Differential effects of acute exercise on distinct aspects of executive function

A variety of motivating factors has spurred the need for intervention strategies that improve cognition and brain function across the life span. For instance, many researchers strive toward identifying methods for delaying the decline in cognitive function associated with normal aging. Additionally, enhancing cognitive and academic performance in children has been a longstanding goal of educational policies and curriculum design.

Fortunately, an abundance of epidemiological and experimental evidence suggest that regular participation in physical exercise is an effective behavioral strategy that benefits cognition across many age groups (e.g., Hillman, Erickson, & Kramer, 2008; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011). A frequently documented outcome of regular exercise includes a disproportionate benefit on executive functions, which refers to a set of cognitive processes that are important for activities of daily living, including working memory, inhibitory and attentional control, decision-making, and planning (Miyake et al., 2000). However, while these observations hold significant implications, an understanding of the mechanisms that account for *how* exercise affects cognition and brain function remains unclear in humans. Consequently, there is no clear consensus about the parameters of exercise (e.g., frequency, duration, intensity, etc.) that maximizes its benefits on the brain and cognition. A better insight into exercise-induced effects on the brain may accelerate the implementation of evidence-based recommendations for improving cognition and brain function.

One approach to addressing this issue might be to examine the acute effects of exercise. Regular exercise is comprised of repeated bouts compounded over time, and thus examining its transient effects may elucidate the process through which the outcomes of regular exercise are
achieved. Accordingly, this study sought to investigate the changes in cognition following a single bout of exercise.

Indeed, evidence from recent meta-analyses indicate that acute exercise has a small positive effect on human cognition (e.g., Chang, Labban, Gapin, & Etnier, 2012). Moreover, like chronic exercise, researchers have identified a disproportionate benefit of acute exercise on cognitive processes that require greater executive control. For example, in a sample of young adults, Pontifex and colleagues (2009) reported that a 30-minute bout of exercise improved conditions of higher working memory load compared to lower loads. Working memory refers to the temporary maintenance of a limited amount of information that is held online in an accessible state. Similarly, Hillman and his colleagues (2003) observed that inhibitory control, another construct of executive function, was also benefitted by a 30-minute exercise bout. Inhibitory control, refers to the control over stimuli that are irrelevant to the task at hand and the inhibition of a pre-potent response.

Inhibitory control and working memory are functionally distinct aspects of executive function that depend on different brain mechanisms (Postle, 2006; Wager et al., 2005); however, the extent to which acute exercise exerts differential effects on these two constructs is unknown. Understanding this distinction might illuminate the effects of exercise on the brain. To this end, the current study extends the current literature on acute exercise effects on cognition by examining the consequences of a single exercise bout on two distinct aspects of executive function within the same sample and study design. Given the unequivocal evidence from animal studies highlighting the effect of exercise on the hippocampus, a brain region critical in learning and memory (e.g., van Praag, 2009), it was predicted that working memory would be more sensitive to acute exercise compared to inhibitory control.
A repeated-measures, acute exercise paradigm was utilized where dependent measures of cognition were assessed before and after a 30-minute bout of exercise (see Figure 1). Each participant was subjected to two manipulations of exercise to assess whether the effects are dependent on intensity levels or cardiovascular engagement. Consistent with previous studies of acute exercise, an active exercise condition involved participants pedaling on a stationary bicycle at a moderate intensity (65% of maximum heart rate). A novel contribution to the literature involves a passive exercise condition, which mimicked the same leg movements and same pedal rate as the active condition by mechanically moving participants’ legs using a motorized pedal within the stationary bicycle. This critical condition minimized the confounds of movement and demand characteristics found in seated-rest controls typically employed in other studies. Leg movement serves as an important confound in acute exercise studies because it remains unclear whether exercise effects are due to arousal mechanisms. Moreover, the passive condition addresses whether exercise effects require cardiovascular engagement, or if ascending activation of arousal systems from leg movement is enough. Finally, by indicating to participants that both conditions are exercises, demand characteristics were reduced.

