RESEARCH NOTE

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Exercise and Working Memory: An Individual Differences Investigation

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In the current work we asked whether executive function, as measured by tests of working memory capacity, might benefit from an acute bout of exercise and, more specifically, whether individuals who are lower or higher in working memory to begin with would be more or less affected by an exercise manipulation. Healthy adults completed working memory measures in a nonexercise (baseline) session and immediately following a 30-min self-paced bout of exercise on a treadmill (exercise session). Sessions were conducted 1 week apart and session order was counterbalanced across participants. A significant Session × Working Memory interaction was obtained such that only those individuals lowest in working memory benefited from the exercise manipulation. This work suggests that acute bouts of exercise may be most beneficial for healthy adults whose cognitive performance is generally the lowest, and it demonstrates that the impact of exercise on cognition is not uniform across all individuals.

Key Words: exercise, exercise performance, psychology

In contrast to traditional views of the mind as an abstract information processor largely divorced from the body and the environment, work exploring the relationship between physical activity and cognition suggests a strong link between cognition and action. Indeed, several recent literature reviews have concluded that a positive relationship exists between exercise and/or physical fitness and cognitive functioning (e.g., Brisswalter, Collardeau, & Arcelin, 2002; Etnier, Nowell, Landers, & Sibley, 2006; Tomporowski, 2003). That is, the fitness of the body seems to carry implications for the fitness of the mind.

Of specific interest in the current work, acute exercise bouts in healthy adults have repeatedly been shown to have a small but positive effect on immediate cognitive functioning. For example, a number of studies have reported increases in P3 amplitude following exercise—an event-related potential believed to be associated with attentional allocation and the updating of working memory. Magnie et al. (2000) found P3 amplitude increases following a bout of maximal aerobic exercise on a cycle ergometer in an acoustic oddball paradigm (requiring participants to monitor and keep track of a prespecified target tone randomly intermixed with

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nontarget tones). Hillman, Snook, and Jerome (2003) also found that a 30-min bout of treadmill exercise was related to increased P3 amplitude while performing a visual attention task (i.e., the Eriksen flanker task) in which individuals had to respond to a target in the presence of distracting stimuli flanking that target. Finally, Kamijo et al. (2004) found P3 amplitude increases following medium-intensity pedaling exercise, as compared with a no-exercise control condition, in a go/no-go reaction time task that required inhibition of a prepotent response.

More recently, Sibley, Etnier, and Le Masurier (2007) demonstrated that 20 min of moderate-intensity treadmill exercise led to improved Stroop performance. Given that critical trials of the Stroop task involve active goal maintenance in the face of interference (e.g., identifying that the word *RED* is printed in blue ink), Sibley and colleagues concluded that exercise facilitates executive attention abilities and, in particular, the ability to maintain attention to goal-relevant cues in demanding situations. Executive attention can be thought of as an attentional capability that allows for the active maintenance of memory representations, such as action plans, goal states, or task-relevant stimuli, in the face of interference (Kane & Engle, 2003). Executive attention is thought to be at the heart of working memory. Indeed, individual differences in working memory predict performance on the Stroop task, especially when active goal maintenance (e.g., "do not read the word") is required (Kane & Engle, 2003).

Despite investigations of the link between acute bouts of exercise and cognition in healthy adults, to our knowledge, no one has asked whether this relationship might differ as a function of individual differences in the cognitive abilities of the performer. Researchers have investigated whether individual differences in exercise-related variables might be a factor in the exercise–cognition link (e.g., aerobic fitness, see Etnier et al., 2006). Thus, it seems logical to ask whether individual differences in cognition-related variables play a moderating role in the relationship between exercise and cognition as well.

In the current work, we turned to an executive attention construct that has received a good deal of interest in the cognitive psychology and cognitive neuroscience literatures: *working memory*. We then asked whether working memory capacity might change as a function of an acute bout of exercise and, more specifically, whether individuals who are lower or higher in working memory to begin with would be more or less impacted by an exercise manipulation.

