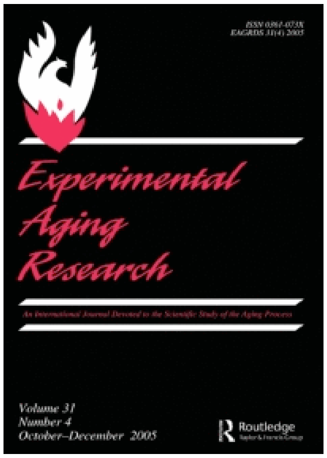

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PHYSICAL ACTIVITY MODERATES TIME-OF-DAY DIFFERENCES IN OLDER ADULTS' WORKING MEMORY PERFORMANCE

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Based on a synthesis of the literature on time of day and physical fitness effects on cognition, the current study examined whether physical activity moderated time-of-day differences in older adults' performance on a working memory task. Sedentary older adults' working memory performance declined significantly from morning to evening, whereas more active older adults performed similarly across the day. This interaction did not extend to performance on a simple reaction time task. A novel explanation based on the selective effect of mental fatigue on executive control processes is proposed.

Numerous studies reveal an age-related decline in executive control functions such as planning, working memory, allocating attentional resources, switching among tasks, and inhibiting irrelevant information (e.g., see Hasher & Zacks, 1994; Kramer, Hahn, Gopher, 1999b; Mayr & Kliegl, 1993). Evidence from imaging studies and patient populations suggests that frontal and prefrontal regions of the brain support executive control processes. Aging appears to have a disproportionate impact on these regions, with older adults showing

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especially marked neurophysiological, neuroanatomical, and neuropsychological changes in the frontal lobe (for review see Shimamura & Jurica, 1994; Buckner, 2004; DeCarli et al., 2005; West, 1996; Whelihan & Lesher, 1985). Note, however, that individuals vary considerably in the rate and magnitude of age-related physical changes in the brain, and as a result, there are substantial individual differences in the behavioral manifestation of these changes. In the current study, we examine the influence of one individual-difference variable, physical activity level, on older adults' performance on working memory and simple reaction time tasks during the morning and evening. Based on the integration of separate literatures on physical activity, time-of-day effects, and mental fatigue, we provide a preliminary test of the hypothesis that sedentary but not active older adults will show a decline in performance from the morning to evening on the working memory task but not the reaction time task.

Executive Control and Physical Activity

Research suggests that physical activity may prevent or attenuate the decline of cognitive functioning that is often associated with normal, healthy aging. For instance, Albert et al. (1995) found that strenuous activity (including daily activities involving physical exertion, such as lawn mowing) was associated with reduced cognitive decline (performance on a battery of neuropsychological tasks including language, memory, conceptualization, and visuospatial ability) in older adults. Yaffe, Barnes, Nevitt, Lui, and Covinsky (2001) also found a significant negative correlation between self-reported engagement in daily physical activities and the risk of age-related cognitive decline, as measured by performance on a modified Mini-Mental State Examination assessing language, memory, and concentration. Similarly, Laurin, Verreault, Lindsay, MacPherson, and Rockwood (2001) observed that low, moderate, or high physical activity levels yielded a protective effect on cognitive function (performance on the Canadian Study of Health and Aging neuropsychological test battery) with aging compared to no activity at all, with higher levels associated with lower risk of cognitive impairment. Recent findings from a randomized trial confirm the suggestions from the above set of cross-sectional studies in showing that significant positive effects on brain functioning can be obtained even via moderate exercise such as walking (Colcombe et al., 2004).

Not all studies report benefits of physical activity or exercise on cognition, however (for review, see Kramer, Hahn, & McAuley, 2000). Hall, Smith, and Keele (2001) provided one theoretical framework that might account for many of the discrepant findings in the literature. Their view is that because frontal and prefrontal cortices appear to be most affected by age, frontal functioning (i.e., executive control processes) will show the largest age-related decrements and will be most markedly affected by physical fitness interventions. A recent meta-analysis supports such a notion. Benefits of aerobic exercise were shown to be greatest in those studies that used cognitive tasks with a strong focus on executive control processes (Colcombe & Kramer, 2003). In a particularly compelling study by Kramer et al. (1999a), performance on a working memory, inhibition, and task-switching task was examined before and after a 6-month exercise intervention. Sedentary older adults were assigned to an aerobic exercise group (walking) or to a nonaerobic exercise group (toning and stretching). The researchers examined performance on selective aspects of the tasks that did and did not require executive control processes. Aerobic and nonaerobic exercisers performed equivalently on the nonexecutive elements (i.e., simple reaction time and performance on nonswitch trials in the task-switching paradigm) before and after intervention. For the executive elements of the tasks (i.e., stop-signal reaction time and performance on switch trials), however, aerobic exercisers significantly improved from pre- to postintervention, whereas nonaerobic exercisers did not show an improvement.

