Effects of an acute bout of exercise on cognitive aspects of Stroop performance

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Abstract:

Recent reviews of the literature have demonstrated that exercise has a positive impact on cognitive performance. The purpose of this study was to assess the impact of an acute bout of aerobic exercise on executive functioning in college-age adults. For the experimental intervention, the effects of 20 min of self-paced moderate-intensity exercise on a treadmill were compared to the effects of a 20-min sedentary control period. Executive functioning was assessed using Stroop color-word interference and negative priming tests. Results indicated that the bout of exercise led to improved performance on the Stroop color-word interference task but no change in performance on the negative priming task. This finding suggests that exercise may facilitate cognitive performance by improving the maintenance of goal-oriented processing in the brain.

Keywords: physical activity | selective attention

Article:

Several reviews of the literature have established that a positive relationship exists between exercise and cognitive performance (Brisswalter et al., 2002; Colcombe & Kramer, 2003; Etnier et al., 1997; Sibley & Etnier, 2003; Tomporowski, 2003a, 2003b). However, in order to be able to make practical applications of this knowledge, a more thorough understanding of this relationship is needed. Performance on cognitive tasks involves a wide range of underlying abilities and processes. Therefore, an important direction for research designed to further our understanding of the exercise and cognition relationship is to study the specific aspects of cognition that are affected by exercise.

It has been suggested in the literature that exercise may exert a positive effect on executive functioning (Colcombe & Kramer, 2003). One test of executive functioning that has been used is the Stroop color-word interference task (Stroop, 1935). On this test, participants view a list of color names (i.e., red, blue, green, and yellow) that are written in colored ink. Participants are required to verbally identify the color of the ink in which each item is written. The interference created when the color name and the color of the ink do not match causes participants to perform the task more slowly than they would if the ink color were paired with a neutral stimulus (i.e., a string of X's). A more detailed description of the task follows in the methods section.

Hogervorst, Riedel, Jeukendrup, and Jolles (1996) found that fifteen trained males (age 18–42 years) demonstrated improved performance on the Stroop color-word test following 60 min of exhaustive exercise on a bicycle ergometer. The result was unexpected, as researchers had hypothesized that the exhaustive exercise would have a negative impact on cognitive performance. Lichtman and Poser (1983) found improvements in performance on the Stroop color-word test in adults following a 45-min exercise class that involved jogging and other physical activities.

Specific details of the cognitive processes underlying the Stroop effect remain unknown, and several models have been proposed in the cognitive psychology literature to explain the phenomenon (see MacLeod, 1991, for a summary). Generally, the Stroop task measures how well an individual can maintain goal-oriented processing and how well he or she can suppress or block a habitual response (MacLeod & MacDonald, 2000). Specifically, the abilities to sustain mental processes and to select appropriate task features play a role in performing the color-word interference task (Spreen & Strauss, 1998). Also, the ability to inhibit the relatively automatic word-reading response is important for task performance. This ability to inhibit irrelevant information has been suggested as a specific executive function that exercising may impact (Tomporowski, 2003b). The possibility that exercise leads to more-efficient inhibitory processes is of particular interest owing to the wide range of cognitive processes that inhibition may underlie. Therefore, it would be valuable to gain an understanding of the role of inhibition in exercise's effect on Stroop performance.

According to Bjorklund and Harnishfeger (1995), "Cognitive inhibition is the suppression of previously activated cognitive contents or processes, the clearing of irrelevant actions or attention from consciousness, and resistance to interference from potentially attention-capturing processes or contents" (p. 143). These functions play an important role in human cognition. As a specific example, inefficient inhibition could result in inefficient selective attention, leading to the intrusion of irrelevant information in working memory. The interference from this irrelevant information could then cause increases in processing time and reductions in recognition and the recall of relevant information (Kramer et al., 1994).

The extant research suggests a positive relationship between physical activity and inhibition. Campbell, Eaton, and McKeen (2002) conducted a study in which the relationship between habitual physical activity, as assessed by actometers, and performance on an inhibition test battery was examined. Results showed that children (age 4–6 years) who accumulated the most activity in the 24-hour activity assessment period demonstrated the best inhibition control on the test. Based on this finding, the authors concluded that children who are highly active demonstrate better inhibition control than their less-active counterparts. The authors argued that high activity levels might provide children with more opportunities to learn to control their actions and behavior.

Although improvements in inhibition following exercise could also be used to explain the aforementioned improved performance on the Stroop task as a result of acute exercise participation, this conclusion should not be made based on the existing research. This is because the Stroop test does not specifically measure inhibition but rather assesses the susceptibility to interference from conflicting stimuli. Improved performance on the Stroop test following exercise could be due to suppression of the irrelevant stimuli (inhibition) or facilitation of the processing of relevant information (Neill, Valdes, & Terry, 1995), both of which are considered to be types of executive functioning. No study to date has specifically and directly measured the effects of acute exercise on inhibition using a Stroop task. Thus, the existing research can be extended by including a negative priming version of the Stroop task, which does allow for specific assessment of inhibitory influences involved in Stroop performance.