Working memory can be thought of as a short-term memory system involved in the attentional control, regulation, and active maintenance of a limited amount of information with immediate relevance to the task at hand (Miyake & Shah, 1999). Working memory is believed to support an array of complex cognitive behaviors ranging from reading comprehension to mathematical problem solving (Beilock & Carr, 2005). Although working memory is often portrayed as a general cognitive construct, it can also be thought of as an individual difference variable—meaning that some people have more of this construct and some less. A variety of academic tasks ranging from problem solving to reasoning reliably vary as a function of individual differences in working memory. In general, the more working memory one has, the better one's performance on these types of tasks will be (Conway et al., 2005). Given that working memory can be thought of as both a general cognitive construct *and* an individual difference measure, and is thought to be an important component of higher-level cognitive performance, it seems like an ideal construct to ask about the relationship between exercise and cognition.

Methods

Participants

Participants ($N = 48$; 31 males, 17 females) were undergraduate college students at a large Midwestern U.S. university (age: $M = 21.5$ years, $SE = .65$ year) recruited from psychology and kinesiology classes. All individuals received course credit for participation.

Procedure

All individuals came to the lab for two sessions (a baseline and exercise session), held at the same time of day, within 1 week of each other. The order of participation in the two sessions was counterbalanced across individuals, such that some participants took part in the baseline session first and some the exercise session first. Participants were asked not to exercise on the days they visited the lab. At the start of the first session, individuals signed informed consent, reported demographic information, and completed a medical health history questionnaire to screen for safe exercise participation. All participants were deemed to be in good health (for questionnaire details, see Sibley et al., 2007). At the end of the second session, individuals received feedback on their aerobic fitness and were debriefed.

Baseline Session. Individuals first completed two working memory measures (described below) counterbalanced across participants. Participants then completed a graded exercise test (GXT) to determine VO_{2max}, which is a measure of oxygen capacity reported in millimeters of oxygen consumption per kilogram of body mass per minute and is generally accepted to be the best single measure of physical fitness (Howley, Bassett, & Welch, 1995). The VO_{2max} measure was used to ensure there were no fitness differences as a function of baseline working memory capacity. The GXT was conducted on a treadmill using the modified Bruce protocol. A computerized indirect calorimetry system collected 30-s averages for oxygen uptake (VO_2) and respiratory exchange ratio (RER). To achieve VO_{2max}, all participants had to meet two out of the three following criteria: RER > 1.1, obtain age-predicted maximum heart rate (HR), or plateau in VO_2 despite an increase in workload.

Exercise Session. Participants completed a 30-min self-paced bout of exercise on a treadmill while wearing a Polar HR monitor. Individuals were instructed to try to keep their heart rate at 60–80% of their age-predicted maximum HR (i.e., 220 minus age). Every 2 min throughout the exercise session, HR and participants' ratings of perceived exertion (RPE) were assessed via participants' verbal responses to Borg's RPE scale ranging from 6 (*no exertion at all*) to 20 (*maximal exertion*). Immediately after exercise, participants completed two more working memory measures.

Working Memory Measures. In both the baseline and exercise sessions, participants completed two well-validated measures of working memory: Operation Span (OSPAN) and Reading Span (RSPAN) (for a review, see Conway et al., 2005). Two separate versions of the RSPAN task and two separate versions of the OSPAN task were used. Individuals received one version of each working memory task during the baseline session and the other version during the exercise session. The specific OSPAN/RSPAN version individuals received in each session was counterbalanced across participants.

The OSPAN involves solving a series of arithmetic equations while attempting to remember a list of unrelated words. Individuals are presented with one equation–word string at a time (e.g., $(5 \times 2) - 2 = 8$? DOG) on a computer and asked to verify aloud whether the equation is correct. Individuals then read the word aloud. At the end of the series, they write down the sequence of words. The RSPAN involves reading a series of sentence–letter strings (e.g., "On warm sunny afternoons, I like to walk in the park.? F). In the RSPAN, individuals read the sentence aloud and are asked to verify whether the sentence makes sense. Individuals then read the letter aloud. At the end of the series, they write down the sequence of letters. In both the OSPAN and RSPAN, each series consists of a random number of strings between 2 and 5. Individuals are tested on three series of each length (12 total). In the current work, OSPAN and RSPAN scores (range: 0–42) consisted of the total number of words/letters correctly recalled.[1]

