Effects of Acute Exercise on Executive Function: A Study With a Tower of London Task

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Abstract:

The purpose of this study is to extend the literature by examining the effects of an acute bout of moderate to vigorous intensity aerobic exercise on the executive functions of planning and problem solving assessed using a Tower of London Task (TOL Task). Forty-two participants were randomly assigned into either exercise or control group, and performed the TOL Task, before and immediately following exercise or a control treatment. The exercise group performed 30 min of exercise on a stationary cycle at moderate to vigorous intensity while the control group read for the same length of time. Results indicated that the exercise group achieved improvements in TOL Task scores reflecting the quality of planning and problem solving, but not in those reflecting rule adherence and performance speed. These findings indicate that an acute bout of aerobic exercise has facilitative effects on the executive functions of planning and problem solving.

Article:

The relationship between acute exercise and cognition has been examined for over four decades (see review in Tomporowski & Ellis, 1986). Although previous empirical studies report inconsistent findings, narrative reviews generally support that participation in acute exercise is associated with improved performance of cognitive tasks performed following the exercise session (see reviews in Brisswalter, Collardeau, & Arcelin, 2002; McMorris & Graydon, 2000; Tomporowski, 2003; Tomporowski & Ellis, 1986), but that results are less consistent when the cognitive task is performed during the exercise session (Dietrich, 2006; Dietrich & Sparling, 2004). This conclusion is supported by the results of a recent metaanalytic review in which Lambourne and Tomporowski (2010) reported that acute exercise benefits cognitive tasks

performed following the exercise session (ES= 0.20), but has a negative effect on cognitive tasks performed during exercise (ES = –0.14).

Given the small but reliable average effect size for cognitive performance performed following acute exercise, researchers have recently begun to test the effects on particular cognitive tasks that might be expected to benefit most from a session of exercise. For example, recent studies have tested the effects on executive function as assessed by a variety of behavioral tasks (Chang & Etnier, 2009a, 2009b; Coles & Tomporowski, 2008; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009; Sibley, Etnier, & Le Masurier, 2006; Tomporowski et al., 2005; Tomporowski & Ganio, 2006) or through neuroelectric measurements (Hillman, Snook, & Jerome, 2003; Kamijo et al., 2004). Importantly, the results of these studies are also mixed with some of these studies reporting larger effects (e.g., Chang and Etnier, 2009a, ES = 0.69; Pontifex et al., 2009, η2 = 0.73) than reported in the meta-analytic review (Etnier et al., 1997), and others failing to show an effect of acute exercise on executive function (Coles & Tomporowski, 2008; Tomporowski & Ganio, 2006). These inconsistent results for executive function tasks may reflect the fact that executive function is itself a broad construct and that exercise may differentially impact various aspects of executive function (Etnier & Chang, 2009).

Executive function is considered to be a higher level or meta-cognitive function that controls a number of more fundamental underlying processes (Alvarez & Emory, 2006). Researchers have broadly defined executive function as cognitive abilities dealing with novelty, planning and acting on appropriate strategies for conducting performance (Rabbitt, 1997), abilities necessary to manage purposeful and goal-directed behavior (Salthouse, 2007), or activities such as volition, planning, purposeful behavior, and effective performance (Lezak, Howieson, Loring, Hannay, & Fischer, 2004). Etnier and Chang (2009) considered the various definitions of executive function and encouraged researchers interested in the effects of exercise on cognitive performance to be aware of the complexity of executive function when determining how to assess this cognitive construct in their research. In addition, they identified the 29 most frequently used measures of executive function based on neuropsychological reviews and clinical investigations; the top five were the Wisconsin Card Sorting Test (WCST), the Stroop Test, the Trail Making Test (TMT), Verbal Fluency, and the Tower of Hanoi/Tower of London Task (TOL Task).

In the acute exercise literature, Pontifex et al. (2009) point out that researchers have primarily focused on executive function in the form of inhibition with a number of studies using the Stroop Test as their cognitive measure (Barella, Etnier, & Chang, 2010; Chang & Etnier, 2009a, 2009b; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Lichtman & Poser, 1983; Sibley et al., 2006) and others using the Eriksen flankers task (Hillman et al., 2009; Hillman et al., 2003; Kamijo et al., 2009; Kamijo, Nishihira, Higashiura, & Kuroiwa, 2007; Stroth et al., 2009).

Recently, researchers have begun to examine the effects of acute exercise on other aspects of executive function including switching as measured by the Task-Switching Test (Tomporowski, Davis, Lambourne, Gregoski, & Tkacz, 2008), inhibiting and updating as measured by the Random Number Generation Task (Audiffren, Tomporowski, & Zagrodnik, 2009), and cognitive flexibility as measured by the Alternate Uses Test (Netz, Tomer, Axelrad, Argov, & Inbar, 2007). Some researchers have also examined the acute effect on executive function by measuring performance on the WCST (Dietrich & Sparling, 2004), which assesses switching, inhibition, updating, and selective attention, and the TMT (Chang & Etnier, 2009a), which assesses inhibition and cognitive flexibility. However, to our knowledge, the only study exploring the effects of exercise on planning is a chronic exercise intervention conducted with

obese children (Davis et al., 2007), and no acute exercise study has tested the effects of exercise on planning ability or problem solving. Planning and problem solving are essential parts of daily life and have been recognized as main components of executive function (Banich, 2009; Lezak et al., 2004; Rabbitt, 1997). Given the evidence that acute exercise benefits many aspects of executive function, it is possible that it could also influence the specific executive function of planning.