The purpose of the present study was to examine the effects of an acute bout of aerobic exercise on the performance of Stroop interference and negative priming tests to assess executive functioning and inhibition in healthy adults. A within-subjects design was used, comparing the effects of exercise to a sedentary control condition. The following hypotheses were proposed for this study: (1) participants will demonstrate improved executive functioning following the exercise condition compared to the control condition and (2) participants will demonstrate greater inhibition following the exercise condition compared to the control condition.

Methods

Participants

Seventy-nine college students were recruited from kinesiology classes at Arizona State University to participate in the study. All participants completed an informed consent form approved by the university's institutional review board.

Measures

A self-paced bout of exercise was employed in the experimental condition. Therefore, a variety of measures were used to monitor the participants' exercise intensity. Heart rate was used as a physiological measure of exercise intensity, accelerometry was used as an objective measure of physical activity, and a questionnaire was used to assess perceived arousal following the experimental conditions.

Heart Rate. Heart rate (HR) was monitored for 5 min before the testing sessions (to assess resting HR), throughout the experimental conditions, and during the cognitive testing sessions. Participants were in a seated position during measurement of resting HR and during the cognitive testing session. Heart rate was assessed using the Polar Vantage XL monitor (Polar Electro Co., Woodbury, NY) over 5-s "epochs" and downloaded using Polar HR monitor software for computer analysis.

Accelerometry. In order to objectively assess the amount of physical activity accumulated in the exercise and control conditions, participants wore an ActiGraph model 7164 activity monitor (MTI ActiGraph, Fort Walton Beach, FL). The ActiGraph is a waist-mounted uniaxial accelerometer that detects vertical accelerations ranging from 0.05–2.0 *g*, and is band limited with a frequency response from 0.25–2.5 Hz (Tyron & Williams, 1996). These parameters detect normal body motion and filter out high-frequency movement such as vibrations. According to the device manufacturer, the acceleration signal is filtered by an analog band-pass filter and digitized by an 8-bit A/D converter at a sampling rate of 10 samples per second. Each digitized signal is summed over a user-specified time interval (epoch), and at the end of each epoch the sum of detected accelerations is stored internally as an activity count, and the accumulator is reset to zero. Previous studies have demonstrated that the ActiGraph accelerometer is a valid and reliable measure of physical activity in adults (Melanson & Freedson, 1995) and children (Fairweather, Reilly, Grant, Whittaker, & Patton, 1999; Trost et al., 1998). For more information on accelerometry, readers are directed to a comprehensive review of the science of accelerometry in the November 2005 issue of *Medicine and Science in Sports and Exercise*.

In the current study, each ActiGraph was checked for calibration using the manufacturer's calibrator before use. ActiGraphs were initialized to record data every 30 s (i.e., 30-s epochs), and activity counts were expressed as the average activity counts per minute over the 20 min for the control and exercise conditions. The ActiGraph accelerometer was mounted on an adjustable strap, and participants wore the strap on their waist with the accelerometer aligned with the midline of their right thigh. ActiGraphs were placed on participants immediately before starting the control and exercise conditions, and were worn throughout the intervention and testing session.

Activity counts for the 20-min exercise and control sessions were uploaded to manufacturer's recommended software and expressed as mean activity counts per minute. In order to categorize the intensity of physical activity using this rate, activity count cut points (thresholds) corresponding with light (<3 METs; <1,952 counts·min^{-1}), moderate (3–5.99 METs; 1,952-5,724 counts·min^{-1}), and vigorous (≥6 METs; >5,724 counts·min^{-1}) physical activity established by Freedson, Melanson, and Sirard (1998) were used. These activity count cut points have been used in previous research (Leenders, Sherman, & Nagaraja, 2000; Masse et al., 1999) with adults.

Activation-Deactivation Adjective Checklist (AD-ACL). In order to assess perceived arousal, participants completed the AD-ACL (Thayer, 1989). The AD-ACL comprises two primary directions—energetic arousal and tense arousal. Both of these dimensions are further divided into energy/tiredness and tension/calmness, respectively. Test–retest reliabilities have been reported as .89 (energy), .89 (tiredness), .93 (tension), and .79 (calmness) (Thayer). This measure was completed immediately following the exercise and controls interventions and at the end of the cognitive testing sessions. Scores on the tiredness and calmness subscales were reverse-scored and added to the energy and tensions scores to produce a composite score that ranged from –30 (low arousal) to +30 (high arousal).

