3 ms), $t(27) = 2.9, p = .007$ (Fig. 2B).

**Sex difference**

Further statistical analyses were conducted to confirm the effects of sex difference on the relationship between exercise and executive function. Analysis for the accuracy and reaction time for the flanker task using mode (walking, sitting) × trial type (congruent, incongruent) × time (before, during, after) × sex (male, female), and for the n-back task using mode (walking, sitting) × target (0-back, 1-back, 2-back) × time (before, during, after) × sex (male, female) revealed no effects of sex in the both tasks.

**Discussion**

The results of the first experiment suggested that adolescents maintained aspects of inhibitory control in the flanker task, but the reaction time of the n-back task (test of working memory) was transiently larger during moderate intensity walking than during rest. Interestingly, the maintenance of inhibitory control during moderate exercise did not concur with previous findings in young adults (Pontifex & Hillman, 2007). Moreover, the present results only partially resembled previous findings in preadolescents (Drollette et al., 2012): Working memory performance was maintained during walking in adolescents as well as in preadolescents, whereas the processing speed of working memory deteriorated during exercise relative to the seated state in adolescents but not in preadolescents. As expected, the influence of exercise on executive function in adolescents was different here than in previous studies of preadolescents (Drollette et al., 2012) and young adults (Pontifex & Hillman, 2007).

Our finding of an adverse effect of exercise on working memory processing speed assessed during exercise agrees well with the transient hypofrontality theory, which proposes that the intense activation of the motor and sensory systems during exercise could occur at the expense of higher cognitive centers of the prefrontal cortex (Dietrich, 2003). It is possible that exercise intensity might interfere with executive function due to attentional conflict in and around the prefrontal region. A second experiment therefore was conducted at a different level of exercise intensity to find influences of moderate-intensity exercise on executive function in adolescents as the brain matures from childhood to young adults.
HRmax) should impair both performance and processing speed in theory, simultaneous moderate intensity exercise (i.e., 70% of the Arab) memory during and after exercise in accordance with the protocol for adolescents. We employed a modified moderate intensity exercise at 70% of estimated maximal HR in adolescents (20-29 yr). They found that executive function was maintained between light (40% peak power output; PPO) and moderate (60% PPO) exercise, whereas deterioration of executive function was observed from moderate (60% PPO) to intense (80% PPO) exercise, suggesting that tasks requiring the function of the prefrontal lobe are more likely to be affected by exercise intensity. According to the results of Experiment 1, simultaneous exercise might differently affect executive function in adolescents and young adults. Although several previous studies defined moderate intensity exercise as 60-70% of HRmax, there are inconclusive results that show effects of moderate intensity exercise on executive function based on HR (Drollette et al., 2012; McMorris, Collard, Corbett, Dicks, & Swain, 2008; Pontifex & Hillman, 2007). To the best of our knowledge, it remains unclear how different exercises of moderate intensity influence executive function in adolescents.

The main purpose of the second experiment was therefore to demonstrate effects on executive function during and after moderate intensity exercise at 70% of estimated maximal HR in adolescents. We employed a modified flanker task and a modified spatial n-back task to assess inhibitory control and working memory during and after exercise in accordance with the protocol of the first experiment. According to the transient hypofrontality theory, simultaneous moderate intensity exercise (i.e., 70% of HRmax) should impair both performance and processing speed in the executive assessment task in adolescents, requiring greater allocation of attention resources to bodily movement than to executive function.

Method

Participants

Twenty-seven adolescent participants (18 male and 9 female) 15-16 years of age (15.8 ± 4.4 yr; Experiment 2) were recruited from Sendai National College of Technology, Miyagi, Japan. Before taking part in the experiment, all participants were fully informed about the experimental protocol and provided written consent to participate. The Ethics Committee of the National College of Technology approved this study.

