

The Effect of Acute Aerobic and Resistance Exercise on Working Memory

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ABSTRACT

PONTIFEX, M. B., C. H. HILLMAN, B. FERNHALL, K. M. THOMPSON, and T. A. VALENTINI. The Effect of Acute Aerobic and Resistance Exercise on Working Memory. *Med. Sci. Sports Exerc.*, Vol. 41, No. 4, pp. 927–934, 2009. **Purpose:** The goal of this investigation was to assess the influence of acute bouts of aerobic versus resistance exercise on the executive control of working memory. **Methods:** Twenty-one young adult participants completed a cardiorespiratory fitness test and maximal strength tests. On subsequent days, task performance measures of reaction time (RT) and accuracy were collected while participants completed a modified Sternberg working memory task before the start of, immediately after, and 30 min after an intervention consisting of 30 min of either resistance or aerobic exercise and a seated rest control. **Results:** Findings indicated shorter RT immediately and 30 min after acute aerobic exercise relative to the preexercise baseline with no such effects observed after resistance exercise or seated rest. Further, in the aerobic condition, a larger reduction in RT from the baseline occurred during task conditions requiring increased working memory capacity. Again, no effect was observed in the resistance exercise or the seated rest conditions. **Conclusion:** These data extend the current knowledge base by indicating that acute exercise-induced changes in cognition are disproportionately related to executive control and may be specific to the aerobic exercise domain. **Key Words:** COGNITION, EXECUTIVE CONTROL, STERNBERG TASK, REACTION TIME

Previous research has indicated that participation in physical activity is associated with increased performance across a variety of tasks involving attention, cognition, and memory (7,9). Accordingly, a growing interest has developed regarding changes in cognition after participation in single “acute” bouts of physical activity to determine the potential health benefits that may derive from such behaviors. Recent reviews and meta-analyses (5,9,34) have suggested that participation in acute aerobic activity exerts a positive influence on cognitive function. Based on research examining chronic physical activity (7,17) and acute exercise bouts (12), it appears that the positive influences derived for cognition are greatest for tasks or task components with greater executive control demands.

The term “executive control” describes a subset of processes involved in the selection, scheduling, and coordination of computational processes that underlie perception, memory, and action (23,24). These processes require conscious awareness, are resource limited, and are

functionally distinct from the processes that they organize (28). As a result of these characteristics, aspects of cognition requiring extensive amounts of executive control (e.g., working memory, response inhibition, mental flexibility) do not habituate or become automatic over time (28). Research examining the effect of acute exercise on cognitive performance has suggested a disproportionately larger benefit for tasks requiring greater amounts of executive control relative to tasks with smaller executive requirements (13,20,35), extending findings examining chronic physical activity participation (7).

Investigations into acute exercise-induced changes in executive control function have primarily used tasks that tap aspects of inhibitory control. Inhibitory control is one aspect of executive control that relates to the ability to gate task irrelevant information in the environment (i.e., interference control) and inhibit a prepotent response to allow selection of the appropriate response (i.e., response inhibition). Several studies have observed improvements in task performance on inhibitory control tasks (i.e., the Stroop and the Paced Auditory Serial Addition tests) after an acute bout of aerobic exercise (13,20,35). Specifically, Hogervorst et al. (13) and Lichtman and Poser (20) both observed facilitation of performance immediately after exercise relative to a control condition on a Stroop task. This task manipulates inhibitory control as participants must inhibit a prepotent response to read a word and activate a weaker response to name the color of the ink in which the word appears. After an hour of aerobic exercise at 70% of maximal work capacity, Hogervorst et al. (13) observed

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Submitted for publication July 2008.

Accepted for publication October 2008.

0195-9131/09/4104-0927/0

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DOI: 10.1249/MSS.0b013e3181907d69

shorter reaction time (RT) only on the condition requiring the greatest amount of executive control relative to the preexercise and the baseline conditions. No such effect was observed for the condition with smaller executive requirements, indicating that acute exercise was selectively beneficial to task conditions requiring greater amounts of inhibitory control. Lichtman and Poser (20) observed similar facilitative yet selective effects after 45 min of aerobic exercise relative to a preexercise condition. Further support for the beneficial effects of acute exercise on inhibitory control has been garnered from Tomporowski et al. (35), who observed facilitations in performance on a Paced Auditory Serial Addition Test after a 30-min recovery period after exercise. Taken together, these results suggest that changes in cognitive function after exercise may be selectively larger for cognitive processes involved with inhibitory control.

