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Effects of Moderate Exercise and Circadian Rhythms on Human Memory

Douglas Potter[1] and Denis Keeling[2]
[1]University of Dundee; [2]Keele University

The effects of exercise and circadian rhythms on memory function were explored in a group of shift workers (mean age 32 yrs). A variant of the Auditory-Verbal Learning Test was used to test memory for word lists at 9:30 a.m. and 12:30, 3:30, and 6:30 p.m. in a repeated-measures design. Without exercise there was clear evidence of a circadian rhythm in memory performance, with peak performance occurring at 12:30 and poorest performance at 3:30. A brisk 10-min walk followed by a 15- to 30-min recovery period resulted in significant improvement in memory recall at all time periods except 12:30. The results of the AVLT task suggest an improvement in both working memory and long-term memory performance. Rhythmic changes in serotonin, epinephrine, norepinephrine, and acetylcholine levels all affect cortical arousal and cognitive function. Exercise may have resulted in altered levels of these neurotransmitters, increased glucose, oxygen, or nutrient levels, or from temporary changes in growth hormone or brain-derived neurotropic factor levels resulting in increased synaptogenesis and neurogenesis. The physiological basis of this temporary improvement in memory remains to be determined, but this simple behavioral intervention may have widespread application in improving memory function in all sections of the population including children and the elderly.

Key Words: diurnal, implicit, explicit, working

Previous studies of the effects of short periods of moderate exercise on memory performance have produced mixed result (for reviews see Etnier et al., 1997; Tomporowski, 2003; Tomporowski & Ellis, 1986). The first aim of this study was to determine whether a short period of moderate exercise followed by a 15-min recovery period improved subsequent ability to encode and recall words in a 15-item list. The second aim of the study was to determine whether circadian rhythms in memory performance might interact with the exercise intervention to produce different levels of performance change at different times of the day.

There has been accumulating evidence of enhanced cognitive function after moderate exercise ever since the studies of Bills (1927). Early reviews by Gutin (1973) and Powell (1975) concluded that moderate exercise can improve cognitive performance. Tomporowski and Ellis (1986) suggested that findings in the literature

[1]Dept. of Psychology, University of Dundee, Dundee DD1 4HN Scotland, U.K.; [2]Dept. of Psychology, Keele University, Staffordshire ST5 5BG, U.K.

were more variable than had been previously suggested. However, they did conclude that short periods of moderate intensity exercise can lead to improved cognitive function. Etnier et al. (1997) carried out a meta-analytic review of 134 studies of both acute and chronic exercise interventions of high and low intensity. Overall, they reported a small but significant improvement in cognitive function with an average effect size of 0.25 standard deviations (*SD* = 0.69) across all studies. In the subset of studies using moderate exercise, the average effect size was 0.84 (*SD* = 0.49). More recently, Tomporowski (2003) reviewed the effects of acute bouts of exercise on cognitive performance either during or after exercise. He concluded that, for submaximal aerobic exercise, improvements in cognitive function were generally observed.

Exercise causes short-term increases in cerebral blood flow and may therefore increase the availability of oxygen, glucose, and nutrients. In addition, exercise also causes short-term increases in levels of norepinephrine, serotonin, and endorphins (see Etnier et al., 1997). Exercise also induces longer-term increases in growth hormone concentration and changes in gene expression related to increased brain plasticity and neurogenesis (Cotman & Engesser-Cesar, 2002; Neeper, Gomez-Pinilla, Choi, & Cotman, 1995; van Praag, Christie, Sejnowski, & Gage, 1999). Thus there are several changes in brain neurophysiology that may be the basis for short- and longer-term improvement in cognitive function as a result of both acute and chronic exercise regimens.

While the majority of studies carried out so far have tested perception, attention, reaction time, or decision making, only a few have specifically tested memory performance. A recent study of the effects of a chronic exercise program of moderate exercise demonstrated significant improvements in executive function in the elderly in tasks that involved tests of planning, scheduling, inhibition, and working memory (Kramer et al., 1999). However, in the case of short bouts of moderate exercise, some studies have reported improvements in memory function, but in most cases no significant improvement in memory function was reported (Tomporowski, 2003).