Planning requires modeling and anticipating the consequences of action before attempting to execute goals that require skill or strategy (Kaller, Rahm, Spreer, Mader, & Unterrainer, 2008; Unterrainer & Owen, 2006). Problem solving is defined as the identification of three essential features (Sternberg & Ben-Zeev, 2001): the initial state, the goal state, and the unobvious behavior that will allow the transformation from the initial state to the goal state. Specifically, to achieve success in a problem-solving task, one has to first create a mental representation of both the initial and goal states and then establish the actions needed to transform from the initial state to the goal state (Unterrainer & Owen, 2006).

The TOL Task is a classical neuropsychological task that has been used frequently to measure planning and problem solving in both clinical and nonclinical populations (Banich, 2009; Berg & Byrd, 2002; Berg, Byrd, McNamara, & Case, 2010; Kaller et al., 2008; Unterrainer et al., 2004). The TOL Task was originally developed to assess planning deficits in frontal lobe patients (Shallice, 1982) and was modified from the Tower of Hanoi to provide a greater variety of problems with different complexity levels. To perform the TOL Task effectively requires the identification and maintenance of goals and subgoals (Polk, Simen, Lewis, & Freedman, 2002) combined with a high level of programming and an ability to understand the effects of sequences of operations required to solve the problem (Dehaene & Changeux, 1997).

Although recent research on the after-effects of acute exercise on cognitive performance has focused on executive function, Etnier and Chang (2009) point out that additional research in this area is necessary to further our understanding of the potential specificity of the relationship with regards to the various facets of executive function. Evidence supports a positive effect of acute exercise on executive function tasks performed following exercise, but the focus has been almost exclusively on measures reflective of inhibition. Given that planning and problem solving are aspects of executive function that are important for everyday functioning, the purpose of the current study was to examine the effect of acute exercise on planning and problem solving as assessed using the TOL Task. It was hypothesized that acute exercise would benefit TOL Task performance measures by improving the accuracy and efficiency of planning and decreasing rule breaking.

Method

Participants

Forty-two right-handed college-age students (male: n = 13, mean age = 22.26 ± 1.94 years; female: N = 29, mean age = 21.97 ± 1.66) were recruited from the National Taiwan Sport University. Participants were instructed to complete a health history questionnaire, a demographic questionnaire, and the International Physical Activity Questionnaire (IPAQ). Inclusion criteria were assessed using the Physical Activity Readiness Questionnaire (PAR-Q) to ensure there were no potential risk factors for the participant to perform a single bout of aerobic

exercise. These processes follow the guidelines of the American College of Sports Medicine (ACSM, 2010). The number of participants was based upon a power analysis using a 2×2 mixed design with the effect size estimated from a study testing the effects of resistance exercise on executive function in middle-aged adults (effect size f = 0.31) (Chang & Etnier, 2009a), power = 0.8 and alpha at .05. The protocol was approved by the committee for institutional review board.

Materials

IPAQ.   The IPAQ was applied to assess participant's amount of physical activity for descriptive purposes, to determine the initial exercise intensity level, and for consideration as a statistical covariate. It was developed as an international surveillance tool to measure physical activity level cross-nationally (Bauman et al., 2009; Craig et al., 2003) and the Taiwan version of the IPAQ has been established by Liou, Jwo, Yao, Chiang, and Huang (2008). Data from the IPAQ can be converted to metabolic equivalents (METs) based on frequency and duration of physical activity and using estimates of intensity, and MET-minutes per week are interpreted as representing low (< 600), moderate (600–1500), and high (>1500) levels of physical activity..

PAR-Q.   The PAR-Q consists of seven questions regarding the presence of conditions that would contraindicate exercise. Participants were only included when all of the questions were answered with no (ACSM, 2010).

Exercise-Related Measures

Heart Rate.   Heart rate (HR) was monitored by a HR monitor (Mode S 610i; Polar Electro, Finland), a short-range radio telemetry device, during the entire experimental process. The monitor consists of an elastic band that is strapped around the chest to hold a rubber pad (that contains the HR measuring device with the transmitter) in place just below the sternum. The participant's HR is displayed on the face of the wristband receiver. Data displayed on the receiver is based upon 5-s HR averages. The examiner recorded HR at 1-min intervals through the treatment period.

Heart Rate Reserve.   The use of heart rate reserve (HRR) is one of the recommended methods for establishing exercise intensity (ACSM, 2010). Heart rate reserve is calculated as maximal HR minus resting HR (Karvonen, Kentala, & Mustala, 1957). Maximal HR was estimated using an indirect formula: $206.9 - (0.67 \times age)$ (Gellish et al., 2007). Then the target HR was calculated by multiplying HRR by the target intensity (as a percentage) and then adding back the resting HR.