Despite these initial inquiries into the effect of acute exercise on inhibitory aspects of executive control, little research has examined this relationship concerning other aspects of executive control. Additional insight may be gained with tasks that tap other executive functions, such as working memory, to assess whether changes in cognition after acute exercise generalize to multiple executive components or whether they are selective to inhibitory control. Thus, one purpose of this study was to extend the acute exercise-cognition database to include aspects of executive control involved in working memory function. Working memory describes a subset of processes involved in the active storage, maintenance, and manipulation of information to be retrieved within a brief interval (15,26). One means by which to assess this aspect of executive control is through the Sternberg task (33), which requires participants to encode a series of stimuli into their working memory to decide whether a probe stimulus that is presented at a later time point was present in the encoded series. This task allows for the manipulation of executive control requirements by increasing the number of stimuli that must be encoded, with longer series associated with longer RT (33) and decreased response accuracy (21) due to the increased working memory capacity required to encode and to maintain relevant information.

To further develop the acute exercise-cognition database, investigation is also necessary into whether different acute exercise modalities differentially modulate changes in cognition. To date, the vast majority of research has investigated changes in cognition after an acute bout of aerobic exercise, whereas only a single study has investigated the effect of acute resistance exercise on cognitive function (i.e., [18]). Resistance exercise and aerobic exercise represent a distinct spectrum of exercise that is characterized by different physiological demands (i.e., cardiovascular, musculoskeletal, metabolic, etc.). Accordingly, the investigation of acute resistance exercise may provide further insight into the overall relation of health behaviors such as physical activity to cognition.

Krus et al. (18) observed a deficit in perceptual sensitivity after 20 s of pushing against a spring-opposed push board, which required participants to use large muscle groups in their chest, arms, and legs. Given that aerobic exercise-induced changes in cognition typically manifest as facilitations in performance, the observed decrease in perceptual sensitivity to a brief bout of resistance exercise may indicate that nonaerobic exercise exerts a differential relationship to cognition from that of aerobic exercise. Accordingly, the second purpose of the current study was to *expand* the acute exercise-cognition database to include resistance exercise and compare it with aerobic exercise during performance on a working memory task. Given the paucity of previous research, an initial approach may be to compare the recommendations of two governing bodies regarding aerobic exercise, with guidelines set forth by the American College of Sports Medicine (ACSM) (1), and resistance exercise, with guidelines set forth by the National Strength and Conditioning Association (NSCA) (2). Although unmatched in physiological and metabolic demands, these protocols provide an applied perspective in the comparison of the effects of two standard exercise protocols on cognition.

In the absence of a rich literature base examining acute resistance exercise and cognition, some understanding of this relationship may be gained through the examination of research on chronic resistance training. Previous research in this area has yielded mixed results, but some evidence suggests that chronic resistance training results in facilitation of select aspects of cognition involved with memory and attention. Specifically, both Perrig-Chiello et al. (25) and Cassilhas et al. (6) observed improvement of short-term memory in older adults after as little as 8 wk of chronic resistance training, with Cassilhas et al. (6) also observing improvements in long-term memory, executive control, and attention after 24 wk of chronic resistance training. Alternatively, Lachman et al. (19) observed no change in working memory in a sample of 210 older adults after 3 and 6 months of resistance training. Further, Tsutsumi et al. (36) observed no change in mental arithmetic and star tracing after 12 wk of resistance training in a sample of 45 older adults. Accordingly, consensus has not been reached concerning the relation between resistance exercise and cognition. It may be that these discrepant findings are a result of differences in cognitive demands across tasks, and that the utilization of tasks that require variable cognitive demands (such as through the manipulation of executive control requirements) may be necessary to elucidate the relationship between resistance exercise and cognition.

Thus, the current study examined the influence of an acute bout of resistance exercise on executive control function engendered by a working memory task relative to acute aerobic exercise and seated rest. To replicate previous research and to examine the immediate (13,20) and prolonged (12,35) impact of acute exercise on cognition, working memory was assessed using task performance

measures (i.e., RT, response accuracy) during a modified Sternberg task administered before the start of, immediately after, and 30 min after each of the exercise interventions (i.e., resistance exercise, aerobic exercise) and the control condition (i.e., seated rest). It was hypothesized that task performance indices of working memory would be facilitated by both acute exercise modalities. That is, shorter RT latency and increased response accuracy would be observed after both the aerobic and the resistance exercise interventions, relative to seated rest, with improved performance during trials necessitating greater amounts of working memory. Such a pattern of results would provide additional evidence for the disproportionately larger effect of acute exercise on tasks requiring greater amounts of executive control.

METHODS

Participants

Twenty-one undergraduate students (nine females, age = 20.2 ± 0.3 yr) from the University of Illinois at Urbana-Champaign served as participants. All participants provided written informed consent that was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign and completed the Physical Activity Readiness Questionnaire (PAR-Q), a questionnaire designed to provide sufficient preactivity screening to detect potential risk factors that might be exacerbated by acute exercise participation. Additionally, participants completed a health history and demographics questionnaire, reported being free from any neurological diseases, and reported normal or corrected-to-normal vision based on the minimal 20/20 standard. Table 1 presents participant demographics.