A potentially confounding factor in the study of the effects of exercise on cognitive function is the influence of circadian rhythms on levels of cortical arousal (Carrier & Monk, 2000). Blake (1967) showed a clear post-lunch decrement in performance using measures of reaction time, serial search, and signal detection. This evidence is consistent with the finding that there is an increase in traffic accidents around this time (Lavie, 1991; Mitler, Hajdukovic, Shafor, Hahn, & Kripke, 1987). The "post-lunch dip" may arise from a 12-hr harmonic of the temperature circadian rhythm. "Morning types" show more of a post-lunch dip (Horne, Brass, & Pettit, 1980; Monk & Leng, 1986). Kleitman (1963) provided some of the early evidence for a parallel between circadian rhythm in body temperature and time-of-day effects in performance of simple repetitive tasks.

In a series of studies of the effects of circadian rhythm on memory, Folkard reported that maximum performance in working memory tasks occurs about midday and that immediate memory performance peaks in late morning, but that peaks in working memory performance may depend on working memory load (Folkard, 1975; Folkard, Knauth, & Monk, 1975). In reviewing the early literature on memory performance, Folkard (1983) concluded that the best time of day for optimal performance very much depended on the precise nature of the task.

Current theories are based on an assumed interaction between time since awakening and circadian rhythm (Johnson et al., 1992; Monk & Carrier, 1997, 1998; Wright, Hull, & Czeisler, 2002). Johnson et al. (1992), for example, showed that short-term memory, subjective alertness, and numeric calculation all followed the circadian rhythm of body temperature, with poorest performance at lowest body temperature in the early hours of the morning. If individuals stayed awake for up to 60 hours, then body temperature and cognitive performance continued to follow this cycle, but there was an additional gradual reduction in cognitive performance the longer the person stayed awake.

Similar observations have more recently been reported by Wright et al. (2002) using a forced desynchrony protocol. They found a clear relationship between body temperature, attention, and working memory function, though notably the pattern was far less distinct for a test of long-term memory. Wright et al. also observed a steady decrement in performance as time since awakening increased, though again this pattern was less clear in the long-term memory task.

Our level of awareness and behavioral efficiency is modulated by regional changes in the levels of serotonin, dopamine, norepinephrine, and acetylcholine, and these changes are associated with specific changes in control of behavior as well as the operation of long-term memory processes (Potter, Pickles, Roberts, & Rugg, 2000; Robbins & Everitt, 1995). As both exercise and circadian rhythms affect neurotransmitter and neurohormone levels, it is likely that changes resulting from exercise or circadian rhythms will have some common basis.

In the present study of memory performance during normal waking hours, two effects were predicted on the basis of previous research. The first prediction was that long-term memory performance would vary systematically during the day, that is, performance would peak at midday and become impaired in midafternoon but recover in the evening. The second prediction was that a short period of moderate exercise, followed by a short recovery period prior to testing, might improve long-term memory function. In the present study memory was tested using a variant of the Auditory-Verbal Learning Test. This supraspan word list-learning task provides a measure of immediate word span on the first trial, but on subsequent trials it becomes a test of long-term memory. A possible limitation of this kind of memory task is the use of differing strategies to remember the word lists. To control for this, we employed a within-subjects repeated-measures design.

Methods

Participants

Participating in this study were 31 male shift workers. Average age was 32.65 years (*SD* = 7.48). The participants were recruited from four groups of workers (shift teams) who followed a shift rotation designed to provide 24-hr, 7-days-a-week cover. The shift pattern was 4 days on (8 a.m.–8 p.m.) followed by 4 days off, then 4 nights on (8 p.m.–8 a.m.) followed by 4 days off. All participants were tested when they were on day shifts. This population was chosen as they generally followed the same activity routine during the day and all workers ate the same meals together at the same times. All participants were treated as a single sample since they all took part in all 8 conditions in the experiment.