Ratings of Perceived Exertion.   The ratings of perceived exertion (RPE), developed by Borg (1998), provides a subjective rating of each individual's perception of effort during exercise. The original Borg scale ranged from 6 to 20. RPE was recorded at 2-min intervals during the exercise session.

Exercise Protocol

Exercise modality, intensity, and duration were considered for the acute exercise protocol. Aerobic exercise using a cycle ergometer was selected as the exercise modality. Exercise intensity was set at moderate to vigorous intensity for all participants. Based upon ACSM guidelines (ACSM, 2010), participants with different levels of physical activity behavior might experience the intensity of the exercise differently; therefore the exercise intensity was initially set between 50–70% HRR with the specific percentage of HRR based upon each participant's physical activity level as assessed with the IPAQ (Bauman et al., 2009).

Target HRR for participants with high, moderate, and low activity levels were set at approximately 70%, 60%, and 50% HRR, respectively. To confirm that all participants experienced this exercise stimulus as moderate to vigorous in intensity, RPE was recorded and used in conjunction with % HRR to guide adjustments to the exercise intensity. The entire exercise duration was 30 min and consisted of warming up for 5 min, exercising at 14–17 on the RPE scale for 20 min, and cooling down for 5 min. The speed was set at 70 rpm. Workload was increased by 15 W every 2 min in the warm-up and exercise stage until the participant reached his/her initial target HR. During the 20 min of exercise, exercise intensity was increased if RPE was lower than 14, but was held constant when RPE was between 14 and 17. The acute exercise protocol was designed based upon ACSM guidelines (ACSM, 2010).

Tower of London Task

Since Shallice developed the TOL Task, a variety of modified versions have been created such as the Tower of London-Drexel Task (TOLDX) (Culbertson, Moberg, Duda, Stern, & Weintraub, 2004; Culbertson & Zillmer, 1998), the five-disc TOL Task (Ward & Allport, 1997), four-rod TOL Task (Kafer & Hunter, 1997), and the TOL-R Task (Schnirman, Welsh, & Retzlaff, 1998). For this study, the Tower of London-Drexel 2nd edition Task was used because of several advantages of this task. These include the elimination of the requirement to repeat trials for problems that were not successfully completed, the inclusion of problems that require six and seven moves to raise the "ceiling" of the measure, the provision of detailed instructions for administration and interpretation, and the existence of a comprehensive normative base for healthy controls from age 7 to more than 60 years (Culbertson et al., 2004; Culbertson & Zillmer, 2005).

The TOL Task apparatus consists of two identical wooden boards (30 × 7 × 10 cm) and two sets of three beads (blue, green, and red). Each board consists of three vertical pegs where the tallest peg (Peg 1) can hold three beads at most, the middle peg (Peg 2) can hold only two beads, and the shortest peg (Peg 3) can only hold one bead. One wooden board was used by the participant with the beads in a standard start configuration. Another wooden board was controlled by the examiner who demonstrated 10 test problems. The 10 test problems (adult version) have different difficulty levels which are identified by requiring a minimum number of moves from two to sevem (Figure 1). Participants were instructed to move beads from the start configuration to the goal/final configuration with as few moves as possible without violating either of the TOL Task rules. The possible rule violations were Rule Violation Type I: placing or trying to place more beads on a peg than it can physically support, and Rule Violation Type II: removing two beads from the peg at the same time. To effectively perform, participants must identify the goal configuration, consider possible subgoals that approach the goal configuration, and maintain the sequence of operations required to achieve the subgoals; therefore, planning and problem solving are tested. The administration of the TOL Task required 25–30 min.
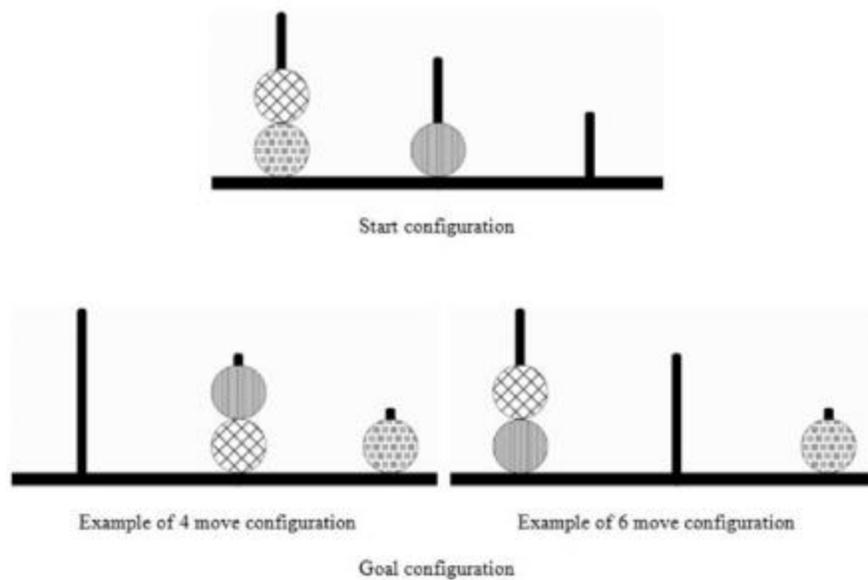
Figure 1 — An example Tower of London Task with start configuration and goal configuration with four and six moves.