Procedure

Cognitive tasks and statistical analyses were the same as in Experiment 1. In Experiment 2, each participant walked on the treadmill at an intensity of 70% maximal heart rate (HRmax: 208 ± 7 × age; Machado & Denadai, 2011; Mahon et al., 2010). The participants wore an HR monitoring chest band, and the HR was monitored on the wrist-type receiver attached to the side bar of the treadmill. Within the initial warm-up session of 5 min, the participants ran on the treadmill, the grade and speed of which was adjusted so that the HR reached the target range (target HR ±5%). The initial grade was 0%. In the first 2 min, the speed was increased by 2.5 km/h/min. When the HR of the participants did not reach the target range, the treadmill speed was increased by .5 km/h/min in the next minute. When the HR did not reach the target range at this point, the grade was increased within the next 2 min at 5%/min. In case, the HR exceeded the target range, the grade of the treadmill was decreased by 2.5%/min, so that the participants ran at the target HR range after 5 min of warm-up (see Table 1). All procedures were conducted by five experimenters in accordance with guidelines established through consensus of all experimenters. Because participants of the study were students, we had to respect their study times and class hours. Consequently, the experiments were performed on weekdays in the afternoon between 2:15 PM and 8:15 PM, and on weekends between 9:00 AM and 5:30 PM. In order to minimize the potential circadian effect on cognitive functions, we carefully allocated sessions 2 and 3 of each participant on different days, but at similar times. The average inter-individual difference in the time of the day between session 2 and 3 among the participants was 1.2 ± 1.8 h (experiment 1 and 2). As in Experiment 1, Participants were told not to be involved in vigorous physical activities such as sports the day before the experimental sessions they were assigned. They were also told to report before the experimental sessions, in case they happened to be involved in vigorous physical activities or to have experienced serious mental distress, so that their sessions could be postponed or canceled and allocated on other days without mental and physical load that might affect cognitive functions.

Results

Flanker task

In the flanker task, accuracy or RT of two participants differed by more than three SDs from the mean of all participants; the data from these participants were excluded.

Response accuracy. The main effect of trial type was significant, t(1, 24) = 27.3, p < .001, r² = .53, with greater accuracy for congruent than for incongruent arrays, t(24) = 5.2, p < .001. Further analyses indicated no significant effects involving mode, Fs ≤ 2.9, p’s ≥ .102, r² = .108 (Fig. 3A).
**Response accuracy.** The main effect of target was significant, $F(1.3, 30.4) = 52.9, p < .001, \eta^2 = .68$, as were the Target × Time interaction, $F(4, 96) = 2.9, p = .04, \eta^2 = .109$, and the Mode × Time interaction, $F(2, 48) = 10.6, p < .001, \eta^2 = .306$. Decomposition of the Mode × Time interaction by examining the effect of mode within each time revealed an effect of mode during the task, but not before or after the task. Post hoc analyses indicated that mean accuracy was lower during walking (93.7% ± 2.9%) than during resting (96.0% ± 2.1%), $t(24) = 4.5, p < .001$. Examination of the time effect within each mode revealed a time effect for the exercise session but not for the rest session. Post hoc analyses revealed that participants’ response accuracy in the exercise session was greater after walking (95.8% ± 1.9%) than during walking (93.7% ± 2.9%), $t(24) = 4.0, p < .001$ (Fig. 4A).

**n-back task**

In the n-back task, accuracy or RT of two participants differed by more than three SDs from the mean of all participants; the data from these participants were excluded.

**Reaction time.** Significant main effects were found for trial type, $F(1, 24) = 122.3, p < .001, \eta^2 = .836$, with shorter RTs for congruent than for incongruent arrays, $t(24) = 11.1, p < .001$, and for time $F(2.48) = 6.8, p = .003, \eta^2 = .22$, with shorter RTs after the task than before or during the task $t(24) \geq 2.75, p \leq .011$. There were no significant effects involving mode, $Fs \leq 2.4, p’s \geq .13, \eta^2 = .092$ (Fig. 3B).