An interesting possibility is that physical activity and improved cardiovascular health might improve blood flow to the frontal and prefrontal cortex, and thereby attenuate or delay age-related decrements in executive control processes. Note that the largest age-related reductions in cerebral blood flow have been localized to the frontal and prefrontal areas (Gur, Gur, Obrist, Skolnick, & Reivich, 1987; Mathew, Wilson, & Tant, 1986; Schroeter, Zysset, Kruggel, & von Cramon, 2003; Shaw et al., 1984). Rogers, Meyer, and Mortel (1990) found that physical activity level moderated these reductions in blood flow. Over a 4-year span, they observed a decline in regional cerebral blood flow for sedentary retirees, but not for working older adults or active retirees. In a subsequent study, Colcombe et al. (2004) used functional magnetic resonance imaging to examine performance on the Eriksen Flanker Task as a function of aerobic fitness level. In the incongruent condition of the task, aerobically fit participants performed significantly better and recruited frontal brain regions to a greater extent than nonfit participants. This set of findings suggests that the benefits of aerobic exercise on cognition may reflect improved cardiovascular fitness, cerebral blood flow, and/or the effective recruitment of neural regions involved in cognitive control, rather than exercise-related improvements in general arousal or affect, as suggested by some (e.g., Emery & Blumenthal, 1991; McMorris & Graydon, 2000).

Executive Control, Time of Day, and Mental Fatigue

An additional factor that appears to affect executive control functioning is time of day. Studies show that older adults perform significantly better in the morning than in the evening on inhibition, working memory, and selective attention tasks that involve executive control processes. For example, older adults performed better in the morning than in the evening on a Stroop task, Trail Making Part B, and stop-signal task (May & Hasher, 1998), a negative priming task (Intons-Peterson, Rocchi, West, McLellan, & Hackney, 1998), and working memory tasks involving interference (Hasher, Chung, May, & Foong, 2002) and distraction (West, Murphy, Armilio, Craik, & Stuss, 2002).

An intriguing parallel exists between the exercise literature and time-of-day literature. As observed in the exercise literature, time of day appears to selectively affect older adults' executive control processes. The time-of-day effects described above pertain to selective attention, inhibition, and the monitoring and manipulation of information in working memory, all of which are considered executive control functions (Miyake et al., 2000). Yoon, May, and Hasher (1999) have, in fact, proposed a framework for these time-of-day effects that is similar to Hall et al.'s (2001) framework for exercise effects. Yoon and colleagues (1999) propose that older adults' performance on tasks requiring inhibition or suppression (one type of executive control process) will be affected by time of day, whereas performance on tasks requiring activation processes will not.

We hypothesize that time-of-day effects may be influenced by the degree to which older adults experience progressive mental fatigue across the day. Mental fatigue can be conceptualized as the fatigue one might experience after a day filled with prolonged or demanding cognitive activities. Mental fatigue has been linked to corresponding decreases in the activation or availability of mental resources (Lorist et al., 2000). We hypothesize that this mental fatigue may be moderated by older adults' level of cardiovascular fitness. We further suggest that executive control processes may be disproportionately affected by this mental fatigue because of the disproportionate neurophysiological and cerebrovascular changes that occur in frontal and prefrontal brain areas with age.

A recent study provides support for the specific influence of mental fatigue on executive control processes supported by frontal regions. Van der Linden, Frese, and Meijman (2003) administered two complex tasks commonly used to assess executive function, the Wisconsin Card Sorting Task (WCST) and the Tower of London (TOL), to fatigued and nonfatigued participants. Participants in a fatigue group performed a simulated scheduling task continuously for two hours prior to performing the experimental tasks. Control participants filled the 2-hour gap with activities that were not mentally demanding. This manipulation mimics the type of fatigue one might expect to encounter after a day in the office or a day filled with other mentally demanding activities. Fatigue ratings confirmed that the manipulation was effective. Subsequent analyses showed that fatigue did not impair performance overall, but had a selective detrimental impact on the executive control measures from the WCST and TOL tasks.