Seven TOL Task performance scores were computed (Berg et al., 2010): total move score, total correct score, rule violation score, time violation score, total initial time, total executive time, and total planning-solving time based upon the TOL Task technical manual (Culbertson & Zillmer, 2005). Past research has shown that over a 140-day period the test–retest reliabilities for the seven TOL Task are acceptable (r = 62–.81) for all tasks except rule violation(r = .28) (Culbertson et al., 2004).

Total move score is the number of actual bead moves minus the minimum number of solution moves for each problem. When a participant exceeded 20 moves or a problem was not solved within 2 min, 20 moves was set as a maximal move score to avoid the inflation of total move scores and to limit frustration for the participants. Total correct score is the number of problems solved in which only the minimum number of moves was used. The rule violation score is the number of Type I and Type II rules violations. A time violation score was recorded when the participants failed to complete a problem within 1 mine (range from 1 to 10). Total initial time was measured by stopwatch by the examiner, and is defined as the summation of the time from the presentation of each goal problem by the examiner to the time when the participant initially lifted a bead off a peg (first move). Total execution time represents the time from the initiation of the first move to the completion or discontinuation of problem solving for each problem. Lastly, total planning-solving time is computed by the summing total initial time and total execution time. The suggested interpretations for the TOL Task performance scores are presented in Table 1.

Table 1 The Potential Cognitive Processes Underlying TOL Task Performance Scores

Variable	Potential Indices / Underlying Cognitive Process
Total move score	Quality of executing planning
Total correct score	Working memory process (both spatial and object)
Rule violation score	Ability to govern and control executive planning
Time violation score	Quality of cognitive processing and output, motor control, perseverative responding, or attentional allocation
Total initial time	Inhibition and thoughtful preparation to a problem
Total execution time	Quality of executive planning once solution templates are implemented
Total planning-solving time	Appraised overall speed of executive planning

Note. The above meanings are summarized based upon the TOL Task technical manual (Culbertson & Zillmer, 2005).

Procedure

Participants came to the laboratory individually for two testing sessions. In Session 1, each participant was presented with a brief introduction to the experiment, was given an informed consent, and was asked to complete the PAR-Q, health history, demographic, and IPAQ questionnaires. Participants meeting the inclusion criteria were randomly assigned into either an aerobic exercise group or the control group. Height and weight were measured and participants were asked to put on the HR monitor. Resting HR was assessed after participants sat quietly in a comfortable chair in a dimly lit room for 20 min.

In Session 2, each participant was given instructions and demonstrations on the TOL Task. The participant then performed 10 prescribed problems of the TOL Task as pretest data. Participants in the aerobic exercise group then performed an acute cycling ergometer protocol, while participants in the control group were asked to read materials related to aerobic exercise for a period of time that was similar to the entire exercise duration. Following their respective treatments, participants were asked to conduct the TOL Task again as posttest data. Heart rate was measured throughout the pretest, during the treatment condition, and at the posttest. Pretest HR was identified as HR immediately before the treatment condition began. Maximal HR during treatment was the highest HR during the treatment period. Average HR was the average across the 20-min exercise bout for the exercisers and was the average across the treatment period for the control participants. Posttest HR was identified as HR after cooldown for the exercisers and at the end of the treatment period for the control participants. For both groups, this was immediately before performing the TOL Task. In total, both sessions lasted approximately 1 hr and 30 min, and after completion participants were given 15 U.S. dollars for compensation and briefed on the purpose of the experiment.

Statistical Analyses

This was a mixed randomized controlled trial design with group and time as independent variables. To ensure that the control and exercise groups were equivalent on potential confounds, independent samples t tests were used to compare demographic data between the two groups. To test the exercise intensity manipulation, a mixed 2 (group: exercise vs. control) × 3 (time: pretest

HR, average HR, posttest HR) analysis of variance (ANOVA) was conducted for HR. Then, to test the effect of exercise on executive function, analyses of seven TOL Task performance scores were conducted using 2 (group: exercise vs. control) × 2 (time: pretest vs. posttest) mixed ANOVAs. An alpha of 0.05 was used as the level of statistical significance; however, Bonferroni adjustments were made to control for the experimentwise inflation of alpha. For all ANOVAs, significant interaction effects were followed up with tests of simple effects which were then followed up with Fisher's least significant difference post hoc tests if needed. Effect sizes (ES) using Cohen's d (the mean difference of the groups divided by the pooled standard deviation) and partial eta-square (η2p) were reported for main effects and significant interactions.

Results

Potential Confounds

There were no significant differences (p > .05) between the groups in age, education, height, weight, BMI, IPAQ, or resting HR. Means, standard deviations, and the t test values for participant demographic information are presented in Table 2.

Manipulation Check

Results of the 2 × 3 mixed ANOVA for HR revealed that there were significant main effects for group, $F(1, 40) = 239.52$, $p < .001$, η2p = .86, and time, $F(2, 80) = 346.35$, $p < .001$, η2p = .90, and a significant interaction of group × time, $F(2, 80) = 377.18$, $p < .001$, η2p = .90.