Working Memory Task

A modified Sternberg (33) task was used, which required participants to encode a memory set containing an array of three, five, or seven letters and decide whether a single probe letter was present in the encoded array. The memory

sets were comprised of all capitalized consonants and contained no alphabetical consonant strings (i.e., JKLMN), whereas the probe letters were lowercase consonants, bilaterally flanked by one, two, or three “?” to match the memory set in physical size and visual content. A right thumb press indicated that the probe was present, and a left thumb press indicated that the probe was absent from the encoded letter array. Probes presence/absence occurred with equal probability, and participants were instructed to respond to the probe letters as quickly and accurately as possible. One block of 102 trials counterbalanced with 34 trials in each set size was presented focally on a computer monitor at a distance of 1 m, with participants being instructed to respond as quickly but as accurately as possible. All stimuli were 7-cm tall white letters presented on a black background for 2000 ms (encoded array) and 200 ms (probe letter), with a 1500-ms response window. A randomized, interstimulus interval of 2000, 2500, or 3000 ms was used throughout the task block with a 1700-ms intertrial interval.

Cardiorespiratory Fitness Assessment

Maximal aerobic power ($\dot{V}O_{2max}$) was measured using a motor-driven treadmill and a modified Balke protocol (1), which involved walking/running on a treadmill at a constant speed with increasing grade increments of 2% every 2 min until volitional exhaustion occurred. A computerized indirect calorimetry system (K4b2; COSMED, Rome, Italy) collected breath-by-breath values for oxygen consumption. A Polar HR monitor (Model A1; Polar Electro, Kempele, Finland) measured HR throughout the test, and a rating of perceived exertion (RPE) (3) was taken at the end of every 2-min stage. Relative peak oxygen consumption was expressed in milliliters per kilogram per minute and was based on a maximal effort when the participants achieved two of the following four criteria: no change in HR with an increase in exercise workload/intensity; a RPE ≥ 17 ; a respiratory exchange ratio ≥ 1.15 ; or a plateau in oxygen consumption corresponding to an increase of less than 150 mL in oxygen uptake despite an increase in workload (22).

Procedure

Day 1—baseline testing. On the first laboratory visit, participants completed an informed consent and the PAR-Q to screen for any previous health issues that may be exacerbated by acute exercise. Participants were then fitted with a Polar HR monitor (Model A1; Polar Electro) and had their height and weight measured using a stadiometer (to the nearest 0.5 cm) and a beam balance platform scale, respectively. A fitness assessment was then conducted, including a cardiorespiratory fitness test ($\dot{V}O_{2max}$) and strength tests to measure 1-repetition maximum (1RM) on seven exercises (triceps press, bicep curls, bench press, lat pulls, military press, single leg curl [dominate leg], and

TABLE 1. Participant demographics and fitness values (± 1 SE).

Measure	All	Males	Females
<i>N</i>	21	12	9
Age (yr)	20.2 \pm 0.3	20.3 \pm 0.4	20.1 \pm 0.6
BMI ($\text{kg}\cdot\text{m}^{-2}$)	22.9 \pm 0.7	22.4 \pm 0.6	23.6 \pm 1.3
RPE _{max}	17.9 \pm 0.2	18.0 \pm 0.3	17.8 \pm 0.2
HR _{max} (bpm)	193.4 \pm 1.5	192.6 \pm 2.3	194.6 \pm 1.7
$\dot{V}O_{2max}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	54.6 \pm 2.3	60.1 \pm 2.6	47.3 \pm 2.5
Triceps press max (lb)	63.6 \pm 4.9	79.2 \pm 4.1	42.8 \pm 3.9
Bicep curl max (lb)	57.9 \pm 4.7	73.3 \pm 3.7	37.2 \pm 3.2
Bench press max (lb)	144.1 \pm 13.6	187.1 \pm 12.1	86.7 \pm 9.3
Lat pull max (lb)	123.3 \pm 7.6	148.8 \pm 5.1	89.4 \pm 6.4
Military press max (lb)	78.3 \pm 7.9	102.1 \pm 8.0	46.7 \pm 5.0
Leg curl max (lb)	46.2 \pm 3.4	54.2 \pm 4.2	35.6 \pm 3.1
Leg press max (lb)	153.8 \pm 9.0	168.3 \pm 10.5	134.4 \pm 13.9

BMI, body mass index; RPE_{max}, maximum ratings of perceived exertion at the completion of the cardiorespiratory fitness assessment; HR_{max}, maximum HR at the completion of the cardiorespiratory fitness assessment; $\dot{V}O_{2max}$, maximum oxygen consumption at the completion of the cardiorespiratory fitness assessment.

single leg press [dominate leg]) using a Body-Solid EXM3000S multistation gym. This protocol adhered to the testing guidelines recommended by the ACSM (see Table 1 for HR_{max}, $\dot{V}O_{2max}$, and 1RM data). Participants completed a health history and demographics questionnaire during the 10-min rest between the cardiorespiratory fitness test and the 1RM strength tests.