The present study further examined whether mental fatigue, as it builds across the day, has a selective effect on executive control performance. A working memory task was used to assess the executive control functions of updating and switching attention between competing items in working memory. This task was modeled after one developed by Garavan, Ross, Li, and Stein (2000) and requires individuals to keep a running count of the number of stimuli presented for each of two categories of items. Past research has revealed significant activation in frontal and prefrontal cortices during performance of this task in a group of younger adults (cf. Garavan et al.). We expected that sedentary and active older adults would perform similarly on this task in the morning as both groups would presumably be at their peak level of mental alertness. We hypothesized, however, that sedentary older adults would be susceptible to mental fatigue across the day and would therefore show a significant decline in working memory performance during the evening session. On the other hand, it was hypothesized that active older adults would experience less mental fatigue across the day, and were therefore expected to perform similarly on the working memory task from the morning to evening session. No such activity by time-of-day interaction was expected for the nonexecutive control measure, simple reaction time. To our knowledge, this is the first study to examine the potential moderating effect of physical activity on older adults' time-of-day differences in executive control performance.

METHOD

Participants

Thirty-five older adults ($M = 72.5$; range = 61–88) participated in the study. The older adults were recruited from the Fort Collins community and volunteered to participate without monetary compensation. They were high-functioning older adults in independent living situations. Exclusion criteria included past history of head trauma with loss of consciousness, psychiatric illness, or dementia, as determined by self report. Prior to setting up an appointment, participants were asked if they had been diagnosed with, were receiving treatment for, or had a prior history of dementia (such as Alzheimer's disease). All participants reported normal or corrected vision and spoke English as their primary language. On average the sample reported 15.03 ($SD = 2.96$) years of formal education. Average self-reported health ratings were good ($M = 1.77$, $SD = .6$, where 1 = excellent, 2 = good, 3 = neutral, 4 = poor, 5 = very poor).

Procedure

For the working memory task, participants first read self-paced instructions on the computer monitor indicating that sequences of small and large squares would be given. A sample of each type of square was shown. Large squares were 20 cm by 20 cm and small squares were 3 cm by 3 cm, both outlined in black on a white background. Squares were individually presented in the center of a computer monitor using Superlab Pro for Windows Version 1.05 (Cedrus Corporation, 1998). Participants were instructed to maintain separate running counts of the number of small and large squares that were presented and to rehearse the counts each time a new square was presented. They were informed that feedback would be given after each trial.

Once the instructions were understood, participants pressed the space bar to begin a practice trial. The word "ready" appeared for 2000 ms, and then the to-be-counted squares were shown one at a time for 2000 ms each. Each square was preceded by a fixation point that appeared for 150 ms. At the end of the sequence, participants were cued to report the number of squares of each size, writing these numbers in the appropriate position on an answer sheet. Unlimited time was given to record the responses. Once the counts were recorded, the participant pressed the space bar and feedback was presented on screen for 5 s, informing the participant of the correct counts for that trial. After the practice trial, 16 test trials were given, each proceeding in the same fashion as the practice trial. Individual trials lasted approximately 1 min and were separated by 10 s. A 2-min break was provided after the first eight trials.

On test trials, 11 to 14 squares were presented and trial difficulty was varied by manipulating the number of switches from one type of square to the other. Low-difficulty trials had just one switch during the sequence, whereas high-difficulty trials consisted of

n switches, where n equals the total number of squares in the sequence divided by two. Eight low- and eight high-difficulty trials were presented in a pseudorandom order such that an equal number of high- and low-difficulty trials were presented during each half of the experiment.

Participants also completed a simple reaction time task. For this task, participants pressed the "j" key on the keyboard in response to a 200-ms, 75-dB, 1000-Hz tone. The beginning of each trial was marked by the presentation of a fixation cross in the center of the screen for 300 ms. After the fixation cross appeared, participants pressed the spacebar when ready to begin. Immediately after the space bar was pressed, a tone was delivered and participants were to respond as quickly as possible to the onset of the tone. Following the completion of 10 practice trials, 30 test trials were given and reaction time (RT) was recorded, with RT cutoffs of 100 and 900 ms.