Given that there was a significant interaction effect, follow-up simple effects were used to decompose the interaction of group × time. A significant effect for time was found for the exercise group, $F(2, 38) = 4578.17$, $p < .001$, η2p = .96, but not for the control group, $F(2, 42) = 2.30$, $p > .05$. For the exercise group, pretest HR was significantly lower than average HR which was significantly higher than posttest HR. In addition, posttest HR was significantly higher than pretest HR. Moreover, the simple effects also showed that average HR, $F(1, 40) = 64\,733.46$, $p < .001$, and posttest HR, $F(1, 40) = 17\,474.08$, $p < .001$, were significantly higher for the exercise group than the control group (Figure 2). No significant differences between groups were observed for pretest HR, $F(1, 40) = 4.37$, $p > .05$.

Table 2 Means and Standard Deviations for Participant Demographic Information

Variable	Control (n = 22) M (SD)	Exercise (n = 20) M (SD)	t (40)
Female (n)	73%	65%	—
Age (years)	22.09 (2.20)	22.45 (1.64)	0.60
Education (years)	16.4 (0.82)	16.5 (0.91)	−0.54
Height (cm)	166.95 (9.37)	166.25 (9.14)	−0.25
Weight (kg)	62.82 (16.29)	63.15 (12.70)	0.07
BMI (kg/m²)	22.21 (3.36)	22.74 (3.52)	0.50
IPAQ (METs)	2002.04 (1517.74)	2557.74 (2097.75)	0.44
Resting HR (bpm)	67.80 (10.96)	65.73 (7.32)	0.71

Note. BMI = body mass index. IPAQ = International Physical Activity Questionnaire. METs = metabolic equivalents. Resting HR = resting HR assessed in session. bpm = beats per minute.
*p < .05.
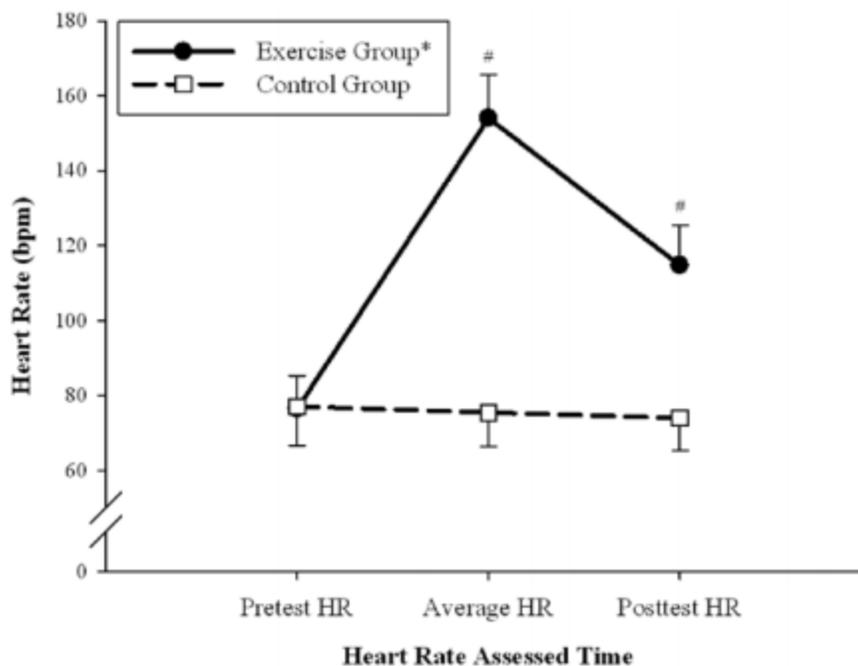
Figure 2 — Heart rate (mean and standard deviation) across experimental protocol. *Note.* *Significant difference between pretest, average, and posttest for this group. #Significant difference between groups.

During the treatment, %HRR was 69% for the exercise group and 7% for the control group. For the exercise group, the average highest RPE was 16.3 and the overall average RPE was 15.2. Additional descriptive statistics for the exercise manipulation check are presented in Table 3.

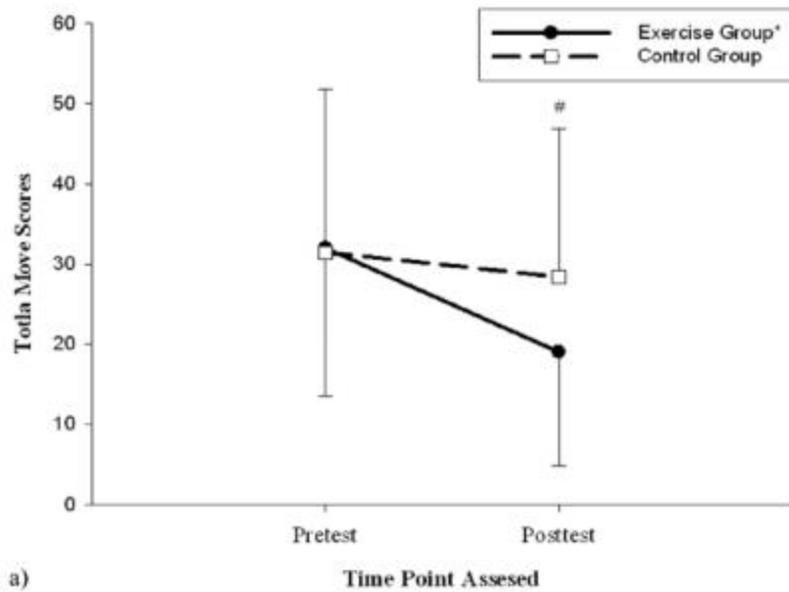**Table 3** **Means and Standard Deviations for Heart Rate (HR)**