Table 1 Word Lists Used in Modified Auditory-Verbal Learning Test

List 1	List 2	List 3	List 4	List 5	List 6	List 7	List 8
Drum	Desk	Doll	Dish	Violin	Orange	Book	Window
Curtain	Ranger	Mirror	Jester	Tree	Armchair	Flower	Barn
Bell	Bird	Nail	Hill	Scarf	Toad	Train	Hand
Coffee	Shoe	Sailor	Coat	Ham	Cork	Rug	Weather
School	Stove	Heart	Tool	Suitcase	Bus	Meadow	Home
Parent	Mountain	Desert	Forest	Cousin	Chin	Harp	Hot
Moon	Glasses	Face	Water	Earth	Beach	Salt	Balloon
Garden	Towel	Letter	Ladder	Knife	Soap	Finger	Mouse
Hat	Cloud	Bed	Girl	Stair	Hotel	Apple	Crayon
Farmer	Boat	Machine	Foot	Dog	Donkey	Chimney	Fountain
Nose	Lamb	Milk	Shield	Banana	Spider	Button	Rose
Turkey	Gun	Helmet	Pie	Radio	Bathroom	Log	Stranger
Color	Pencil	Music	Insect	Hunter	Casserole	Key	Stocking
House	Church	Horse	Ball	Bucket	Soldier	Rattle	Teacher
River	Fish	Road	Car	Field	Lock	Gold	Toffee

Materials

A variant of the Rey Auditory-Verbal Learning Test was used (Lezak, 1995). This supraspan list-learning test consists of 15 concrete nouns of equivalent word frequency. Eight lists of 15 words (Table 1) were employed in this study to avoid practice effects. All lists had been previously tested for equivalent memorability (Crawford, Stewart, & Moore, 1989). The order of presentation of lists was counterbalanced across participants (Table 1).

Design

All participants took part in all conditions in this experiment. A repeated-measures general linear model analysis of variance ($2 \times 4 \times 5$) was employed with factors of Exercise/No Exercise, Time of Day (9:30 a.m., 12:30, 3:30, and 6:30 p.m.) and Word Recall Trial (1–5). Based on the experimental prediction that memory performance would peak at 12:30 and be worst at 3:30, planned comparisons were made between memory performance at 9:30 a.m. and 12:30 p.m., and at 9:30 a.m. and 3:30 p.m. in both exercise and no-exercise conditions. Effect sizes (ES) are reported where appropriate.

Procedure

Testing sessions were conducted with groups of 5–11 volunteers in a quiet meeting room during the day shift. In the exercise condition the participants went, as a group, for a brisk self-paced 10-min walk around the perimeter of their workplace. This was followed by a 15- to 30-min recovery period. Volunteers were recruited from four shift teams. The volunteer team members in each group were tested

Table 2 Sequence of Exercise, Time Conditions, and Word Lists Experienced by Each Shift Team Over 2 Consecutive Day Shifts

Test Sequence	Time of Test	Shift Team 1	Shift Team 2	Shift Team 3	Shift Team 4
No exercise	9:30 a.m.	List 1	List 8	List 7	List 6
Exercise	12:30 p.m.	List 4	List 3	List 2	List 1
No exercise	3:30 p.m.	List 5	List 4	List 3	List 2
Exercise	6:30 p.m.	List 8	List 7	List 6	List 5
Exercise	9:30 a.m.	List 2	List 1	List 8	List 3
No exercise	12:30 p.m.	List 3	List 2	List 1	List 8
Exercise	3:30 p.m.	List 6	List 5	List 4	List 7
No exercise	6:30 p.m.	List 7	List 6	List 5	List 4

together during their day shifts. Order of testing is shown in Table 2. On the first day the participants exercised at 12:30 and 6:30 p.m., and on the second day they exercised at 9:30 a.m. and 3:30 p.m. In each testing session, auditory presentation of the 15 words took place at a rate of 1 word every 1,300 ms. After the presentation the participants were asked to write down as many of the words they could remember in any order in one minute. They then immediately hid their responses from view. The list presentation and recall attempt was repeated five times.