**Sex difference**

Omnibus analyses revealed a trial type × time × sex on accuracy for the flanker task, $F(2, 46) = 3.7, p = .032, \eta^2 = .14$. Decomposition of the interaction observed lower accuracy in incongruent than congruent across same time condition (i.e., before, during and after) in both male $t(15) \geq 3.1, p’s \leq .007$ and female $t(8) \geq 2.7, p’s \leq .028$. Moreover, a target × sex interaction on accuracy for the n-back task was observed, $F(1.3, 30.3) = 4.0, p = .045, \eta^2 = .15$. Decomposition of the interaction observed greater mean accuracy for O-back than for 1-back and for 0-back and 1-back that for 2-back in both male $t(15) \geq 4.8, p < .001$ and female $t(8) \geq 3.9, p < .005$. Furthermore, the analysis revealed a time × sex interaction on reaction time for the n-back task, $F(2, 46) = 3.3, p = .048, \eta^2 = .12$. Decomposition of the interaction showed faster reaction time after the test compared to before and during the test in both male $t(15) \geq 5.1, p < .001$ and female $t(8) \geq 3.2, p < .012$. There were no significant interactions between mode and sex in both tasks.

**Discussion**

The main goal of Experiment 2 was to examine the influence of moderate intensity exercise on executive function during and after moderate exercise intensity (70% HRmax) in adolescents. As in Experiment 1, we confirmed that adolescents maintained attentional aspects of inhibitory control. Because the flanker task revealed almost the same results as in the first experiment, we will report those results in the General Discussion. The main finding was a transient decline in working memory during moderate intensity exercise. More precisely, exercise intensity at 70% of HRmax led to worse performance of working memory, with increased reaction time. This result agrees with previous research in which executive function deteriorated during exercise (Labelle et al., 2013; Lo Bue-Estes et al., 2008; McMorris et al., 2009; Pontifex & Hillman, 2007). Our findings also coincide with predictions of the transient hypofrontality theory, with performance and processing speed of working memory functions transiently declining during moderate intensity exercise (i.e., 70% HRmax); following exercise, these functions recovered to the level of pre-exercise and seated states. According to the transient hypofrontality theory, the bodily movement of walking should interfere with an ability subserved by the frontal lobe. As expected, executive function, which relies on the frontal cortex, was disrupted during moderate exercise in adolescents.
General discussion

The primary goal of this study was to demonstrate how moderate-intensity exercise affects executive function in adolescents. The results of both Experiments 1 and 2 revealed that adolescents maintained inhibitory control during moderate-intensity exercise. As for working memory, however, reaction time declined transiently during moderate-intensity exercise. Further, response accuracy for working memory deteriorated during moderate exercise at only 70% of HRmax. This indicates that acute moderate-intensity exercise partially affects executive function (i.e., inhibitory control and working memory) in adolescents.

To the best of our knowledge, this is the first study to demonstrate the deterioration of working memory during moderate-intensity exercise in adolescents. There may be several possible reasons for exercise-induced transient decline in executive function. First, previous studies of the effects of moderate exercise at 60% of HRmax on event-related brain potentials (ERPs) revealed that N1 and N2 amplitudes at the parietal site decreased while P2 and P3 amplitudes at the frontal site increased, suggesting that more attention was allocated to gross bodily movement than to executive function (Pontifex & Hillman, 2007). These findings concur with the transient hypofrontality theory, which proposes that intense activation of the motor and sensory systems during exercise may occur at the expense of higher cognitive centers of the prefrontal cortex (Dietrich, 2003). Alternatively, it has been established that exercise-induced stress may impair working memory through an increase in catecholamines (McMorris et al., 2009). The prefrontal cortex, which is responsible for working memory, is vulnerable to exposure to stress-induced catecholamines (Arnsten, 2009). Moreover, acute physical exercise provokes an increase in circulating cortisol level (Wahl, Zinner, Achtzehn, Bloch, & Mester, 2010), which is associated with poor memory function (Newcomer et al., 1999). The involvement of exercise stress in the present study, however, is not likely because the exercise in this experiment, namely walking, even if it was a brisk type of walking, is a well-elaborated accustomed task most likely to be without exercise stress. Taken together, it is possible that a well-accommodated type of exercise without special attention suggests the brain task allocation may occur with an activity which does not require special attention, attentional conflict or mental load.