Variable	Control M (SD)	Exercise M (SD)
Maximal HR (bpm)	193.65 (1.32)	193.43 (0.98)
Resting HR (bpm)	67.80 (10.96)	65.73 (7.32)
Pretest HR (bpm)	77.05 (10.43)	76.40 (8.81)
Maximal HR during treatment (bpm)	81.14 (1.04)	160.40 (11.79)
Average HR (bpm)	75.37 (9.15)	153.98 (11.49)
%HRR	0.07 (0.04)	0.69(0.08)
Posttest HR (bpm)	73.91 (8.63)	114.75 (10.95)
Maximal RPE	–	16.30 (1.78)
Average RPE	–	15.24 (1.59)

Note. bpm = beats per minute. Maximal HR = maximal HR estimated using Gellish et al. (2007). Resting HR = resting HR assessed in Session 1. Pretest HR = HR assessed immediately before the treatment condition began. Maximal HR during treatment and average HR = maximal and average HR assessed during the 20 min of exercise or reading. Posttest HR = HR assessed after cooldown and before assessing TOL Task. Maximal RPE and Average RPE = maximal RPE and average RPE assessed during the 20 min of exercise or reading.
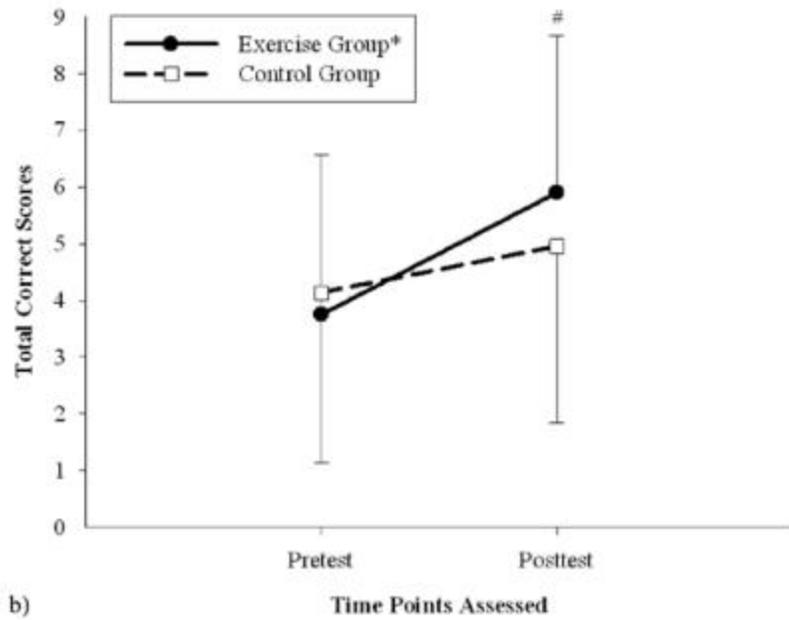
TOL Task Performance Scores

Descriptive statistics of TOL performance scores are presented in Table 4. For total move score, a 2×2 mixed ANOVA revealed that there was a significant main effect for time, $F(1, 40) = 17.64$, $p < .001$, $\eta2 p = .31$, but not for group, $F(1, 40) = 0.70$, $p > .05$. There was a significant interaction of group by time, $F(1, 40) = 6.77$, $p = .01$, $\eta2 p = .15$. Follow-up simple effects showed that total move score decreased significantly from pretest to posttest for the exercise group, $F(1, 21) = 26.39$, $p < .01$, $\eta2 p = .58$, whereas no significant change from pretest to posttest was found for the control group, suggesting exercise benefits total move score (Figure 3a).

Similar findings were observed for total correct score, where there was a significant main effect for time, $F(1, 40) = 31.34$, $p < .001$, $\eta2 p = .44$, but no main effect for group, $F(1, 40) = 0.10$, $p = .75$. A significant interaction of group $\times$ time, $F(1, 40) = 6.31$, $p = .02$, $\eta2 p = .14$, was revealed. Follow-up simple effects showed that the total correct score increased significantly from pretest to posttest for the exercise group, $F(1, 19) = 48.06$, $p < .01$, $\eta2 p = .72$, whereas no significant difference was found in the control group, suggesting exercise benefits total correct score (Figure 3b).

Figure 3 — TOL Task performance scores (mean and standard deviation) as a function of time and group on (a) total move score and (b) total correct score. *Note.* *Significant difference between pretest and posttest for this group. #Significant difference between groups.