Days 2, 3, and 4—experimental sessions. Laboratory visits 2, 3, and 4 were counterbalanced across subjects to minimize any order or learning effects. During these visits, participants completed the Sternberg task before, immediately after, and 30 min after the experimental condition, which consisted of either 30 min of aerobic exercise, resistance exercise, or seated rest. Before the start of each experimental session, participants were administered 20 practice trials. During each visit, HR and oxygen consumption were measured throughout the session using a Polar HR monitor (Model A1; Polar Electro) and a K4b2 breath-by-breath computerized indirect calorimetry system (K4b2; COSMED). The aerobic exercise session was based on the ACSM guidelines for improving aerobic capacity, with participants completing 30 min of aerobic exercise on a motor driven treadmill at an intensity of 60%–70% of $\dot{V}O_{2max}$. The resistance exercise session was designed to provide an exercise stimulus similar in duration to aerobic exercise and was based upon the NCSA guidelines for improving muscular capacity (2). During the 30-min resistance exercise condition, participants completed three sets of 8–12 repetitions at 80% of their 1RM for each of the seven major muscle groups using a Body-Solid EXM3000S multistation gym. Additionally, participants were given a 60-s rest between each set and a 90-s rest between each exercise to ensure that they were able to complete at least eight repetitions during each set. If participants were unable to complete a minimum of eight

repetitions, a 5% reduction in target weight on the subsequent set occurred. Lastly, the seated rest condition was designed to serve as a control condition to index the influence of repeated testing on task performance. During the seated rest condition, participants sat quietly by themselves for 30 min, were provided an assortment of popular magazines to read, and were monitored to ensure that they did not fall asleep or stand up and move around. See Table 2 for HR, oxygen consumption ($\dot{V}O_2$), and other condition specific information for each experimental condition.

Statistical Analysis

Statistical analyses were conducted for physiological measures of HR and $\dot{V}O_2$ using a 3 (mode: aerobic exercise, resistance exercise, seated rest) \times 5 (time: rest, pretest, experimental condition, posttest, 30 min posttest) repeated-measures MANOVA. Additional statistical analyses were conducted separately for absolute measures of RT and response accuracy using a 3 (mode: aerobic exercise, resistance exercise, seated rest) \times 3 (time: pretest, posttest, 30 min posttest) \times 3 (set size: 3 letters, 5 letters, 7 letters) repeated-measures MANOVA. Analyses of relative measures of RT and response accuracy were conducted separately using a 3 (mode: aerobic exercise, resistance exercise, seated rest) \times 2 (time: [(posttest – pretest) / pretest] [(30 min posttest – pretest) / pretest]) \times 3 (set size: 3 letters, 5 letters, 7 letters) repeated-measures MANOVA. Analyses with three or more within-subjects levels used the Wilks' lambda statistic, and *post hoc* comparisons were conducted using Tukey's HSD tests. Estimates of effect size, partial eta-square (η^2), were reported for significant main effects and interactions. All analyses used a significance level of $P = 0.05$.

TABLE 2. HR, oxygen consumption ($\dot{V}O_2$), and other condition-specific information for each experimental condition (± 1 SE).

Mode	Measure	All	All (% Max)	Males	Females
Seated rest	Average HR (bpm)	67.9 \pm 1.8	35.1 \pm 0.9	66.9 \pm 2.1	69.2 \pm 3.3
	Average $\dot{V}O_2$ (mL·kg ⁻¹ ·min ⁻¹)	4.8 \pm 0.3	8.9 \pm 0.5	5.4 \pm 0.3	4.0 \pm 0.4
	Average HR (bpm)	161.6 \pm 2.0	83.6 \pm 1.0	163.5 \pm 2.4	159.0 \pm 3.2
Aerobic exercise	Average $\dot{V}O_2$ (mL·kg ⁻¹ ·min ⁻¹)	33.8 \pm 1.3	62.5 \pm 1.4	36.4 \pm 1.6	30.4 \pm 1.3
	Average speed (mph)	5.3 \pm 0.2	—	5.7 \pm 0.2	4.8 \pm 0.2
	Average grade (%)	1.0 \pm 0.0	—	1.0 \pm 0.0	1.0 \pm 0.0
	Average RPE	11.1 \pm 0.3	62.2 \pm 1.7	11.6 \pm 0.3	10.5 \pm 0.5
	Average HR (bpm)	122.5 \pm 2.6	63.3 \pm 1.2	125.4 \pm 2.7	118.8 \pm 5.0
	Average $\dot{V}O_2$ (mL·kg ⁻¹ ·min ⁻¹)	12.9 \pm 0.8	23.9 \pm 1.1	14.7 \pm 1.0	10.5 \pm 0.6
Resistance exercise	Triceps press average weight (lb)	47.9 \pm 3.7	75.5 \pm 1.3	59.4 \pm 3.1	32.6 \pm 3.2
	Triceps press average reps	11.6 \pm 0.3	—	11.5 \pm 0.4	11.8 \pm 0.2
	Bicep curl average weight (lb)	40.3 \pm 3.3	70.1 \pm 1.5	50.6 \pm 2.8	26.7 \pm 2.6
	Bicep curl average reps	11.5 \pm 0.2	—	11.3 \pm 0.4	11.7 \pm 0.2
	Bench press average weight (lb)	106.5 \pm 10.2	74.1 \pm 1.2	137.2 \pm 9.9	65.6 \pm 7.5
	Bench press average reps	10.6 \pm 0.4	—	10.2 \pm 0.5	11.2 \pm 0.4
	Lat pull average weight (lb)	92.5 \pm 5.8	75.4 \pm 1.5	111.4 \pm 4.6	67.4 \pm 4.5
	Lat pull average reps	11.7 \pm 0.2	—	11.6 \pm 0.2	11.7 \pm 0.2
	Military press average weight (lb)	49.3 \pm 4.8	63.5 \pm 1.9	62.6 \pm 5.2	31.5 \pm 4.1
	Military press average reps	10.1 \pm 0.3	—	9.3 \pm 0.5	11.2 \pm 0.3
	Leg curl average weight (lb)	29.8 \pm 2.2	65.8 \pm 2.8	35.6 \pm 2.3	22.2 \pm 2.2
	Leg curl average reps	11.8 \pm 0.1	—	11.7 \pm 0.2	12.0 \pm 0.0
	Leg press average weight (lb)	116.5 \pm 7.3	76.1 \pm 1.8	127.3 \pm 9.3	102.2 \pm 10.2
	Leg press average reps	11.9 \pm 0.1	—	12.0 \pm 0.0	11.9 \pm 0.1