Working memory is at heart the ability to focus attention on a central task and execute its required operations while inhibiting irrelevant information, regardless of what that central task is. The RSPAN and OSPAN tasks are designed to measure this ability—believed to be an important component of complex cognitive performance. Indeed, not only are RSPAN and OSPAN tasks highly correlated, latent-variable approaches (in which the variance common to different span tasks is statistically extracted to yield a pure, or latent, working memory variable) have demonstrated that a collective executive attention construct is a better predictor of higher-level cognitive performance (e.g., general fluid intelligence, G*f*) than domain-specific measures alone (see Kane et al., 2004).

Results

In line with previous research, RSPAN and OSPAN scores in the current work were highly correlated in both the baseline ($r = .76$, $p < .001$) and exercise ($r = .66$, $p < .001$) sessions. Given these high correlations, as well as previous latent-variable approaches demonstrating that RSPAN and OSPAN assess a common working memory construct predictive of higher-level cognitive performance (Kane et al., 2004), and following common practice in the literature (see Beilock & Carr, 2005), we averaged the scores on these two measures to capture working memory in the baseline and exercise sessions.[2]

Span scores averaged across the two working memory tests in the baseline session ranged from 20 to 41 ($M = 31.44$, $SE = 0.69$) and in the exercise session ranged from 24 to 40.5 ($M = 31.83$, $SE = .61$).[3] As a first step toward exploring the impact of an acute bout of exercise on working memory performance as a function of individual differences in working memory capacity, we began by dividing individuals into four equal quartiles (ns = 12) based on an average of their performance on the working memory tasks performed in the baseline condition without exercise (low quartile: $M = 24.67$, $SE = .76$; middle-low quartile: $M = 30.96$, $SE = .21$; middle-high quartile: $M = 33.38$, $SE = .22$, high quartile: $M = 36.75$, $SE = .55$).

We next compared average performance on the two working memory measures taken in the baseline session with average performance on the two working memory measures taken in the exercise session in a 2 (session: baseline, exercise) × 4 (quartile: low, middle-low, middle-high, high) repeated-measures ANOVA, with the second factor between subjects. A significant Session × Quartile interaction

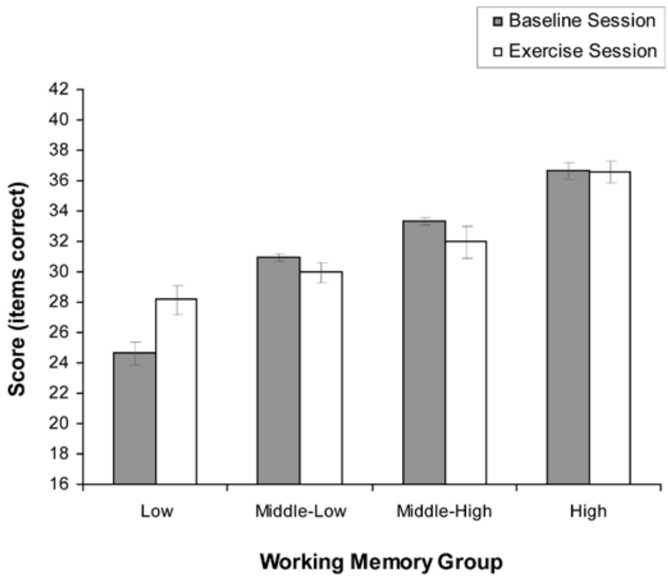

Figure 1 — Working memory scores (range 0–42) for the baseline and exercise sessions for the four working memory groups (i.e., low quartile, middle-low quartile, middle-high quartile, high quartile).

obtained, $F(3, 44) = 6.83$, $p < .001$, $\eta_p^2 = .38$. As seen in Figure 1, those lowest in working memory (i.e., low quartile group) significantly increased their working memory score from the baseline to exercise session, $t(11) = 3.46$, $p < .01$, $d = 1.22$. Individuals in the other three quartiles did not, $t(11) = .73$, $p > .48$; $t(11) = 1.42$, $p > .18$; and $t(11) = .26$, $p > .79$, respectively. Thus, exercise positively affects executive function as measured by tests of working memory capacity, but only for those who are lowest in working memory to begin with.[4]