Table 4 Means, Standard Deviations, and Effect Sizes for TOL Task Performance Scores

Variable	Control Group			Exercise Group		
	Pretest *M (SD)*	Posttest *M (SD)*	ES	Pretest *M (SD)*	Posttest *M (SD)*	ES
Total move score	31.45 (20.42)	28.40 (18.55)	−0.16	32.00 (18.40)	19.05 (14.28)	−0.79
Total correct score	4.14 (3.00)	4.95 (3.11)	0.27	3.75 (2.83)	5.90 (2.77)	0.77
Rule violation score	0.27 (0.70)	0.90 (0.29)	1.18	0.10 (0.45)	0.00 (0.00)	−0.31
Time violation score	0.23 (0.43)	0.00 (0.00)	−0.76	0.50 (1.10)	0.50 (0.22)	0.00
Total initial time	25.53 (13.97)	20.66 (7.60)	−0.43	36.31 (22.75)	31.38 (19.04)	−0.24
Total execution time	164.00 (65.64)	126.87 (38.13)	0.69	188.80 (83.06)	124.74 (63.18)	−0.87
Total planning-solving time	188.70 (68.72)	147.54 (37.65)	−0.74	225.36 (90.68)	156.11 (72.85)	−0.84

Note. Effect size (ES) is calculated by Cohen's *d*.

For the rule violation score, no significant results emerged. For the time violation score, there was only a main effect for time, $F(1, 40) = 6.67$, $p < .05$, $\eta2p = .14$, with fewer time violations occurring at the posttest.

For TOL Task time-related variables (total initial time, total executive time, and total planning-solving time), there were only main effects for time, $F(1, 40) = 6.69$, $p < .05$, $\eta2p = .14$; $F(1, 40) = 28.04$, $p < .001$, $\eta2p = .41$; and $F(1, 40) = 30.39$, $p < .001$, $\eta2p = .43$, respectively. Shorter times were recorded at the posttest than at the pretest for all measures. However, the main effects for group and the interaction of group by time were not significant for any of these variables.

Discussion

Recent research focused on the influence of acute exercise on executive function following acute exercise has generally shown that there is a positive effect for measures of inhibition. However, only a few studies have explored the effects on other aspects of executive function, and no study has examined the effect for measures of planning and problem solving. The present study was designed to examine the effect of acute aerobic exercise on planning and problem solving, as measured by the TOL Task.

The exercise manipulation check indicated that participants were exercising at a moderate to vigorous intensity (69% HRR). Thus, results indicated that after participating in a single session of moderate to vigorous aerobic exercise, participants in the exercise group had significantly lower total move scores and significantly greater total correct move scores than participants in the control group, which indicated improvements in planning and problem solving. However, there were no significant differences between the two groups on violation and time-related scores from the TOL Task, indicating that acute aerobic exercise had no influence on speed of performance or on errors with respect to the rules of the task. These results suggest that the benefits of acute exercise for planning and problem solving are evident in the quality of the planning and problem solving and are not a result of a speed-accuracy trade-off. In other words, because the number of errors did not increase and the speed of performance was equivalent, exercisers improved performance without sacrificing accuracy and without simply speeding up their performance.

The TOL Task is a well-established and widely used neuropsychological test of planning ability with multiple subcomponent assessments (Unterrainer et al., 2004). Total move score is the primary measure of planning, a main aspect of executive function (Culbertson & Zillmer, 2005), and is described as indicative of problem-solving efficiency (Berg & Byrd, 2002). It also reflects the quality of conducting planning (Culbertson & Zillmer, 2005). Specifically, the planning and problem solving required to accomplish the TOL Task involve processes that transform current mental representations to goal states through the generation and consideration of multiple potential approaches. Therefore, efficiently solving the problems with fewer total moves after acute exercise reflects efficiency in recognizing both initial and goal states, anticipating future events, and storing representations of intermediate states that can guide movements from the initial to the goal state.

The benefits of acute exercise for specific aspects of cognition might be reflective of the activation of specific brain regions. In particular, performance of the TOL task appears to be reliant on activation in the frontal area. Lazeron et al. (2000) compared brain images during performance of an adapted TOL Task condition and a control condition and found that

participants performing the TOL Task activated frontal structures bilaterally in the middle frontal gyrus and in part of the inferior frontal sulcus. In addition, fMRI studies have consistently reported that the processes required to perform the TOL Task involve the prefrontal lobe, particularly the dorsolateral frontal region (Lazeron et al., 2000; Newman, Greco, & Lee, 2009; van den Heuvel et al., 2003). Given that acute exercise resulted in an improvement in total move scores in this study, evidence of an association between acute exercise and frontal activity would suggest then this as a possible mechanism of the effects. This view has been supported by recent findings using multichannel functional near-infrared spectroscopy; acute moderate exercise is linked to better executive function performance and more activation in left dorsolateral prefrontal cortex, suggesting that the dorsolateral prefrontal cortex is a likely neural substrate underlying acute exercise and executive function (Yanagisawa et al., 2010).