RPE, ratings of perceived exertion during aerobic exercise; average HR, mean HR during the experimental condition; average $\dot{V}O_2$, mean oxygen consumption during the experimental condition.

RESULTS

Preliminary Analysis

Preliminary analyses were conducted for pretest behavioral measures of performance (RT and response accuracy) to verify that pretest measures were not significantly different using a 3 (mode: aerobic exercise, resistance exercise, seated rest) \times 3 (set size: 3 letters, 5 letters, 7 letters) repeated-measures MANOVA. The omnibus analysis revealed nonsignificant effects of mode for RT, $F(2, 19) = 0.21$, $P = 0.81$, $\eta^2 = 0.02$, and response accuracy, $F(2, 19) = 0.33$, $P = 0.73$, $\eta^2 = 0.03$.

Physiological Measures

HR. The omnibus analysis revealed main effects of Mode, $F(2, 19) = 176.8$, $P < 0.001$, $\eta^2 = 0.95$, and time, $F(4, 17) = 355.4$, $P < 0.001$, $\eta^2 = 0.99$, which were superseded by a mode \times time interaction, $F(8, 13) = 351.8$, $P < 0.001$, $\eta^2 = 0.99$. Decomposition of this interaction by examining mode within time revealed increased mean HR for aerobic exercise relative to resistance exercise and increased mean HR for resistance exercise relative to seated rest during the experimental manipulation, t 's (20) ≥ 13.7 , $P < 0.001$. Additionally, mean HR was found to be increased for aerobic exercise and resistance exercise relative to seated rest, t 's (20) ≥ 7.4 , $P < 0.001$ (Fig. 1), for the posttest and 30 min posttest. No such effects were observed during the rest and pretest stages, t 's (20) ≤ 1.4 , $P > 0.19$.

Oxygen consumption. The omnibus analysis revealed main effects of mode, $F(2, 19) = 177.7$, $P < 0.001$, $\eta^2 = 0.95$, and time, $F(4, 17) = 207.5$, $P < 0.001$, $\eta^2 = 0.98$, which were superseded by a mode \times time interaction, $F(8, 13) = 128.6$, $P < 0.001$, $\eta^2 = 0.99$. Decomposition of this interaction by examining mode within time revealed increased mean oxygen consumption for aerobic exercise relative to resistance exercise and increased mean oxygen consumption for resistance exercise relative to seated rest during the experimental manipulation, t 's (20) ≥ 13.2 , $P < 0.001$. During the posttest, mean oxygen consumption was found to be elevated for aerobic and resistance exercise relative to rest, t 's (20) ≥ 4.1 , $P < 0.001$; however, during the 30 min posttest, mean oxygen consumption only remained elevated for resistance exercise relative to seated rest, t (20) ≥ 3.0 , $P = 0.007$ (Fig. 1). No such effects were observed for during the rest stage and pretest, t 's (20) ≤ 1.5 , $P > 0.16$.