Stroop. Executive functioning and inhibition were measured using a Stroop color-word test (Stroop, 1935). There were three conditions in this test: a color naming test, a color-word interference test, and a negative priming test. In the color naming test, a string of the letter ex (e.g., XXXXX) was written in red, blue, yellow, or green ink. Participants were required to, as quickly as possible, verbally identify the ink color in which the string of letters was written. In the color-word interference test, participants were again required to state the ink color of the word. However, in this version the stimuli were the words *red*, *blue*, *green*, or *yellow*, with the ink color being unrelated to the word on the slide—for example, the word *red* written in blue ink. In the negative priming condition, the ink color of each word was the same as the color word stimulus on the previous item. For example, if the color word on the previous item was *blue*, the ink color of the current item would be blue. Past research has demonstrated that performance is slower on this negative priming version of the Stroop than on the normal color-word interference condition (Dalrymple-Alford & Budayr, 1966; Neill, 1977) because subjects are required to respond to the current item with the color that was just previously inhibited (Neill et al., 1995). Thus, when participants are better able to inhibit a previously viewed color word, this actually results in a decrement in performance because they are slower to verbalize that color name as the correct answer on the current trial.

The color-word interference test does not measure inhibition per se but rather assesses susceptibility to interference from conflicting stimuli. The negative priming test imposes all the same demands on the participant that the interference task does with the addition of extra inhibitory influences. Accordingly, different patterns of results on the interference and negative priming tests provide varying degrees of support for the hypothesis that exercise increases inhibition. If participants demonstrate better performance on both the interference and negative priming tests after the exercise condition as compared to the control condition, this will suggest that exercise does not impact inhibition and that other mechanisms are responsible for improvements in Stroop performance. However, an improvement on interference performance and a decrement on negative priming performance following exercise would indicate that the bout of exercise led to an increase in inhibition.

Slides were presented on a computer screen in list format in blocks of thirty, with two blocks each of the color naming test, the color-word interference test, and the negative priming test. Order of administration of the three conditions was counterbalanced across participants. Each block was scored as the total time to complete all 30 items, and then the average of the two blocks served as the participant's score for the condition.

Procedures

A within-subjects design with two conditions was used. Participants engaged in an exercise condition and a sedentary control condition. Both sessions were performed within 1 week of each other and were held at the same time of day. Order of participation of the two conditions was randomized and counterbalanced across participants. Participants were asked not to engage in any structured exercise on the day of their testing sessions and were asked not to smoke or consume caffeine for 2 hours prior to the session.

After completing the informed consent and a basic demographic information sheet, a heart rate monitor and ActiGraph accelerometer were placed on each participant and he or she was allowed to rest quietly for 5 min in order to determine a resting heart rate. For the control condition, participants were asked to sit quietly and were supplied with reading material for the 20-min intervention. On the exercise-testing day, participants were instructed that they would be participating in a 20-min bout of exercise. On both days, participants were told that they would be taking a few short tests immediately after the 20-min period. The exercise bout consisted of self-paced running and/or walking on a treadmill. Participants were instructed to select a comfortable, moderately intense workload and to adjust the speed and/or grade during the exercise bout if necessary. Rating of Perceived Exertion (RPE; Borg, 1974) was used as a guideline to explain exercise intensity to the participants. The scale ranges from 6 (*very, very light*) to 19 (*very, very hard*). Specifically, participants were instructed to work at a level between 11 (*fairly light*) and 14 (*somewhat hard*).

A self-paced bout of exercise was chosen in order to maximize effects on cognitive performance and to improve the ecological validity of the intervention. There is a considerable amount of evidence that moderate intensities of exercise will lead to the largest gains in cognitive performance (Tomporowski, 2003b). However, it has also been suggested in the literature that the impact of exercise on cognitive performance is dependent upon the participant's level of fitness and/or level of experience with exercise. Depending on fitness levels, the relative intensity of a fixed workload (e.g., jogging for 20 min at 6 MPH) may vary from individual to individual, as might the *perceived* intensity of an individually determined objective workload (e.g., percentage of maximal oxygen uptake), in this case depending upon the individual's experience with exercise. If the perceived intensity is either too high or too low, it is likely to have a negative impact on affective responses, which in turn may influence cognitive performance. By allowing the participants to self-select exercise intensity, the likelihood of obtaining a moderate *perceived* workload is maximized. A self-paced bout of exercise also has the greater external validity than exercising at an externally determined fixed workload when considering typical exercise patterns outside a lab setting.

Immediately following the 20-min intervention, participants proceeded to an adjacent room for cognitive testing where they were seated in front of a computer monitor. Participants completed, in this order, the AD-ACL, the Stroop tests (in random order), and the AD-ACL again. This session was typically less than 10 min in duration and was videotaped for scoring purposes.

Statistical Analyses

A paired-samples *t* test was used to test the difference in activity counts between the control and exercise conditions. This analysis was included as a manipulation check that the participants did, in fact, engage in significantly more physical activity during the exercise condition than in the control condition. In order to examine heart rate across the conditions, a 2 × 3 (condition: exercise, control × time: baseline, experimental condition, and cognitive testing) repeated-measures analysis of variance (RM ANOVA) with repeated measures on both factors was conducted. To test differences in AD-ACL scores, a 2 × 2 (condition: exercise, control × time: beginning of cognitive testing session, end of cognitive testing session) RM ANOVA was run with repeated measures on both factors. Paired-samples *t* tests with Bonferroni corrections were used to test simple effects in the event of significant interactions.