Measures of VO_{2max} did not differ across the working memory groups (low quartile: $M = 46.14$, $SE = 3.04$; middle-low quartile: $M = 43.62$, $SE = 2.28$; middle-high quartile: $M = 45.16$, $SE = 2.65$, high quartile: $M = 47.78$, $SE = 1.68$), $F < 1$, nor did age, $F(3, 44) = 1.43$, $p > .24$; the distribution of males and females, $F < 1$; or from where participants were recruited (i.e., from psychology or kinesiology classes), $F < 1$. There were also no group differences in HR intensity during exercise (low quartile: $M = 145.59$, $SE = 2.69$; middle-low quartile: $M = 147.89$, $SE = 4.47$; middle-high quartile: $M = 147.24$, $SE = 2.84$, high quartile: $M = 151.32$, $SE = 1.70$), $F < 1$; in percentage of maximal HR during exercise (low quartile: $M = 74.10\%$, $SE = 1.83\%$; middle-low quartile: $M = 74.77\%$, $SE = 1.92\%$; middle-high quartile: M = 73.87%, $SE = 1.43\%$, high quartile: $M = 75.61\%$, $SE = .90\%$), $F < 1$; and in perceived exertion ratings during exercise (low quartile: $M = 11.96$, $SE = .31$; middle-low quartile: $M = 11.38$, $SE = .62$; middle-high quartile: $M = 10.90$, $SE = .43$, high quartile: $M = 11.74$, $SE = .55$), $F < 1$. Thus, it would be difficult to explain the interaction reported above in terms of differences in these variables.

Discussion

Although researchers have explored the relationship between acute bouts of exercise and cognitive performance in healthy adults, to our knowledge, this work is the first study to ask whether this relationship might differ as a function of individual differences in the cognitive abilities of the performer. Individual differences in cognitive constructs such as working memory are predictive of a wide range of higher-level cognitive behaviors (Beilock & Carr, 2005; Conway et al., 2005). Thus, it is important to understand how factors such as exercise might differently influence cognition as a function of variations in cognitive ability.

We found that only those individuals lowest in working memory benefited from an acute bout of exercise. Previous work has demonstrated that exercise training has the greatest impact on the cognitive tasks that draw heavily on executive attention/working memory resources and that such effects are especially robust for older adults (see Kramer & Hillman, 2006). Similarities between older adults and lower working memory younger adults (such as the college student sample used in the current work) have been found in terms of a number of executive attention abilities (e.g., inhibitory ability; see Miyake & Shah, 1999). Thus, it follows that younger adults lowest in working memory may have the most to gain via an exercise manipulation. Moreover, Mahar et al. (2006) recently demonstrated that increased physical activity improved on-task behavior in the classroom (e.g., engagement in task learning), and it did so most for those students least engaged to begin with. Lower working memory individuals are thought to be more easily distracted and likely to wander off task than those higher in working memory (Conway et al., 2005). Thus, there may be a relationship between children most likely to be distracted in the classroom and working memory. If so, physical activity interventions may have the greatest impact on these students.

One might be concerned that the design of our study leaves open an alternative interpretation for our results. Namely, that regression to the mean rather than exercise per se is responsible for our effects (e.g., maybe the low quartile group could only improve their working memory scores from the baseline session). If regression to the mean were driving our results, however, then we would expect those highest in working memory in the baseline session to show a decrease in performance in the exercise session. That is, if regression to the mean were at play, it should occur on both ends of our working memory continuum. This is especially true given that our baseline working memory scores were normally distributed. As indicated by the Kolmogorov–Smirnov Z test, $Z = .910$, $p = .38$, the distribution of our baseline working memory scores were not significantly different from a normal distribution. As seen in Figure 1, those highest in working memory do not show such a data pattern.