Task Performance Measures

Absolute RT. The omnibus analysis revealed a main effect of set size, $F(2, 19) = 112.8$, $P < 0.001$, $\eta^2 = 0.92$, with longer RT associated with an increase in set size, t 's (20) ≥ 5 , $P \leq 0.001$. Additionally, a main effect of time, $F(2, 19) = 15.1$, $P < 0.001$, $\eta^2 = 0.61$, which was superseded by a mode \times time interaction, $F(4, 17) = 3.4$,

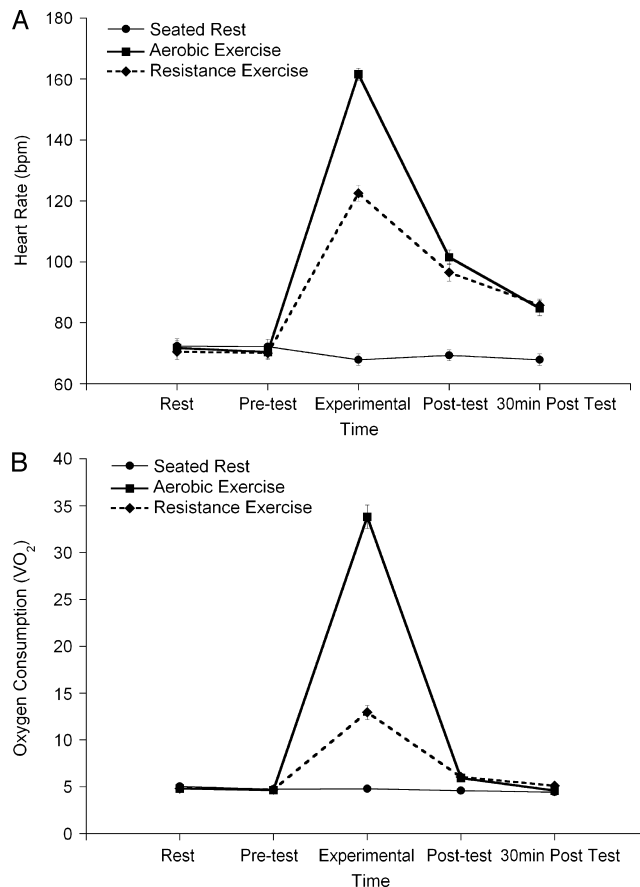


FIGURE 1—Mean HR (bpm; ± 1 SE) and oxygen consumption ($\dot{V}O_2$) values across the entire experimental protocol.

$P < 0.05$, $\eta^2 = 0.44$, was observed. Decomposition of this interaction by examining time within each mode revealed a main effect for the aerobic condition, $F(2, 19) = 25.5$, $P < 0.001$, $\eta^2 = 0.73$, with shorter RT for the posttest and 30 min posttest relative to the pretest, t 's (20) ≥ 5.1 , $P \leq 0.001$. No such main effect was observed for the resistance exercise, $F(2, 19) = 2.5$, $P = 0.11$, $\eta^2 = 0.21$, or seated rest, $F(2, 19) = 3.3$, $P > 0.06$, $\eta^2 = 0.26$, conditions (Fig. 2). Lastly, no mode \times time \times set size interaction was observed, $F(8, 13) = 2.4$, $P = 0.08$, $\eta^2 = 0.59$.

Absolute response accuracy. The omnibus analysis revealed a main effect of set size, $F(2, 19) = 89.4$, $P < 0.001$, $\eta^2 = 0.9$, with decreased accuracy associated with an increase in set size, t 's (20) ≥ 7.7 , $P \leq 0.001$ (Table 3). No mode \times time \times set size interaction was observed, $F(8, 13) = 1.6$, $P = 0.22$, $\eta^2 = 0.49$.

Relative RT. The omnibus analysis revealed a main effect of mode, $F(2, 19) = 6.9$, $P = 0.005$, $\eta^2 = 0.42$, which was superseded by a mode \times set size interaction, $F(4, 17) = 4.2$, $P = 0.02$, $\eta^2 = 0.5$. Decomposition of this interaction by examining mode within each set size revealed a larger reduction in relative RT for aerobic exercise relative to resistance exercise and seated rest for set sizes 5 and 7, t 's (20) ≥ 3.05 , $P \leq 0.006$ (Fig. 3). No such effect was observed for set size 3, t 's (20) ≤ 1.6 , $P \geq 0.13$. No mode \times

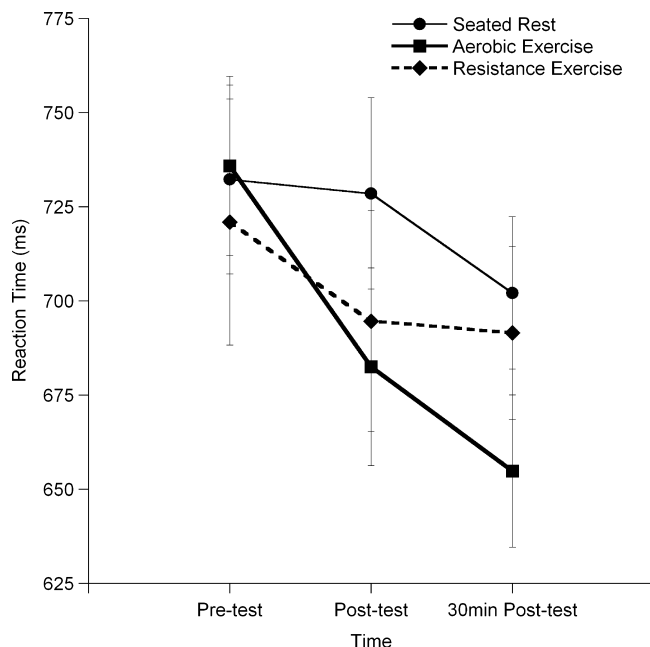


FIGURE 2—Change in absolute RT (ms; ± 1 SE) as a function of time (pretest, posttest, and 30 min posttest). Note the shorter RT after aerobic exercise that was not evident after the other two interventions.