In the present study, therefore, the negative effect of simultaneous exercise on working memory is probably due to the attentional conflict between coordination of bodily movement and executive function and exercise-induced stress. Because most participants in this study tended to live a sedentary lifestyle, their working memory may be sensitive to moderately higher exercise intensity. Further study is needed to examine the influence of various exercise intensities, from low to high, in order to demonstrate whether executive function is dependent on exercise intensity in adolescents.

The present study did not show a positive effect of exercise on executive function after exercise. No improvements in executive function could be attributed to the resting period. Using functional near-infrared spectroscopy (fNIRS) in young adults, Yanagisawa et al. (2010) observed that enhancement in prefrontal cortex activation significantly coincided with improvement in cognitive performance 15 min after exercise. Electrophysiological study using ERP showed improvements of executive function with increased P3 amplitude after approximately 25 min of resting time in preadolescents (Hillman et al., 2009). A meta-analytic study reported that 0–10 min of cessation of exercise is negatively associated with cognitive performance, whereas longer than 11 min of rest period after exercise has benefits to cognitive function (Chang, Labban, Gamin, & Etien, 2012). In the present study, cognitive assessment was conducted approximately 5 min after exercise, when the participant's HR level returned to a level within 10% of baseline; this may have been too brief an interval for further brain activation.

According to previous research investigated into the effect of post-exercise on executive function in adolescent population (Budde et al., 2008; Hogan et al., 2013), these findings suggested that 10–20 min of acute moderate intensity exercise (at approximately 60% HRmax) tends to positively affect attentional aspects of cognitive function in adolescents aged 13–16 years. However, because these research did not provide specific information about the length of rest period after exercise, the time course of effects of rest period on executive function after moderate intensity exercise remains unclear in adolescents.

In contrast to our findings, Nanda, Balde, and Manjunatha (2013) reported that cognitive aspects of memory function improved after moderate intensity exercise at 70% of heart rate reserve. The method of their study resembled our experiment, in that the post-exercise rest period was based on the time at which heart rate returned to within 10% of the basal heart rate. However, there are no reports concerning effects of the length of rest period after exercise (Nanda et al., 2013). Considering the inconsistencies in these results, further research is required to assess appropriate timing of cognitive task after exercise based on both time and heart rate.

With regard to the positive mechanisms underlying the effect of post-exercise on executive function, previous studies have indicated that exercise-induced neurotrophic factors are significantly related to improvements of brain function (Loprinzi, Herod, Cardinal, & Noakes, 2013). Winter et al. (2007) suggested that serum brain-derived neurotrophic factor (BDNF) after acute
exercise is associated with effective verbal acquisition in young adults. As for BDNF, this neurotrophic factor is dependent on exercise intensity and duration. Schmolesky, Webb, and Hansen (2013) suggested that 20–40 min of vigorous and moderate intensity exercise significantly increased BDNF levels. Previous research concurred that high intensity exercise induced a greater level of serum BDNF (Schmidt-Kassow et al., 2012). Given that the neurotrophic factor is associated with increased brain volume, which plays a key role in memory function (Erickson et al., 2011), the beneficial effect might reflect the relationship between exercise and executive function in young participants. Animal studies have indicated that insulin growth factor 1 (IGF-1) and vascular endothelial growth factor (VEGF) also have substantial effects on the modulation of synaptic plasticity (Ding, Vaynman, Akhavan, Ying, & Gomez-Pinilla, 2006; Licht et al., 2011) and neurogenesis (Gluckman et al., 1992), which contributes to improvements of cognitive function (Cetinkaya et al., 2013; Voss, Vivar, Kramer, & van Praag, 2013). An empirical human study has revealed that IGF-1 is positively associated with intelligence in children aged 8–9 years (Gunnell, Miller, Rogers, & Holly, 2005). Thus, it is possible that the effect of exercise-induced neurotrophic factors (e.g., BDNF, IGF-1 and VEGF) may contribute to improvements of executive function. Furthermore, although these neurotrophic factors might be related to the post-exercise rest period, to the best of our knowledge, there are no studies that have investigated the effect of exercise-induced BDNF, IGF-1 and VEGF in adolescents. The possibility that exercise-induced neurotrophic factors affect cognitive aspects of the executive function of adolescents requires further research.