Results

The effects of exercise and time of day on the mean number of words recalled across five recall attempts is illustrated in Figure 1. Moderate exercise followed by a 15-min rest period produced a significant overall increase in number of words recalled, $F(1, 30) = 41.69$, $p < 0.001$, ES = 0.582. There was a significant interaction between exercise and time of day, $F(3, 90) = 6.43$, $p = 0.001$, ES = 0.177. This effect can be seen clearly in Figure 1. In the no-exercise condition, mean words recalled varied with time of day. A separate analysis of variance of the no-exercise data confirmed that this variation was significant, $F(3, 90) = 5.81$, $p = 0.001$.

Comparisons between the 9:30 a.m. and 12:30 p.m. recalls revealed a non-significant trend ($p = 0.067$) for improved memory performance, while comparison between the 9:30 a.m. and 3:30 p.m. recalls revealed a significant ($p = 0.028$) reduction in memory performance. In contrast, recall data for the exercise conditions did not differ significantly at different times of day, $F(3, 90) = 1.89$, $p = 0.136$. This was not predicted and therefore post hoc comparisons of memory scores with and without exercise at each time of day were carried out. This revealed a significant effect of exercise at 09:30 a.m. ($p = 0.005$, ES = 0.349), 3:30 p.m. ($p < 0.001$, ES = 0.652), and 6:30 p.m. ($p = 0.005$, ES = 0.234), but no effect at 12:30 p.m.

As expected, participants recalled progressively more words with each attempt to recall words from a particular list, $F(4, 120) = 744.48$, $p < 0.001$. There was a significant interaction between exercise and recall trial, $F(4, 120) = 2.68$, $p = 0.035$. The effect of exercise on the mean number of words recalled on consecu-

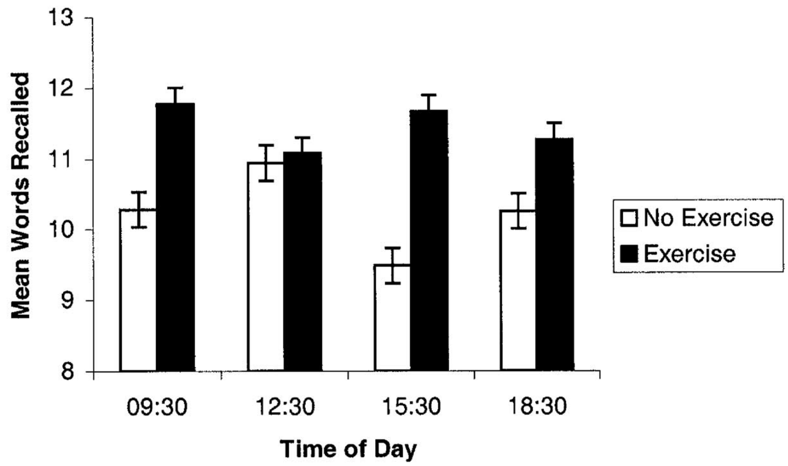

Figure 1 — Interaction between time of day and effect of exercise on memory. Memory performance without exercise follows a circadian rhythm. Exercise improves memory with the exception of performance at 12:30 p.m. Error bars = ± 1 *SE*.

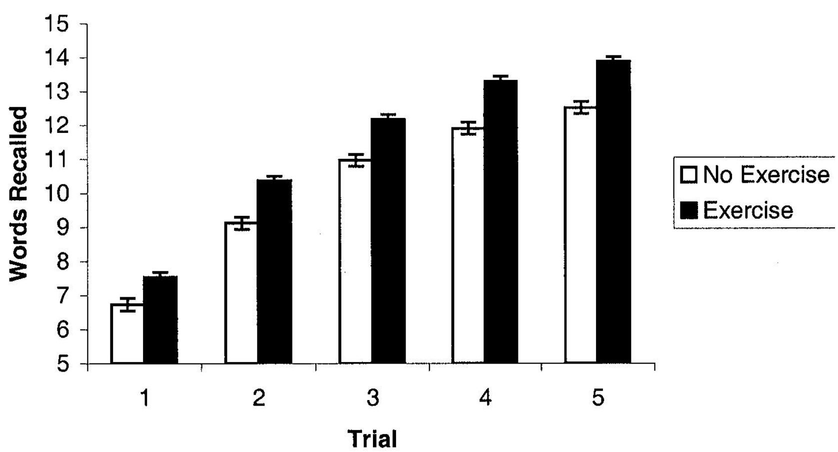

Figure 2 — Interaction between recall trial and effect of exercise on memory. Exercise has more effect on recall in the last four trials than the first trial. Error bars = ± 1 *SE*.