A self-report measure was used to determine participants' physical activity level. Each participant completed Voorrips, Ravelli, Dongelmans, Deurenberg, and Staveren's (1991) physical activity questionnaire. This questionnaire has been validated for use with older-adult participants and gathers information about daily household (e.g., grocery shopping, climbing stairs), leisurely (e.g., swimming, walking, biking), and sport activities (e.g., badminton, golfing). Following Voorrips et al., an overall physical activity score was computed based on the intensity and frequency (hours per week) of participants' reported activities. Voorrips et al. reported a range of scores between 1.2 and 31.4 for an older adult sample, with a mean score of 13.6 and an approximated median score of 11. The scores from the current sample were comparable, ranging from 1.8 to 31.6 with a slightly lower mean and median score of 10.4 and 9.06, respectively. Voorrips et al. reported a test-retest reliability of .89 and a strong correlation between scores on the questionnaire and 24-h activity recalls (.78) and pedometer measurements (.73).

A median split was used to assign participants to one of two groups, sedentary or active. The sedentary group ($n = 17$) was composed of participants scoring below the median score (9.06) on the questionnaire and the active group ($n = 18$) was composed of participants who scored at or above the median score. Table 1 includes mean scores for household, leisure, and sport activities. Active and sedentary older adults did not differ in age, but did differ in years of formal education, fitness ratings, and health ratings (see Table 1).

Table 1. Characteristics of the sample as a function of physical activity level

	Sedentary	Active	p-value
Number	17	18	–
First session morning	9	10	–
First session evening	8	8	–
Age			
Mean	73.4	71.6	.48
SD	8.3	6.9	–
Education			
Mean	13.9	16.1	.02
SD	2.5	3.0	–
Self-reported health			
Mean	2.0	1.6	.03
SD	.5	.6	–
Self-reported fitness			
Mean	2.4	1.7	.02
SD	.9	.8	–
Household score			
Mean	1.6	1.7	.42
SD	.26	.42	–
Leisure score			
Mean	3.0	11.1	.00
SD	2.0	4.6	–
Sport score			
Mean	.35	3.2	.00
SD	1.4	3.9	–

Note: For self-reported health and fitness, a scale of 1 to 5 was used, with lower scores referring to better health or fitness.

Working memory and reaction time performance were examined for the sedentary and active groups as a function of time of day. Each participant completed the tasks during a morning session (beginning at 8:00 AM) and an evening session (beginning at 5:00 PM). Time of first and second session was randomly assigned to each participant prior to the collection of any data. Of the 35 participants, 18 attended a morning session following by an evening session, and 17 attended an evening session followed by a morning session (see Table 1 for a breakdown of session order for each group). During the first session, participants completed the physical activity questionnaire, a demographics questionnaire that gathered information on education, health history, and daily mental activities, and the cognitive tasks. During the second session, participants once again completed the cognitive tasks. The reaction-time task was administered before the working memory task in both sessions. Overall, the first session lasted approximately 1 h and the second session lasted approximately 1/2 h. Activities occurring between testing sessions were not restricted.

RESULTS

Analyses were conducted to examine the effects of physical activity and time of day on performance of the working memory and simple reaction time tasks. An alpha level of .05 was used for all analyses. For the working memory task, the proportion of correct counts at each time of day was computed for each participant. The mean proportion of correct counts was examined using a 2×2 mixed analysis of variance (ANOVA) with physical activity level and time of day as factors.[1] This analysis revealed a significant interaction between physical activity level and time of day, $F(1,33) = 4.60$, $MSE = .01$, $p < .05$ (Figure 1). Planned comparisons showed that the sedentary and active groups performed similarly during the morning session, $F(1,33) = 0.05$, $MSE = .07$, $p > .10$. Furthermore, planned comparisons revealed that performance significantly decreased from morning ($M = .66$, $SD = .28$) to evening ($M = .58$, $SD = .30$) for the sedentary group [$F(1,33) = 4.07$, $MSE = .01$, $p = .05$], but was equivalent in the morning ($M = .64$, $SD = .28$) and evening ($M = .68$, $SD = .25$) for the active group, $p > .10$.[2] To provide a better sense of the distribution of time-of-day differences in each group, we computed a working memory difference score by subtracting the working memory score from the evening session from the working memory score from the morning session for each participant. A value of 0 therefore indicates no change across the day, a negative value reflects a decline across the day, and a positive value reflects improvement across the day. Using these difference scores, the 95% confidence interval for the sedentary group was $-.168$ to .003, whereas the 95% confidence interval for the active group was $-.045$ to .125. The interaction remained significant when participants in the sedentary ($n = 13$) and active groups ($n = 13$) were matched on the

[1]A main effect of trial difficulty was observed for the working memory task, with high difficulty trials ($M = .56$) resulting in less accurate performance than low difficulty trials ($M = .73$), $F(1, 33) = 69.36$, $p < .01$. However, trial difficulty did not interact with either time of day or physical activity level, thus we collapsed across both levels of trial difficulty for the subsequent analyses reported in the results section.