The present results contradicted previous findings that inhibitory control deteriorated during exercise in young adults (Pontifex & Hillman, 2007), and that working memory function was maintained during exercise in preadolescents (Drollette et al., 2012). Sowell, Thompson, Tessner, and Toga (2001) observed the emergence of a Statistical Parametric Mapping (SPM) pattern representative of loss of gray matter in the dorsal cortices of the frontal cortex and suggested an increase in the volume of white matter in the prefrontal cortex as the brain matures from childhood to adolescence. Because there is a positive association of executive function with structural connectivity of white matter of the prefrontal brain area (Madsen et al., 2010), the reaction pattern of the brain in the present participants may reflect a transitional phase in brain maturation.

Moreover, the activity in the frontal brain also changes with age: A functional magnetic resonance imaging (fMRI) study showed age-related increases in activity in the left inferior frontal gyrus, orbitofrontal gyrus, and insula during a Go/No-Go task in participants ranging from 8 to 20 years of age (Tamm, Menon, & Reiss, 2002). Given that frontal cortex plays an important role in executive function, these developmental changes in the brain may account for the disparate effects of exercise on inhibitory control and working memory from preadolescents to young adults. Our findings may thus indicate that a transitional stage of brain maturation from preadolescence to young adulthood may be reflected in the changing effect of moderate intensity exercise on executive function. Further research needs to encompass a larger age range of participants, from preadolescents to young adults, in the same experimental protocol.

The present study has several limitations. The first limitation was that participants were relatively inactive. Hogan et al. (2013) revealed that more physical fit adolescents showed improved executive function performance after 20 min of moderate exercise at 60% of HR relative to a pre-exercise condition. Because greater physical fitness is associated with improvements in executive function, participants of a variety of fitness levels should be recruited to examine the effects of individual physical capacity on executive function during and after moderate-intensity exercise. Therefore, further empirical research is needed to consider other potential variables that influence executive function in adolescents. The second limitation was the effect of circadian rhythms on executive function. There were different baseline heart rates in Experiment 1 and Experiment 2 (see Table 1), and participants’ baseline heart rates were relatively high. These facts are possibly due to circadian rhythms, considering this experiment was performed on different days and at different times. Given that cognitive aspects of attention and memory are dependent on circadian rhythms (Manly, Lewis, Robertson, Watson, & Datta, 2002; Wright, Hull, & Czeisler, 2002), circadian rhythms may have partially mediated the relation between exercise and executive function. However, we minimized the possibility by allocating the experiment days in session 2, 3 as the same times in different days as possible (mean different hours between session 2 and 3 = 1.2 ± 1.8 h). To better understand the relationship between exercise and executive function, future research needs to considerably elucidate the interaction effect of exercise, executive function, and circadian rhythms in adolescents. Finally, the number of male and female participants in this study was imbalanced: There were a few female participants compared to the number of males. Schweinsburg, Nagel, and Tapert (2005) revealed that male adolescents responded faster than females in spatial working memory tasks. In addition, the pattern of brain activation was different in response to spatial working memory tasks among males and females: Males demonstrated higher activation in the right frontopolar superior frontal gyrus and right anterior cingulated than females (Schweinsburg et al., 2005). Our current study confirmed no significant interaction of sex difference on the relationship between exercise and executive function, suggesting that sex difference appeared to have relatively small impact on executive function involved in exercise among adolescents. Considering the previously reported gender-specific effects on executive function and brain activation, however, future research is necessary to examine how gender difference is involved in the relationship between exercise and executive function.

We have shown that moderate-intensity exercise selectively affects executive function in adolescents. Thus, exercise-induced changes in cognition should be carefully considered when executive function is required during physical effort. Future research should extend beyond a laboratory-based setting into the domains of sports and physical activities of daily living in order to define criteria for the achievement of successful performance.

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References