To test the effects of exercise on Stroop performance, ANOVA procedures for crossover designs (Hills & Armitage, 1979) were used. To test the effects of exercise on Stroop performance, separate 2 × 2 (condition: exercise, control × order: control first, exercise first) RM ANOVAs with repeated measures on the condition factor were run for each version of the Stroop task. Post hoc analyses with Bonferroni corrections were conducted on significant interactions. Effect sizes were calculated using Hedges's *g*, which is the mean difference of the groups divided by the pooled standard deviation (Hedges & Olkin, 1985). Although past research does not lead us to expect gender differences in the effects, our sample did allow for an examination of gender effects. However, no significant effects were found for gender in the Stroop analyses. Therefore, all analyses were conducted with gender excluded.

Results

Participants

Three female participants were excluded from analyses because their exercise heart rates were below 40%HRR and/or their activity counts were greater than 2 standard deviations below the mean for the sample. This yielded a sample of 39 male and 37 female participants. The participants ranged in age from 19 to 35 years old ($M = 22.50$, $SD = 3.10$). The ethnicity of the sample population was 80.2% White/Caucasian, 7.9% American Indian/Alaskan Native, 6.6% Hispanic, 3.9% Asian/Pacific Islander, and 1.3% African American. The mean body mass index (BMI) was 25.46 ($SD = 4.29$) for males and 21.95 ($SD = 2.71$) for females.

Manipulation Check of Condition

The mean activity level (counts per minute) for the exercise and control condition were 9,462 ($SD = 2{,}635$) and 31 ($SD = 143$), respectively. The mean activity level for the exercise condition corresponded to vigorous physical activity using the activity count cut points established by Freedson et al. (1998). The mean activity level for the control group was not significant from zero, $t(76) = 1.89$, $p > .05$. A paired-sample *t* test demonstrated that the physical activity levels between the exercise and control conditions were significantly different, $t(74) = –31.11$, $p < .001$.

The 2 × 3 (condition: exercise, control × time: baseline, experimental condition, and cognitive testing) RM ANOVA on HR yielded significant main effects for condition, $F(1, 140) = 855.60$, $p < .001$, and time, $F(2, 140) = 1{,}318.29$, $p < .001$. There was a significant condition × time interaction, $F(2, 140) = 1{,}214.91$, $p < .001$. Simple main effects were calculated, using paired-samples *t* tests and RM ANOVA with Bonferroni corrections, for condition at each time point and time within each condition, respectively, because both types of simple main effects yield useful information. Heart rate was significantly higher for the exercise condition than for the control condition at all three time points: baseline, $t(70) = –2.74$, $p < .05$, $ES = 0.27$; experimental condition, $t(70) = –36.82$, $p < .001$, $ES = 5.78$; and cognitive testing, $t(70) = –19.17$, $p < .001$, $ES = 2.18$. This shows that HR was significantly higher during the experimental condition and the cognitive testing session of the exercise condition than it was during the corresponding time points of the control condition. The difference in HR at baseline, while statistically significant, is so small as to be of no practical importance. Within the exercise condition, there was a significant effect for time, $F(2, 140) = 1{,}369.77$, $p < .001$. Paired-samples t-tests reveal HR was greater during the exercise condition than at baseline, $t(70) = 40.46$, $p < .001$, $ES = 6.35$, and greater during the exercise condition than during cognitive testing, $t(70) = 35.67$, $p < .001$, $ES = 3.44$. Also, HR remained elevated during the cognitive testing compared to baseline, $t(70) = 27.45$, $p < .001$, $ES = 3.39$. Within the control condition, there was a significant effect for time, $F(2, 140) = 335.40$, $p < .001$. Heart rate was significantly higher during the experimental condition than it was at baseline, $t(70) = 18.89$, $p < .001$, $ES = 0.75$. Heart rate during cognitive testing was higher than at baseline, $t(70) = 21.35$, $p < .001$, $ES = 1.43$, and during the experimental condition, $t(70) = 12.10$, $p < .001$, $ES = 0.65$. The increases in HR seen across the control condition were much smaller than the changes seen during the exercise condition, and were likely due to the mild stress of the cognitive testing.

The results of the AD-ACL condition × time RM ANOVA yielded a significant main effect for condition, $F(1, 75) = 222.88$, $p < .001$, which indicates perceived arousal was higher following the exercise condition than following the control condition. There was also a significant main effect for time, $F(1, 75) = 44.63$, $p < .001$, and a significant condition × time interaction, $F(1, 75) = 135.58$, $p < .001$. Means and standard errors for the AD-ACL at each time point are presented in Table 1. As with the HR data, simple main effects were calculated within both factors. Paired-samples *t* tests were done to compare perceived arousal between the exercise and control conditions at each point in time and to compare perceived arousal from the beginning to the end of cognitive testing within each experimental condition. Perceived arousal was higher at the beginning of the cognitive testing session following exercise than following the control condition, $t(75) = –19.17$, $p < .001$, $ES = 3.04$, and remained so at the end of the cognitive testing session, $t(75) = –4.50$, $p < .001$, $ES = .58$. Within the exercise condition, there was a significant decrease in arousal from the beginning to the end of the cognitive testing, $t(75) = 3.13$, $p < .01$, $ES = –0.41$. Within the control condition, there was a significant increase in arousal from the beginning to the end of the cognitive testing, $t(75) = –12.23$, $p < .001$, $ES = 1.54$. These findings indicate that, in general, participants perceived higher levels of activation following the exercise condition than following the control condition, and specifically this difference in perceived arousal was greater at the beginning of the testing session than at the end. This pattern of changes in perceived arousal is due to both an attenuation of arousal as time progressed after the exercise session and an increase in arousal following the control condition, likely due to the speeded nature of the cognitive tasks.