[2]An additional ANOVA using physical activity and testing session order as between subjects factors and time of day as a within subjects factor was performed. Although a main effect of session order was observed, such that performance on the working memory task was significantly better during the second testing session than the first [$F(1, 31) = 16.94$, $p < .01$], differential order effects were not observed for the sedentary and active groups, $p = .92$.

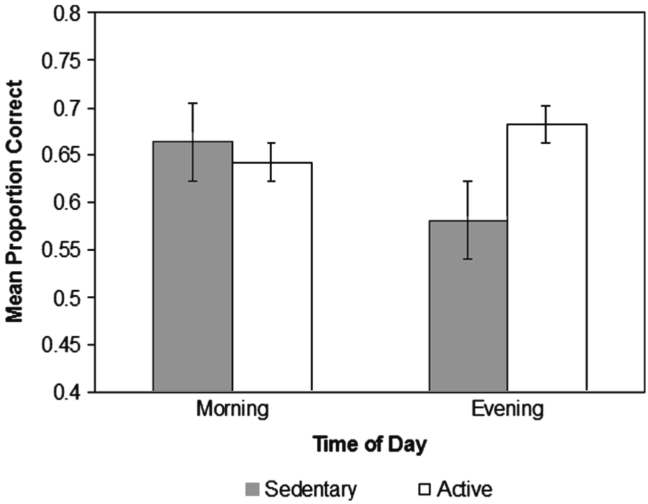

Figure 1. Mean proportion of correct counts on the working memory task as a function of physical activity level and time of day. Error bars represent standard errors.

basis of education level, $F(1,24) = 5.53$, $MSE = .01$, $p < .05$.[3] The main effect of time of day was not significant, nor was the main effect of physical activity level, ps $> .10$.[4]

For the simple reaction time task, two participants were eliminated because they did not complete the task during both sessions, and a third was eliminated because of a computer error. For the remaining 32 participants, we computed the mean reaction time for each time of day and submitted these scores to a 2×2 mixed analysis of variance

[3]Participants were selected on the basis of a perfect or closest match of education level with a participant in the opposite activity group. As a result, the education level was equivalent for the reduced sample of sedentary ($M = 14.5$, $SD = 2.6$) and active ($M = 14.9$, $SD = 2.6$) older adults, $p > .05$. This matching process also resulted in similar health ratings for the sedentary ($M = 2.0$, $SD = .6$) and active groups ($M = 1.7$, $SD = .6$) and similar ages for the sedentary ($M = 73.6$, $SD = 8.0$) and active ($M = 71.7$, $SD = 7.5$) groups, ps $> .05$. The ANOVA using these matched samples showed that performance significantly decreased from morning ($M = .71$) to evening ($M = .61$) for the sedentary group [$F(1,24) = 4.54$, $MSE = .01$, $p < .05$], but was equivalent in the morning ($M = .60$) and evening ($M = .66$) for the active group, $p > .10$.

[4]A secondary analysis was conducted in order to address the potential sample specificity of the median split by assigning participants to active or sedentary groups on the basis of the observed clustering of physical activity scores. The sedentary group was composed of participants who scored at or below 9.4, while the active group scored at or above 11.6. This analysis yielded the same pattern of results as obtained with our median-split analysis.

(ANOVA) with physical activity level and time of day as factors. The interaction between physical activity level and time of day was not significant. Sedentary older adults performed similarly in the morning ($M = 404$, $SD = 156$) and evening ($M = 427$, $SD = 106$), as did active older adults, Ms $= 363$ ($SD = 105$) and 359 ($SD = 100$), respectively. The main effects were not significant (ps $> .10$). To ensure that working memory findings held in this slightly reduced sample, the ANOVA for the proportion of correct counts was rerun using the 32 participants who completed the simple reaction time task. The analyses revealed a significant interaction between physical activity level and time of day that was consistent with the previous analysis, $F(1, 30) = 4.30$, $MSE = .01$, $p < .05$. Planned comparisons revealed that the sedentary and active groups performed similarly in the morning (Ms $= .63$ and $.67$), $p > .05$. However, performance significantly declined from the morning to the evening ($M = .54$) for the sedentary group, $p < .05$, but remained consistent from morning to evening ($M = .70$) for the active group, $p > .05$. The main effect of time of day was not significant, nor was the main effect of physical activity level, ps $> .10$.