One might also notice that we did not include a nonexercise control group. Everyone served as their own baseline, completing both a baseline and exercise session, counterbalanced in order. Working memory is believed to be a relatively stable, traitlike factor. For example, OSPAN measures separated by several months in time show high test–retest reliability ($r = .88$, Klein & Fiss, 1999). Thus, it seems unlikely that a nonexercise control group would show significant changes over time. Moreover, even if such changes were possible, it is unclear why they would be limited to those lowest in working memory—especially given the fact that regression to the mean does not seem a likely explanation for the current findings. Nonetheless, including such a control in future work would be beneficial.

It is also important to note that the 0–42 range of our working memory measures put no group within ceiling or floor range. Floor and ceiling effects might be possible if the performance of the low and high quartiles did not significantly differ from the span end points, meaning that these groups had no room to move down to 0 or up to 42, respectively. However, there were significant differences between the low and high quartile groups and their respective span end points in both the baseline (low quartile: $t(11) = 32.37$, $p < .001$; high quartile: $t(11) = 9.51$, $p < .001$) and exercise (low quartile: $t(11) = 30.62$, $p < .001$; high quartile: $t(11) = 7.85$, $p < .001$) session. Thus, it does not seem likely that such effects were at play.

Although future work is needed to elucidate the precise mechanisms by which the exercise effects seen in the current work occur, the current findings highlight the fact that the impact of exercise on cognition is not uniform across all individuals. Not only does this work suggest that acute bouts of exercise may be most beneficial for those whose cognitive performance is generally the lowest, it also carries implications for conducting and interpreting studies examining the effect of acute exercise bouts on cognition. For example, researchers exploring the effect of exercise on executive function who are sampling at different ends of the working memory continuum (perhaps because the student samples at their respective universities have very different cognitive makeups) may come to different conclusions. Thus, it seems important to take into account individual differences in cognitive abilities when exploring the relationship between cognition and physical activity in healthy adults.

In conclusion, the current experiment takes a new step in the demonstration of how the body influences cognitive processing, a step that individuates the influence of an acute bout of exercise on healthy adult cognitive performance as a function of the cognitive capacities of the performer. Our results not only carry implications for understanding the link between cognition and action, but also shed light on the importance of exploring moderator variables on both ends of this relationship.

Notes

1. This is a partial credit, load-weighted scoring procedure. We chose partial credit scoring because it is recommended by Conway et al. (2005). Nonetheless, it is important to point out that using an all-or-none scoring procedure resulted in the same significant pattern of results as that reported herein. Conway et al. expressed a less strong preference with respect to the weighting of items within the working memory measures. Thus, we chose load-weighted scoring because it is most commonly used in the working memory literature and our span scores were normally distributed (see Discussion for further details).

2. We also created a composite working memory measure of RSPAN scores (Baseline: $M = 31.85$, $SE = .75$; Exercise: $M = 32.15$, $SE = .66$) and OSPAN scores (Baseline: $M = 31.02$, $SE = .71$; Exercise: $M = 31.52$, $SE = .67$) by standardizing the independent measures prior to averaging them. As one might expect given the similarity of means and *SE*s in these scales, the standardized composite produced the same significant pattern of results as that reported herein. Moreover, we also looked at working memory scores separately for the OSPAN and RSPAN tests. Using either measure alone as a working memory index in the baseline and exercise session produced the same significant pattern of results as that reported.

3. No participants' accuracy in the arithmetic or sentence-verification portions of the span tests fell below an 80% accuracy criterion. This criterion has been previously used to exclude individuals thought not to be performing the arithmetic or sentence-verification portions of the span tests successfully (Beilock & Carr, 2005). Thus, all individuals were retained in the data analyses.

4. We also examined performance differences from the baseline to exercise session using working memory as a continuous variable. Correlating this difference (i.e., exercise session scores minus baseline session scores) with a continuous measure of baseline working memory revealed a significant negative relationship, $r = -.51$, $p < .001$. As working memory increased, the positive impact of exercise decreased (a larger difference indicates a greater exercise benefit). Although this relationship was significant, as is seen in Figure 1, those lowest in working memory show the only significant exercise effect. Such a finding aligns well with work by Hillman, Belopolsky, Snook, Kramer, and McAuley (2004), suggesting that physical activity may influence performance in a threshold-type manner. That is, in terms of the current work, it seems that below a given working memory level exercise has a positive effect and above this level it does not.

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