Table 1. Statistics for Physiological and Perceived Arousal

Variable	***M***	***SE***
Baseline Heart Rate		
Exercise	65.30	1.02
Control	62.80	1.15
Heart Rate During Experimental Condition		
Exercise	151.75	2.05
Control	70.23	1.19
Heart Rate During Cognitive Testing		
Exercise	100.62	1.42
Control	76.72	1.17
AD-ACL 1		
Exercise	8.88	0.89
Control	–15.54	0.96
AD-ACL 2		
Exercise	5.38	1.04
Control	–0.49	1.27

Note. AD-ACL 1 refers to the Activation-Deactivation Adjective Checklist measurement at the beginning of the cognitive testing session, and AD-ACL 2 refers to the measurement at the end of the testing session.

Effect of Exercise on Stroop Performance

Errors were monitored during the Stroop tasks to ensure that participants were not making a speed/accuracy trade-off. Errors on the Stroop tests were defined as trials on which the incorrect color was named and no correction was made. Error rates were less than 1% for both the control session (M = 0.76%) and the exercise session (M = 0.14%), with most participants making no errors at all. Therefore, a speed-accuracy trade-off was not considered to be an issue, and performance was examined in terms of time to complete each task.

Table 2. Means and Standard Errors for Stroop Task Performance as a Function of the Condition × Order Interaction

Condition	***M***	***SE***
Stroop Color		
Exercise (overall)	15.292	0.372
Control-exercise order	14.489	0.549
Exercise-control order	16.095	0.473
Control (overall)	15.578	0.271
Control-exercise order	16.489	0.376
Exercise-control order	14.667	0.334
Stroop Interference		
Exercise (overall)	19.244	0.371
Control-exercise order	17.762	0.448
Exercise-control order	20.726	0.488
Control (overall)	19.983	0.430
Control-exercise order	21.281	0.627
Exercise-control order	18.685	0.516
Stroop Negative Priming		
Exercise (overall)	22.510	0.558
Control-exercise order	20.275	0.549
Exercise-control order	24.745	0.831
Control (overall)	22.774	0.512
Control-exercise order	24.646	0.704
Exercise-control order	20.902	0.616

Means and standard errors for performance on the Stroop tests are presented in Table 2. For the color version of the Stroop test, the main effect for condition was not significant, $F(1, 74) = 1.41$, $p > .05$, $ES = -0.10$. This indicates that the exercise intervention did not produce a significant improvement in Stroop color test performance. The main effect for order also was not significant, $F(1, 77) = 0.04$, $p > .05$. The condition × order interaction was significant, $F(1, 74) = 50.45$, $p < .001$. In a crossover design, the condition × order interaction is aliased with a session main effect (Jones & Kenward, 2003; Kuehl, 2000). That is, a condition × order interaction is likely indicative of a systematic difference in performance from one session to the next (i.e., a practice effect on the dependent measure), rather than a true interaction of order (which was a randomized factor) with condition. Post hoc analyses reveal that participants in the control-first group completed the Stroop task faster following the exercise condition than the control condition, $t(37) = -5.18$, $p < .001$, and that participants in the exercise-first group completed the Stroop task faster following the control condition than the exercise condition, $t(37) = 4.93$, $p < .001$ (see Figure 1). This pattern of results is interpreted as a significant session effect and indicates that participants performed the Stroop color task faster during the second session (i.e., for the control-first group, the exercise condition was the second session; for the exercise-first group, the control condition was the second session). This indicates that there was a significant learning or practice effect for the task, independent of the condition or order factors.