DISCUSSION

The primary purpose of the present study was to examine working memory performance as a function of time of day for sedentary and active older adults, and to compare this pattern to that observed with a non-executive, simple reaction time task. Consistent with the hypothesis outlined in the Introduction, a significant decline in working memory performance was observed from the morning to evening for sedentary older adults, whereas active older adults performed similarly at the two testing times. The time of day by physical activity interaction did not extend to performance on the non-executive task, simple reaction time. To our knowledge, this is the first study to report a moderating effect of physical activity on older adults' time-of-day differences in executive control performance.

The results provide preliminary support for our hypothesis that sedentary but not active older adults experience progressive mental fatigue across the day. This mental fatigue would presumably affect executive control processes more so than other types of cognitive processes (see also Lorist et al., 2000; van der Linden et al., 2003). Furthermore, physical fitness would be expected to selectively enhance performance on executive control tasks that are dependent on the frontal lobes (Kramer et al., 1999a). Although the benefits of physical activity observed in the current study may relate to enhanced blood flow to frontal regions, other possible explanations exist. For instance, compared to less fit older adults, physically fit older adults have been found to exhibit reliably less age-related tissue loss in frontal lobe regions (Colcombe et al., 2003) and exhibit enhanced functioning of neural networks involved in attentional control including the frontal lobes (Colcombe et al., 2004). Studies involving animal models have shown that fitness is associated with additional positive effects on the brain including enhanced levels of brain derived neurotrophic factor which is thought to support neuronal survival and neurogenesis, and enhanced levels of insulin-like growth factor, which plays a role in blocking apoptosis (for review, see McAuley, Kramer, & Colcombe, 2004). Furthermore, given the selective effects of physical activity on working memory performance in the current study, it is important to note that animal models have shown that increases in exercise are associated with an increase in dopamine (D2) receptors in the brain (DeCastro & Duncan, 1985; Gilliam et al., 1984). Decline in D2 receptors has been linked with impairments in executive control performance in healthy older adults (Volkow et al., 1998). Additional research is needed to elucidate the precise underlying mechanism(s) involved in the maintenance of working memory performance across the day for active older adults.

Although the present data extend on the findings of Colcombe and Kramer (2003) in showing that daily physical activity may assist older adults in maintaining the efficiency of executive control processes across the day, one limitation of the current study is that we did not include a direct assessment of cardiovascular fitness. As such, we can not be certain that cardiovascular fitness is the key variable that moderates the time-of-day effect. A number of studies showing significant benefits of physical activity on cognitive function have relied upon self-reports of physical activity (Albert et al., 1995; Laurin et al., 2001; Rogers et al., 1990; Yaffe et al., 2001), and the particular physical activity measure used in the current study does correlate with cardiovascular health (cf. Voorrips et al., 1991). Furthermore, the difference we observed in physical activity between the sedentary and active groups primarily reflected differences in their frequency and intensity of engagement in leisure and sport activities, which are generally more strenuous and aerobic in nature compared to household activities. A recent study by Barnes, Yagge, Satariano, and Tager (2003) questions the use of self-reports, however. In their study, a direct measure of aerobic fitness level, but not self-reported physical activity level, was predictive of the decline in cognitive function over a 6-year period. Future research can address this concern by examining the relationship between time-of-day effects and direct measures of cardiovascular fitness such as $VO_{2\,max}$.

An existing explanation of time-of-day effects states that differences in cognitive performance across the day reflect variations in circadian arousal patterns. By this view, there are age-related changes in circadian rhythms that produce the observed interactions between age and time of day (May, Hasher, & Stolzfus, 1993). Although the present study did not test this explanation, it may be the case that both circadian arousal and mental fatigue are important in predicting time of day effects, or that these factors are interrelated. Indeed, some research suggests that physical activity influences circadian arousal patterns (Atkinson, Coldwells, & Reilly, 1993; Harma, Ilmarinen, & Yletyinen, 1982). Additional research is needed to examine this possibility, as well as the possibility that physical activity, like stimulants such as caffeine, may help counter declines in memory performance across the day by virtue of its impact on general arousal or physiological energy (Ryan, Hatfield, & Hostetter, 2002). Because intervening activities such as the ingestion of caffeine were not controlled prior to or between testing sessions in the current study, we are uncertain as to whether such activities impacted individual differences in performance across the day. The need for additional research notwithstanding, the present study is important in suggesting for the first time that engagement in physical activity may moderate time-of-day differences in older adults' executive control performance.

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