Methods

Participants

Twenty-six healthy younger adults (mean age = 25.23 years (SD = 2.85); twelve males) were recruited using the University of Iowa mass e-mail service. This study was approved by the Institutional Review Board of the University of Iowa and all participants provided written informed consent and any contraindications to the exercise protocol by completing the Physical Activity Readiness Questionnaire (PAR-Q). A detailed health-history questionnaire, neuropsychological battery, as well as a battery of physical activity questionnaires were administered.
**Materials and Measures**

All exercise sessions involved cycling on a motor-driven stationary bicycle (Theracycle 200, Franklin, MA) that was adjusted for comfort. For each session, heart rate was continuously recorded using a Polar heart-rate monitor (Model RS800CS, Polar Electro, Kempele, Finland). Maximum heart rate \( (HR_{\text{max}}) \) was based on an age-predicted calculation: \( 220 - \text{age} \).

**N-back task.** Working memory was assessed with a modified \( n \)-back task where participants were presented a continuous stream of faces separated by a 3-second delay and instructed to detect whether the current face matched the one presented \( N \) faces previously (see Figure 2). Participants compared the current face to either one face (1-back condition) or two faces (2-back condition) presented previously in the sequence. Performance on this task relies on successful encoding, maintenance, and retrieval of stimuli, and has also been shown to depend on hippocampal engagement (e.g., van Vugt, Schulze-Bonhage, Litt, Brandt, & Kahana, 2010). The task consisted of a total of 4 blocks, alternating between 1-back and 2-back with 14 trials in each block. Total \( n \)-back task duration was approximately 9 minutes.

**Flanker task.** Inhibitory control was assessed using a modified Erikson flanker task where participants were instructed to respond as quickly and accurately as possible to the direction of a target arrow while ignoring two flankers on each side (see Figure 3). The congruency of the flanking items to the target arrows was manipulated, resulting in three conditions: congruent (CON), incongruent (INC), and neutral (NEU). In congruent trials, the flanking arrows pointed in the same direction as the target arrow (e.g., \( > > > > > \)) and in neutral trials, the target arrow was surrounded by dashes (e.g., \( - - > - - \)). Critically, in the incongruent trial, the flanking arrows pointed in the opposite direction as the target arrow (e.g., \( < < > < < \)), requiring the greatest level of inhibitory control over the flanker arrows in order to execute an
accurate response. For each of the task conditions, 40 trials were presented randomly with right and left target arrows occurring with equal probability, yielding a total of 120 trials. Total flanker task duration was approximately 5.5 minutes.

**Procedures**

All participants visited the laboratory on three occasions separated by at least one week.

**Pre-experimental session.** The first visit served as a pre-experimental session where participants provided written consent, completed health history and physical activity history questionnaires, and received an orientation to the exercise testing procedures. During this orientation phase, participants were first familiarized to cognitive tasks and self-report measures of arousal. To minimize the confound of learning effects on cognitive tasks during experimental sessions, participants completed both tasks. After practicing the cognitive tasks, a heart rate transmitter was strapped onto each participant and they were informed of the exercise conditions as described above. In order to minimize demand characteristics, experimenters refrained from using the terms “active” or “passive” when interacting with participants. Participants were instructed that the one exercise condition involved their legs being exercised by the machine, while the other exercise required that they pedal against the machine’s resistance until their heart rate reached a target heart rate zone (60 – 70% of their age-predicted HR\(_{\text{max}}\)). Then, a calibration protocol was administered to identify a suitable pedal rate for both exercise conditions and also to reduce novelty effects. Briefly, after adjusting seat position to the proper height and comfort, participants alternated between passive and active cycling at incremental pedal rates until reaching a desired rate for both exercise conditions. These parameters were then used for their experimental sessions. Following the calibration protocol, the pre-experimental session was
concluded by practicing another set of cognitive tasks to ensure that any observed effects from
the experimental sessions were a result of the exercise manipulation and not from practice.