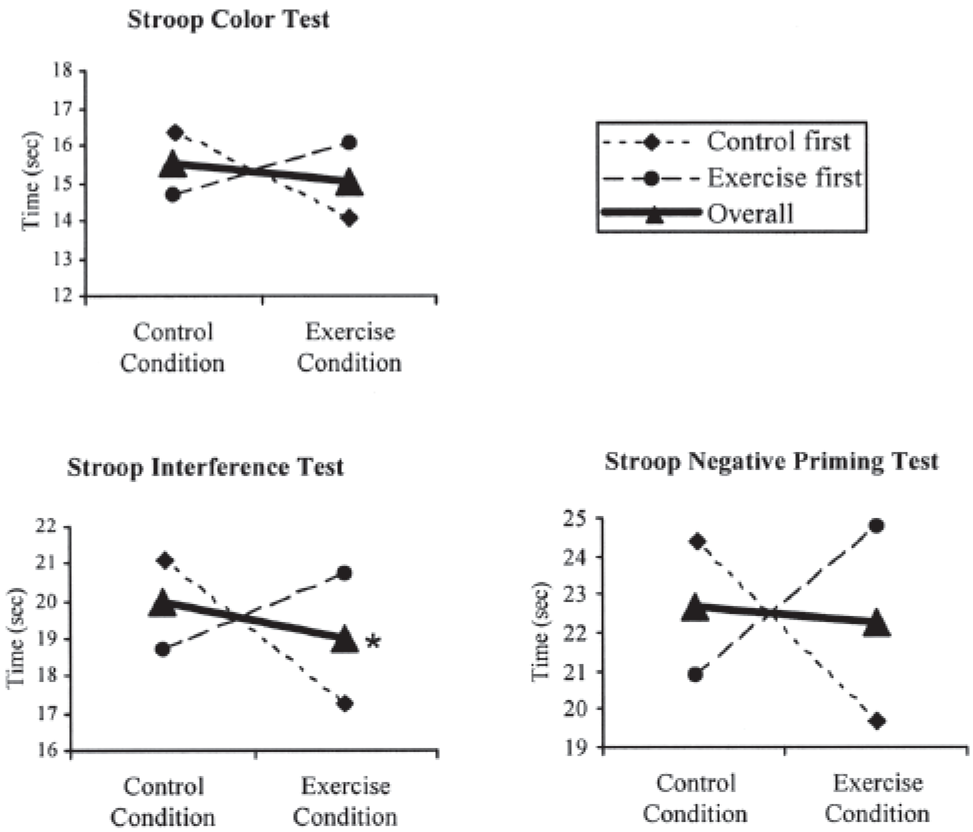

Figure 1. Performance on the Stroop tests for the condition × order interaction and the condition main effect. * indicates a statistically significant effect, $p < .01$.

The interference version of the Stroop test did produce a significant main effect for condition, $F(1, 74) = 7.16$, $p < .01$, $ES = –0.21$. Performance was faster following the exercise condition ($M = 19.244$ s, $SE = 0.371$) than following the control condition ($M = 19.983$ s, $SE = 0.430$). The order main effect was not significant, $F(1, 74) = 0.07$, $p > .05$. The condition × order interaction was significant, $F(1, 74) = 101.12$, $p < .001$. Post hoc analyses reveal that participants in the control-first group completed the exercise condition faster than the control condition, $t(37) = –8.54$, $p < .001$, and that participants in the exercise-first group completed the control condition faster than the exercise condition, $t(37) = 5.35$, $p < .001$ (Figure 1). As with the color version of the Stroop test, this pattern of results represents a significant session effect, such that participants performed the Stroop interference task faster during their second session.

For the negative priming version of the Stroop, the condition effect was not significant, $F(1, 74) = 0.70$, $p > .05$, $ES = –0.06$, indicating that the exercise intervention did not lead to a significant change in Stroop negative priming test performance. The main effect for order also was not significant, $F(1, 74) = 0.16$, $p > .05$. The condition × order interaction was significant, $F(1, 74) = 168.17$, $p < .001$. Post hoc analyses reveal that participants in the control-first group completed the exercise condition faster than the control condition, $t(37) = –9.01$, $p < .001$, and that participants in the exercise-first group completed the control condition faster than the exercise condition, $t(37) = 9.43$, $p < .001$ (Figure 1). Again, this pattern of results represents a significant session effect, such that participants performed the Stroop interference task faster during the second session.

Discussion

The purpose of this study was to test the effects of an acute bout of exercise on executive functioning in a sample of healthy young adults. Participants completed a series of Stroop tasks after engaging in 20 min of moderate intensity exercise on a treadmill and after sitting quietly and reading for 20 min. Although there was a large learning effect on the Stroop tasks, the pattern of results found in this study suggests that exercise leads to a small but significant improvement in executive functioning related to maintenance of goal-oriented processing.

Participants demonstrated better performance on the Stroop color-word interference task following exercise; however, there was no significant change in performance on the simple color-naming task as a function of exercise condition. This suggests that the impact of exercise was on executive functioning, in particular. If exercise only influenced a nonexecutive aspect of Stroop performance, such as speed of processing, one would expect there to be a concomitant improvement in performance on all three Stroop tasks. However, this was not the case.

This study extends research involving exercise and Stroop tasks by including the negative priming condition so that we can partial out inhibition from interference. *Inhibition* and *interference* are terms that are often used interchangeably in the literature; however, they are not synonymous (Harnishfeger, 1995). "*Interference* refers to susceptibility to performance decrements under conditions of multiple distracting stimuli, such as dual-task performance or selective attention" (Harnishfeger, pp. 188–189). The Stroop color-word interference task assesses interference. A number of cognitive processes are involved in overcoming this interference, including maintenance of goal-oriented processing, which is the ability to keep pertinent information as the focus of attention. Inhibition, which also plays a role in overcoming interference, involves the active suppression of information, such as removal of task-irrelevant information from working memory (Hamm & Hasher, 1992). Inclusion of the negative priming version of the Stroop allows us to see whether it is improvement in goal-oriented processing or inhibition that is the cause of any improvement in performance on the Stroop interference task.