The total correct score represents the number of test problems completed within the minimum number of moves expected (Berg & Byrd, 2002). Culbertson and Zillmer (2005) indicated that total correct score is a measure that is linked to working memory. The difficulty of TOL problems is gauged by the number of moves required to solve the problem. Thus, because the total correct score is indicative of the ability to solve more of the difficult problems, a higher score represents being more able to request or maintain the configurations of goals and subgoals necessary to solve the problem. To solve the problems successfully, participants need to formulate, retain, and implement plans as well as to revise the plans online; these are main characteristics of working memory. The association between TOL and working memory is also supported by other research (Asato, Sweeney, & Luna, 2006; Culbertson et al., 2004).

Thus, the findings with regard to total correct score suggest that acute exercise might also benefit executive function by improving working memory in addition to benefiting planning and problem solving. This finding is consistent with previous research in which shorter reaction times during a working memory task (e.g., modified Sternberg task) were found for an acute aerobic exercise group, but not for acute resistance exercise and control groups (Pontifex et al., 2009). However, there are some studies that have not demonstrated beneficial effects for acute exercise on working memory. Using a free-recall memory test, Coles and Tomporowski (2008) indicated that 40 min of moderate aerobic exercise facilitated long-term memory, but had no influence on working memory or short-term memory. The variety of the study designs with regard to factors such as exercise modality, duration, and intensity and measures of working memory might explain the disparate findings.

Several hypotheses have been proposed to explain how acute exercise affects executive function. Using electroencephalographic (EEG) measures of spectral activity, Kubitz and Pothakos (1997) found that following acute aerobic exercise, participants in an exercise group had higher alpha and lower beta activity suggesting an increase in neuronal synchrony that was interpreted as being indicative of increased efficiency of cognitive functioning. Hillman et al. (2003) used EEG to examine event-related potentials during performance of an executive control task that was performed following an acute exercise session. Results indicated that acute exercise induced larger P3 amplitude and shorter P3 latency which was interpreted as suggesting that exercise benefits executive function via increasing allocation of neuroelectric resources and improvements in stimulus classification speed.

Despite acute exercise benefiting total move score and total correct score, significant results were not observed in violation- and speed-related TOL Task scores. In terms of rule violation and time violation scores, Culbertson and Zillmer (2005) indicated that normal adults rarely commit these violations, suggesting the presence of a probable floor effect. In addition,

with such low violation scores (rule = 0.32; time = 0.31), it is also reasonable to anticipate the relative stability of violation scores between the groups. Lastly, the low reliability of the rule violation score (Culbertson et al., 2004), could explain why exercise was not found to affect this measure. With respect to the total initial time, total execution time, and total planning-solving time, effects of the exercise were not evidenced on any of these speed-related TOL Task scores. One potential explanation is that time-related scores might be independent of the move- and correct-related scores. Phillips, Wynn, McPherson, and Gilhooly (2001) indicated that time-related scores do not result in higher accuracy of TOL performance. However, it is also arguable that the effect of acute exercise on subaspects of planning and problem solving might be affected disproportionately.

Given that this is the first study to explore the effects of acute exercise on the executive function subcomponents of planning and problem solving and the positive findings observed, further research in this area is encouraged and warranted. In particular, we recommend that future researchers consider the following limitations of this study and suggestions for future research. In this study, we controlled exercise intensity using RPE as the guide and selected a range of 14–17, thus relying more on the participant's perception of the exercise intensity than the absolute intensity. Future research should be designed to further our understanding of the potentially different effects of perceived exercise intensity and absolute exercise intensity on the effects of acute exercise on subsequent cognitive performance. In addition, this particular intensity range was selected based upon conclusions from previous reviews that moderate intensity exercise benefits cognitive performance and based upon public health recommendations that people exercise at moderate to vigorous intensity. Recent research has begun to focus on ventilatory threshold as an important intensity level relative to the effects of acute exercise on subsequent cognitive performance (Del Giorno, Hall, O'Leary, Bixby, & Miller, 2010; Ferris, Williams, & Shen, 2007) and this may be an important direction for future research relative to understanding dose-response relationships between exercise intensity and planning and problem solving after exercise. In addition, although the TOL Task has been considered predominately a task of planning and problem solving (Unterrainer et al., 2004), others have suggested that the TOL Task also taps the executive functions of working memory and inhibition (Welsh, Satterlee-Cartmell, & Stine, 1999; Zook, Davalos, DeLosh, & Davis, 2004) and total correct has been specifically implicated as a measure of working memory (Culbertson & Zillmer, 2005). Future research should consider using other tasks that might be even more purely indicative of planning and problem solving to further explore the relationship. Lastly, these results support the recommendation by Etnier and Chang (2009) that researchers interested in the effects of acute exercise on executive function should use multiple tasks including those commonly used in exercise and cognition research and neuropsychological tests of assessing planning and problem solving

In conclusion, the current study demonstrates that a single bout of moderate to vigorous intensity aerobic exercise benefits the executive functions of planning and problem solving performed after the exercise. More specifically, rather than resulting in general improvements for all measures derived from the TOL Task, acute exercise was found to have benefits for scores related to efficiency and accuracy of planning and problem solving rather scores related to violation and speed related performances.

Acknowledgments

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