tive attempts at recall of the same word list is illustrated in Figure 2. It is evident that this interaction reflects a smaller effect of exercise on the first attempt to recall a particular word list than on subsequent recall attempts. There was no three-way interaction between exercise, time of day, and number of recall attempts.

Discussion

In the present study our basic predictions were confirmed. The introduction of a brief period of moderate exercise produced an improvement in memory performance. This finding is consistent with the previous literature (Etnier et al., 1997; Gutin, 1973; Powell, 1975; Tomporowski & Ellis, 1986), though it is not consistent with the findings of the majority of studies using memory measures that were reviewed by Tomporowski (2003). There was clear evidence of a circadian rhythm in memory performance with a peak just prior to lunch and a decrement in performance after lunch, and this is consistent with effects described in previous studies (Blake, 1967; Carrier & Monk, 2000; Folkard, 1975; Folkard et al., 1976).

The learning advantage associated with a brief period of moderate exercise was greater on the last four recall trials than in the first trial of the Auditory-Verbal Learning Test. This finding is consistent with the first trial of the task being more dependent on wordspan (working memory) and subsequent trials being more dependent on long-term memory. This suggests that moderate exercise has a positive effect on both short- and long-term memory mechanisms.

Exercise did not result in improved performance at the 12:30 p.m. testing session. This is unlikely to be due to the fact that performance had peaked at this time, as exercise at other times resulted in improvements that exceeded the 12:30 performance level. The distinguishing feature of this testing period is that it came before a meal whereas the other testing periods all came after a meal. This suggests that exercise might interact with nutrient availability to produce enhanced performance.

There are several possible physiological reasons for these short-term improvements in memory function. It is unlikely that changes in blood flow or glucose availability would have influenced cellular oxygen levels or glucose consumption, as these levels are demand-driven by the brain and tightly controlled within the brain. It is possible that exercise leads to increased nutrient availability, and it is certainly the case that neurotransmitter precursor levels will influence the efficiency of neurotransmission and cellular second-messenger systems. The observation that exercise improved performance at all times following a meal but not at 12:30 may be consistent with this suggestion. Regular bouts of exercise have been shown to increase growth hormone concentrations, increase neurogenesis in the hippocampus, improve memory performance in animals (van Praag et al., 1999) and also bring about improvements in executive function in humans (Kramer et al., 1999).

There was no evidence in the present study that the improvements observed after short bouts of moderate exercise were carried over from one testing period to the next, although no test of executive function was carried out. This does not rule out the possibility of cumulative effects when regular bouts of moderate exercise are taken over extended periods (Cotman & Engesser-Cesar, 2002; Kramer et al., 1999), though such effects may only be seen when the intensity of exercise is greater than that used in the present study.

There are several possible limitations associated with this study. A convenience sample was used rather than a random sample. However, this did allow some control over the timing of food consumption, as well as what was eaten, as the whole shift ate the same meals together. No explicit measures of level of exercise were taken, but all participants were encouraged to engage in aerobic exercise and had ample time to recover before taking the memory tests. It is possible that there were carryover effects from one exercise condition to the no-exercise condition test that occurred a few hours later, but there was little evidence of this in the present study. It is possible that participants expected to perform the task better after exercise and that this was the basis for the improvements we observed. Yet this seems unlikely, as no improvement occurred at 12:30.

In conclusion, the findings of this study suggest that appropriately timed, short and moderate periods of exercise can bring about short-term improvements in memory function and significantly reduce the effects of daytime circadian rhythms on memory performance.

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