The results of this study suggest that the acute bout of exercise did not impact cognitive inhibition. If exercise had increased inhibition, participants should have performed the negative priming version of the Stroop more slowly following the exercise condition than following the control condition, owing to the extra inhibitory influences of that task. However, the results of this study showed that there was no change in performance on the negative priming task following exercise. Because this study showed a null effect (neither improvement or decrement in performance) on the negative priming task, it is possible that there is some effect of exercise on inhibition that was cancelled out by the improved speed of processing associated with the bout of exercise. That is, if there was no effect of exercise on inhibition at all, we predicted there should have been equivalent improvements in performance on both the color-word interference task and the negative priming task in the exercise condition. This prediction is based on the assumption that the demands of the two versions of the task are identical except for the extra inhibitory influences of the negative priming version. However, since speed of processing and inhibition cannot be assessed independently on the Stroop negative priming task, we cannot determine whether this canceling out occurred. Therefore, based on the improved performance on the color-word interference task following exercise and the lack of a significant effect of exercise on negative priming performance, we conclude that exercise facilitates the processing of pertinent information on the Stroop color-word interference task rather than increasing inhibition of irrelevant stimuli.

The findings are consistent with other research examining the relationship between Stroop interference test performance and exercise (Hogervorst et al., 1996; Lichtman & Poser, 1983) and make an important extension to this literature by showing that increases in cognitive inhibition are not likely responsible for the improvements in Stroop performance that are seen following exercise. Tomporowski (2003b), in a recent review, had concluded that the findings from the Hogervorst et al. (1996) and Lictman and Poser (1983) studies described earlier were indicative of an increase in inhibition. This conclusion was premature, however, because the traditional Stroop color-word interference test measures only the susceptibility to interference. The negative priming test must also be included before any inferences can be made about inhibition. In the review, Tomporowski examines the literature on acute exercise and cognitive performance using an information processing model of cognition (Proctor, Reeve, & Weeks, 1990). In this model, cognition is broken down into three phases: stimulus identification, response selection, and response programming. He concludes that exercise seems to affect response selection and response programming, but not stimulus identification. Maintenance of goal-oriented processing fits into the response-selection category of this model. In this sense, the findings of this study are consistent with this information processing model of how exercise affects cognition.

The magnitude of the effect of exercise on Stroop interference task performance found in this study ($ES = -0.21$) was small (Cohen, 1988). It could be argued that the magnitude of this effect is of no practical importance. However, this effect is consistent with Etnier and colleagues' (1997) meta-analysis of over 200 studies on exercise and cognitive performance, which found an overall *ES* of 0.25 and an *ES* for acute exercise of 0.16. Given the complex nature of human cognition and that executive functioning is just one component of cognition, the effect should be considered meaningful and future study of the effect is warranted.

The self-paced nature of the exercise condition and the relatively short duration of the exercise bout are potential limitations of this study. There may be a certain minimum intensity or duration of exercise that must be achieved before effects on particular aspects of cognition (e.g., inhibition) will be seen. Furthermore, the healthy, college-aged sample used in this study may not demonstrate the same cognitive benefit from exercise as would a sample using individuals with less-robust nervous systems and/or lower levels of executive functioning.

There are several routes future research in this area should take. Subsequent research should be designed to determine whether there is a dose–response relationship between the intensity of the acute exercise bout that impacts executive functioning and should also examine the time course of these effects. Studies examining the impact of exercise on different aspects of cognition, such as working memory and selective attention, should further clarify how exercise might facilitate goal-oriented processing. Extension and replication of the current findings using various forms of exercise and methodologies to assess executive functioning will be important to confirm a causal relationship between exercise and cognitive functioning.

References

Bjorklund, D.F., & Harnishfeger, K.K. (1995). The evolution of inhibition mechanisms and their role in human cognition and behavior. In F.N. Dempster & C.J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 141-173). San Diego, CA: Academic Press.

Borg, G.A. V. (1974). Psychological aspects of physical activities. In L.A. Larsen (Ed.), *Fitness, health, and work capacity* (pp. 141-152). New York: MacMillan.

Brisswalter, J., Collardeau, M., & Arcelin, R. (2002). Effects of acute physical exercise characteristics on cognitive performance. *Sports Medicine,* **32**(9), 555-566.

Campbell, D.W., Eaton, W.O., & McKeen, N.A. (2002). Motor activity level and behavioural control in young children. *International Journal of Behavioral Development,* **26**(4), 289-296.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Colcombe, S., & Kramer, A.F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science,* **14**(2), 125-130.

Dalrymple-Alford, E.C., & Budayr, B. (1966). Examination of some aspects of the stroop color-word test. *Perceptual and Motor Skills,* **23**, 1211-1214.