**Experimental Sessions.** Experimental sessions included two within-subject conditions of
exercise (active & passive) and two within-subject conditions of task (flanker task & n-back
task), where order of exercise conditions and order of cognitive tasks was counterbalanced across
participants for a total of four groups. To account for energetic variables not related to exercise,
participants were required to refrain from caffeine and exercise or strenuous physical activity for
12 hours prior to testing. After completing pre-exercise cognitive testing, the participants were
equipped with a heart rate transmitter. Then, a 5-minute warm-up period preceded a 30-minute
steady-state exercise bout at the pedal rate and seat position determined during their orientation
session. For the active exercise, participants gradually increased their heart-rates during the
warm-up. Throughout the course of each exercise session, a standard, non-recognizable music
track was played, and social engagement was controlled for by minimizing interactions between
the experimenter and participant. Additionally, participants were provided ad libitum access to
water, a towel, and a fan throughout the exercise. The exercise was followed by a 5-minute cool-
down period before the participant was immediately escorted across the hall to complete their
post-exercise cognitive testing. The time elapsed between exercise cessation and the start of the
cognitive testing was approximately 6 minutes. After a minimum of one week, participants
returned to the laboratory to complete their other exercise condition. Importantly, a new set of
faces was used for each experimental session to minimize familiarity with stimuli.

**Data Analysis**

For all task performance (i.e., accuracy and reaction time), change in performance as a
function of the exercise manipulation was computed (see Figure 4). For the n-back task, %diff
for both accuracy and reaction time (\(\%\text{diff}_{\text{acc}}\) and \(\%\text{diff}_{\text{RT}}\)) were submitted separately to a 2 (Exercise Condition: Active, Passive) by 2 (Memory Load: 1-back, 2-back) repeated-measures analysis of variance (ANOVA). For the flanker task, task performance (i.e., \(\%\text{diff}_{\text{acc}}\) and \(\%\text{diff}_{\text{RT}}\)) was submitted separately to a 2 (Exercise Condition: Active, Passive) by 3 (Congruency: neutral, congruent, incongruent) repeated-measures ANOVA. To determine the nature of interaction effects, simple effects were examined with paired t-tests.

**Results**

For both the \(n\)-back and flanker tasks, change in performance as a function of the exercise condition and task condition is displayed in Figures 5 and 6. Significant effects of acute exercise on distinct aspects of executive control are indicated. For both the \(n\)-back and flanker tasks, the data are expressed as a significant percentage change in performance (accuracy and reaction time) following manipulations of both exercise conditions (active and passive exercise).

**\(N\)-back Task**

**Accuracy.** The analyses indicated a marginally significant main effect of task condition on \(\%\text{diff}_{\text{acc}}\) \((F(1,24) = 3.32, p = .081)\) with greater \(\%\text{diff}_{\text{acc}}\) for the 2-back condition compared to the 1-back condition. The exercise condition by task condition interaction did not reach significance \((F(1,24) = 2.59, p = .12)\). However, paired-samples t-tests of task condition within exercise condition revealed that the \(\%\text{diff}_{\text{acc}}\) for the 2-back condition was significantly higher than the 1-back condition \((t(24) = 3.012, p = .006)\) in the active exercise condition (see Figure 5). No such effects were observed in the passive exercise condition \((t(24) = .10, p = .92)\). Moreover, paired-samples t-test of the 2-back condition between exercise conditions indicate a greater \(\%\text{diff}_{\text{acc}}\) following active exercise compared to passive exercise \((t(24) = 1.95, p = .063)\). These
analyses suggest that the 2-back condition was selectively influenced by the active exercise condition and not the passive exercise.

**Reaction Time.** No significant main effects or interactions were observed for $\%\text{diff}_{RT}$.

**Flanker Task**

**Accuracy.** Results of the ANOVA revealed a significant main effect of exercise condition on $\%\text{diff}_{acc}$ ($F(1,24) = 4.93, p = .036$). The exercise condition by task condition interaction did not reach statistical significance ($F(2,48) = 1.90, p = .16$). Pairwise comparisons of task conditions between exercise conditions revealed that the $\%\text{diff}_{acc}$ for the incongruent condition was marginally higher in the active condition compared to the passive exercise condition ($t(24) = 1.81, p = .083$). However, the $\%\text{diff}_{acc}$ for the incongruent condition following active exercise was not significantly greater than zero ($t(24) = 1.10, p = .28$) while $\%\text{diff}_{acc}$ following passive exercise was significantly lower than zero ($t(24) = -1.83, p = .080$). This suggests that the main effect of exercise condition was driven by the decrease in accuracy following passive exercise. Together, these analyses reveal a non-specific positive effect of active exercise on accuracy during the flanker task, while passive exercise negatively affected inhibitory control (see Figure 6).