time \times set size interaction was observed, $F(4, 17) = 0.7$, $P = 0.59$, $\eta^2 = 0.15$.

Relative response accuracy. The omnibus analysis revealed a main effect of set size, $F(2, 19) = 5.5$, $P = 0.013$, $\eta^2 = 0.37$, with a larger reduction in response accuracy from the pretest to an average of the posttest and 30 min posttest values for set size 3 relative to set size 5, $t(20) = 3.4$, $P = 0.003$. No mode \times time \times set size interaction was observed, $F(4, 17) = 0.6$, $P = 0.68$, $\eta^2 = 0.12$.

DISCUSSION

The current findings indicated shorter RT latency during a working memory task that was performed immediately and 30 min after an acute bout of aerobic exercise, relative to the pretest. Similar effects were not observed after acute resistance exercise or seated rest, indicating that different modes of exercise have differential effects on the executive control of working memory. Further, shorter RT latency was observed for task conditions requiring increased working memory capacity after aerobic exercise, relative to the pretest, providing support for the view that changes in cognitive function after acute exercise are disproportionately larger for tasks requiring greater amounts of executive control.

Replicating previous research using the Sternberg task, increasing the amount of information required during encoding was associated with longer RT latency (31,33) and decreased response accuracy (14,21). These findings were observed regardless of experimental condition, indicating that an increase in the amount of information during encoding and retrieval processes is related to deficits in task

performance during working memory operations. The current dataset further corroborated previous research examining acute exercise effects on executive control, as increases in the amount of information were associated with larger relative reductions in RT latency after the aerobic condition (13,20). This finding suggests that acute exercise-induced changes in cognition are not selective to inhibitory aspects of executive control but instead are reflective of a disproportionately larger benefit across a variety of tasks requiring extensive amounts of executive control. That is, although selective to tasks with greater executive demands, acute aerobic exercise appears to have a generally beneficial effect across tasks requiring various aspects of executive control.

The current data also replicates previous acute aerobic exercise and cognition research examining both immediate (13,20) and prolonged (35) benefits to task performance, as shorter RT latency was observed immediately and 30 min after the aerobic condition. Novel to this study, however, was the inclusion of acute resistance exercise, which was unrelated to changes in working memory performance, relative to baseline and the control condition. Given the paucity of previous acute resistance exercise and cognition research, it may be that resistance exercise exerts a selective effect on other aspects of cognition separate from working memory. However, these findings do corroborate previous chronic resistance exercise research (19,36), which has observed similar null results after chronic resistance exercise over a 3- to 6-month training period. These findings provide an important extension to the current acute exercise and cognition database by examining working memory—another aspect of executive control, in addition to the comparison of acute exercise modality. Taken together, the data herein indicate that the executive control of working memory is differentially influenced by specific types of acute exercise and suggests that changes in cognition may be specific to aerobic exercise.

Recently, a growing body of research has been aimed at understanding the relation of exercise to mechanisms underlying changes in brain and cognition (for a review, see [11]). Recent investigations using nonhuman animal models have observed a positive association between aerobic exercise and biochemicals known to increase neuronal proliferation (e.g., brain-derived neurotrophic factor [BDNF] and serotonin [37,38]). Given that both serotonin and BDNF have been related to neurogenesis in

TABLE 3. Response accuracy (± 1 SE) for each condition and set size across time.

	Set Size	Pretest	Posttest	30 min Posttest
Aerobic exercise	Size 3	94 \pm 1.0	94.3 \pm 1.0	93.3 \pm 1.3
	Size 5	89 \pm 1.4	91.5 \pm 1.1	90.5 \pm 1.4
	Size 7	80.9 \pm 2.1	78.6 \pm 2.3	79.9 \pm 2.1
Resistance exercise	Size 3	96.1 \pm 0.8	93.1 \pm 0.9	91.4 \pm 0.7
	Size 5	88.4 \pm 1.3	89.3 \pm 1.4	89.1 \pm 1.0
	Size 7	77 \pm 1.7	79.3 \pm 2.2	77.7 \pm 2.2
Seated rest	Size 3	94.2 \pm 0.9	96.4 \pm 0.6	95.2 \pm 0.9
	Size 5	90 \pm 1.6	89.9 \pm 1.4	91.6 \pm 1.3
	Size 7	77.5 \pm 2.0	78.2 \pm 1.6	77 \pm 2.3