Etnier, J.L., Salazar, W., Landers, D.M., Petruzello, S.J., Han, M., & Nowell, P. (1997). The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. *Journal of Sport and Exercise Psychology,* **19**, 249-277.

Fairweather, S.C., Reilly, J.J., Grant, S., Whittaker, A., & Patton, J.Y. (1999). Using the Computer Science and Applications (CSA) activity monitor in preschool children. *Pediatric Exercise Science,* **11**, 413-420.

Freedson, P.S., Melanson, E., & Sirard, J. (1998). Calibration of the Computer Science and Applications, Inc. accelerometer. *Medicine and Science in Sports and Exercise,* **30**(5), 777-781.

Hamm, V.P., & Hasher, L. (1992). Age and the availability of interferences. *Psychology and Aging,* **7**, 56-64.

Harnishfeger, K.K. (1995). The development of cognitive inhibition: Theories, definitions, and research evidence. In F.N. Dempster & C.J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 175-204). San Diego, CA: Academic Press.

Hedges, L.V., & Olkin, I. (1985). *Statistical methods for meta-analysis.* New York: Academic Press.

Hills, M., & Armitage, P. (1979). The two-period cross-over clinical trial. *British Journal of Clinical Pharmacology,* **8**, 7-20.

Hogervorst, E., Riedel, W., Jeukendrup, A., & Jolles, J. (1996). Cognitive performance after strenuous physical exercise. *Perceptual and Motor Skills,* **83,** 479-488.

Jones, B., & Kenward, M.G. (2003). *Design and analysis of cross-over trials* (2nd ed.). Boca Raton, FL: Chapman & Hall/CRC.

Kramer, A.F., Humphrey, D.G., Larish, J.F., Logan, G.D., & Strayer, D.L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging,* **9**(4), 491-512.

Kuehl, R.O. (2000). *Design of experiments: Statistical principles of research design and analysis* (2nd ed.). Pacifi c Grove, CA: Brooks/Cole Publishing.

Leenders, N., Sherman, W.M., & Nagaraja, H.N. (2000). Comparisons of four methods of estimating physical activity in adult women. *Medicine and Science in Sports and Exercise,* **32**(7), 1320-1326.

Lichtman, S., & Poser, E.G. (1983). The effects of exercise on mood and cognitive functioning. *Journal of Psychosomatic Research,* **27**, 43-52.

MacLeod, C.M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin,* **109**(2), 163-203.

MacLeod, C.M., & MacDonald, P.A. (2000). Interdimensional interference in the Stroop effect: Uncovering the cognitive and neural anatomy of attention. *Trends in Cognitive Sciences,* **4**(10), 383-391.

Masse, L.C., Fulton, J.E., Watson, K.L., Heesch, K.C., Kohl, H.W., Blair, S.N., et al. (1999). Detecting bouts of physical activity in a field setting. *Research Quarterly for Exercise and Sport,* **70**(3), 212-219.

Melanson, E.L., & Freedson, P.S. (1995). Validity of the Computer Science and Application, Inc. (CSA) activity monitor. *Medicine and Science in Sports and Exercise,* **27,** 934-940.

Neill, W.T. (1977). Inhibitory and facilitatory processes in selective attention. *Journal of experimental Psychology: Human Perception and Performance,* **3,** 444-450.

Neill, W.T., Valdes, L. A., & Terry, K.M. (1995). Selective attention and the inhibitory control of cognition. In F.N. Dempster & C.J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 207-261). San Diego, CA: Academic Press.

Proctor, R.W., Reeve, E.G., & Weeks, D.J. (1990). A triphasic approach to the acquisition of response-selection skill. In G. H. Bower (Ed.), *The psychology of learning: Advances in research and theory* (pp. 207-240). New York: Academic Press.

Sibley, B.A., & Etnier, J.L. (2003). The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exercise Science,* **15**(3), 243-256.

Spreen, O., & Strauss, E. (1998). *A compendium of neuropsychological tests: Administration, norms, and commentary* (2nd ed.). New York: Oxford University Press.

Stroop, J. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology,* **18**, 643-662.

Thayer, R.E. (1989). *The biopsychology of mood and arousal.* New York: Oxford University Press.

Tomporowski, P.D. (2003a). Cognitive and behavioral responses to acute exercise in youths: A review. *Pediatric Exercise Science,* **15**, 348-359.

Tomporowski, P.D. (2003b). Effects of acute bouts of exercise on cognition. *Acta Psychologica,* **112**(3), 297-324.

Trost, S.G., Ward, D.S., Moorehead, S.M., Watson, P.D., Riner, W., & Burke, J.R. (1998). Validity of the Computer Science and Applications (CSA) activity monitor in children. *Medicine and Science in Sports and Exercise,* **30**, 629-633.

Tyron, W.W., & Williams, R. (1996). Fully proportional actigraphy: A new instrument. *Behavior Research Methods, Instruments, & Computers,* **28**(3), 392-403.