**Reaction Time.** The exercise condition by task condition ANOVA revealed no significant main effects or interactions for $\%\text{diff}_{RT}$.

**Discussion**

In order to better understand the nature behind exercise effects on cognition, the current study aimed to compare the acute effects of exercise on two separate aspects of executive function within the same sample population and experimental setting. In a sample of younger adults, a selective increase in performance on the 2-back condition, compared to the 1-back
condition of the n-back task, following active exercise indicates that the positive effects are greater under conditions in which working memory demands are higher. This positive effect was not observed following passive exercise. Importantly, the current study observed no significant performance improvements on the incongruent condition of the flanker task following the active exercise, which is consistent with the hypothesis that the effects of acute exercise differentially affect aspects of executive function. Working memory, compared to inhibitory control, appears to be more sensitive to acute exercise of moderate intensity. Consistent with animal research emphasizing the selective effects of exercise on the hippocampus, the current results suggest that brain regions affected by acute exercise are related to those involved working memory processes.

The results for the inhibitory control task reported in the current study, however, are inconsistent with previous acute exercise studies (e.g., Kamijo et al., 2009). One possibility that might account for this discrepancy is the difference in timing between cognitive testing and exercise cessation. Kamijo et al.’s (2009) improvements in behavioral performance were obtained within 2 minutes post-exercise, while the current results were obtained 6 minutes after exercise cessation, thus rendering the possibility that the mechanisms underlying the facilitating effect of acute exercise on inhibitory control processes may have rapidly dissipated. Similar to the present findings, Gothe et al. (2013) acquired behavioral performance approximately 5 minutes following acute exercise cessation and reported no significant improvements on the flanker task. This is consistent with other studies reporting no effect of acute moderate intensity exercise on flanker task performance obtained beyond 2 minutes (Hillman et al., 2003; Themanson & Hillman, 2006; 48 and 40 minutes after exercise, respectively). The timescale of improvements on working memory performance in the current report, however, are in agreement with Pontifex et al.’s (2009) observations immediately following their acute exercise protocol,
who found the positive effects of acute exercise on working memory to persist up to 30 minutes post-exercise. Taken together, that the 2-back condition of the n-back task improved within 6 minutes post-exercise in the current study, while the incongruent condition of the flanker task did not, suggests dissociable mechanisms by which acute exercise impacts cognitive function with distinct timecourses. A systematic study of these mechanisms and their timecourses is needed.

Another possibility is that the effects of an acute exercise manipulation may not be as apparent in behavioral measures of performance compared to changes in brain function. Indeed, neuroelectric changes have been observed following acute exercise without manifesting in behavioral measures (e.g., Hillman et al., 2003; Themanson & Hillman, 2006). This raises the question of whether measures of brain function would be more sensitive to the acute effects of exercise. Follow-up studies should employ the acute exercise paradigm with functional neuroimaging outcomes.

In sum, the findings from the current study extend the current literature on acute exercise effects on cognition. First, an active control condition was used instead of a seated-rest condition, which highlights the role of cardiovascular engagement. A second novel contribution of the current results are the differential effects of acute exercise on executive functions. Results from the present report indicates specificity in the mechanisms through which exercise benefits cognition and lead to testable predictions for future studies using an acute exercise paradigm. An acute exercise paradigm proves fruitful for this endeavor because it offers a low-cost and quick assessment of diverse exercise manipulations and their outcomes.
Figure 1. The acute exercise paradigm. Dependent measures were assessed before and after a 30-minute exercise manipulation.

Figure 2. Schematic diagram of the facial N-back task. *Note:* Each face was separated with a 3-sec inter-trial interval.

Figure 3. Schematic diagram of the flanker task.

Figure 4. Change in performance as a function of the exercise manipulation.
Figure 5. % Difference in accuracy as a function of n-back condition and exercise condition. The 2-back condition is selectively benefitted from active exercise.

**$t(24) = 3.012, p < .01$

* $t(24) = 1.95, p = .063$

Figure 6. % Difference in accuracy as a function of flanker task condition and exercise condition. *$t(24) = 1.807, p = .083$
References