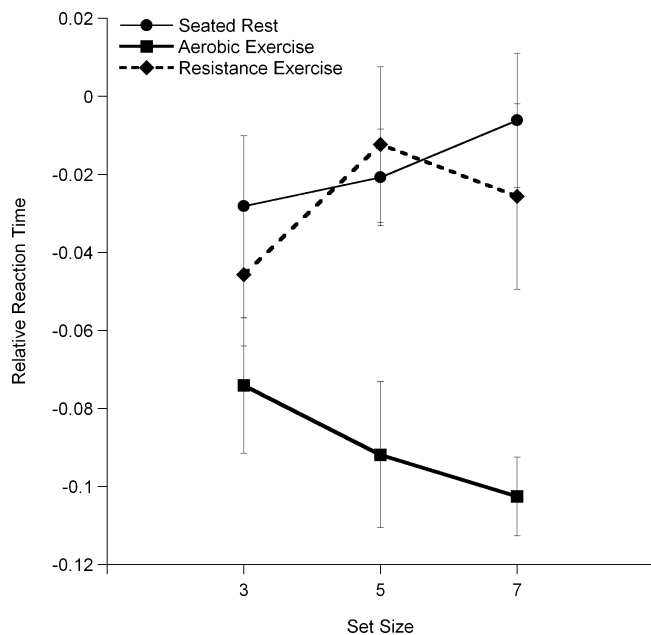


FIGURE 3—Relative RT (± 1 SE) as a function of the modified Sternberg memory set size (three, five, and seven letters). After aerobic exercise, selectively greater change in RT latency was observed from the preintervention values $\{[(\text{posttest} - \text{pretest}) / \text{pretest}] + [(30 \text{ posttest} - \text{pretest}) / \text{pretest}] / 2\}$ for the larger set sizes that place greater demands on working memory.

the hippocampus of nonhuman animals (4,32), a structure involved in the completion of working memory tasks (10), future research should assess the relation between different modes of acute exercise and these biochemicals to provide additional insight into the extent to which they may be potential mechanisms responsible for changes in cognition associated with exercise behavior.

Exercise-induced change in regional cerebral blood flow has also been suggested as a potential mechanism for changes in cognition (for a review, see [27]). Recent nonhuman animal models have observed that exercise-induced increases in cerebral blood flow do not occur globally across all regions of the brain but instead are localized to specific regions involved with locomotion, equilibrium, and cardiorespiratory control as well as areas of the hippocampus (8). Considering that resistance exercise exerts a very different metabolic response compared with aerobic exercise, manifested by lower oxygen consumption despite higher levels of muscular exertion (16), and lower levels of systemic blood flow (29,30), it may be possible that resistance exercise affects cerebral blood flow differently compared with aerobic exercise. Given the cardiorespiratory and metabolic differences between aerobic and resistance exercise, future research should address the

relationship between resistance exercise, cerebral blood flow, and cognition to provide additional insight into the relationship between cognition and exercise behavior.

Future research should also aim to assess the effects of resistance exercise on various aspects of cognition beyond working memory and explore other exercise modalities to better characterize the relation of acute exercise to cognition. Given the interesting distinction between the effects of acute bouts of aerobic and resistance exercise on cognitive performance, future research aimed at controlling specific cardiovascular and musculoskeletal as well as metabolic properties of the exercise stimulus may lead to better understanding of the potential mechanisms mediating this discrepancy. Accordingly, a limitation of the present study was that only a single cognitive task modulating working memory load was used, which allows for little generalization to other aspects of cognition. Although this study extends previous findings and provides evidence that facilitative effects of acute aerobic exercise on cognition may generalize to cognitively demanding executive control tasks, only working memory was investigated. Further, an additional limitation of these data is the inability to gain a mechanistic understanding of the effects of acute exercise on working memory. That is, despite the interesting distinctions observed herein, little is known regarding which component process or processes of working memory were influenced by the various acute exercise bouts. Future research may wish to manipulate various aspects of working memory paradigms to better determine whether acute bouts of exercise affect the capability or the speed to encode or retrieve information, alter perception of the target stimuli, or affect the motor processes inherent in responding.

In summary, general improvements in cognitive performance occurred after acute aerobic exercise of moderate intensity, which were selectively larger under task conditions that placed greater demands upon working memory capacity. A similar relationship was not observed after a standard session of acute resistance exercise or the control condition, indicating a selectively beneficial relationship of acute aerobic exercise on cognition. It is unknown at this time if these differential responses are related to the differential cardiovascular and metabolic demands of the two exercise modes. This pattern of results provides a basis in which to explore potential mechanisms that may be responsible for acute exercise-induced changes in cognition.

This manuscript and the data presented in it were not funded by any federal agency, and therefore, no disclosure is warranted.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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