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Effects of Illumination on Human Nocturnal Serum Melatonin Levels and Performance

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DOLLINS, A. B., H. J. LYNCH, R. J. WURTMAN, M. H. DENG AND H. R. LIEBERMAN. *Effects of illumination on human nocturnal serum melatonin levels and performance.* PHYSIOL BEHAV **53**(1) 153–160, 1993.—In humans, exposure to bright light at night suppresses the normal nocturnal elevation in circulating melatonin. Oral administration of pharmacological doses of melatonin during the day, when melatonin levels are normally minimal, induces fatigue. To examine the relationship between illumination, human pineal function, and behavior, we monitored the overnight serum melatonin profiles and behavioral performance of 24 healthy male subjects. On each of three separate occasions subjects participated in 13.5 h (1630–0800 h) testing sessions. Each subject was assigned to an individually illuminated workstation that was maintained throughout the night at an illumination level of approximately 300, 1500, or 3000 lux. Melatonin levels were significantly diminished by light treatment, $F(2, 36) = 12.77$, $p < 0.001$, in a dose-dependent manner. Performance on vigilance, reaction time, and other tasks deteriorated throughout the night, consistent with known circadian variations in these parameters, but independent of ambient light intensity and circulating melatonin levels.

Human Melatonin Mood Performance Reaction time Vigilance Sleep deprivation Fatigue Circadian rhythm

ENVIRONMENTAL illumination has been shown to be a prime factor in the establishment and maintenance of the rhythmic patterns of physical activity, core body temperature, and time of ovulation (9,11,12). These rhythms are correlated with release of the hormone, melatonin, which is secreted by the human pineal gland throughout the night, but not during the day (1,27,35). Environmental light is known to exert two effects on melatonin secretion:

1. entrainment of its endogenously driven rhythmic pattern with elevated levels occurring at night (27), and
2. acute suppression of its nocturnal elevation in response to light of sufficient intensity [i.e., 1500–2500 lux; (21)].

Melatonin has been shown, in a number of mammalian species, to serve as a Zeitgeber (or time giver) which entrains circadian rhythms. Rhythmic changes in serum melatonin levels may serve to couple various biological rhythms to the day/night light cycle (2,30,40). It might also be anticipated that changes in environmental circumstances which alter the normal light/dark cycle (e.g., transmeridian jet travel; shift work; space flight) would also alter the plasma melatonin rhythm, thereby altering the sleep/wake cycle and compromising performance.

Nocturnal bright light pulses have been used to explore the phase–response curve for entrainment of rhythmic melatonin secretion (21) and sleep/wake behavior (11). Such light pulses have also been used to treat a variety of maladies related to circadian organization (12,31). The fact that therapeutic efficacy typically requires repeated exposure to daily light pulses suggests that the light's action on the entrainment of circadian rhythms underlies its therapeutic effects. The significance of alterations in absolute levels of circulating melatonin has not been adequately examined.

The administration of melatonin during the day causes subjective sleepiness and induces sleep (23,37). This is an acute effect, not dependent on repeated doses, and may represent a direct effect of melatonin that does not involve alterations in the circadian pattern of its secretion. These observations have led us to postulate that the normal increase in nocturnal serum melatonin levels may have a direct influence on sleepiness and fatigue. In an attempt to isolate the effects of changes in absolute levels of circulating melatonin from the effects of its rhythmic occurrence, we sought to manipulate nocturnal melatonin levels experimentally and to assess resulting changes in mood, sleepiness, and performance. One of the fundamental tests of a pharmacologic agent on organic systems is the dose response. That is, if a compound has an influence on an organism, varying doses of the compound should cause corresponding variations in the response (assuming that the response plateau is not ex-

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ceeded). Lewy's observation (21) that acute exposure to a light intensity of 2500 lux totally suppresses nocturnal melatonin secretion, a lower dose of light (1500 lux) partially suppresses, and a still lower dose (500 lux) is without effect, suggests an approach to testing the relationship between endogenous melatonin levels and fatigue. If serum melatonin level does influence fatigue, as measured by mood and behavioral performance, then manipulating nocturnal serum melatonin levels by varying ambient light intensity should cause corresponding variations in fatigue.

The present study was conducted to test the hypothesis that performance changes observed under varying nocturnal light intensities would differ, and that these differences would parallel the light-induced changes in serum melatonin levels. A nocturnal working environment was simulated to test the practical relevance of ambient light intensity on performance.

METHOD

Twenty-four healthy male subjects (mean age = 23 ± 1.16 SEM, range: 19–39 years) participated in this study. Prior to admission to the study, each subject signed an informed consent form, had a physical examination to ensure that he was in good health, and completed two 1.5-h training sessions to familiarize him with testing procedures and the performance test battery. Subjects were also screened for depressive symptoms using the Hamilton Depression Rating Scale (18) with a special addendum for seasonal affective disorder (32). This protocol was approved by the MIT Clinical Research Center Advisory Board and Committee on the Use of Humans as Experimental Subjects. All subjects were paid for their participation in the experiment.

This study was implemented using a pseudoplacebo-controlled, repeated-measures, within-subjects, 3 × 3 Latin square design. Because the relative light intensity of a broad spectrum light may be discernible to subjects, a true placebo was not possible. Thus, a pseudoplacebo-controlled condition was devised by manipulating subjects' expectations. When subjects were initially briefed as to the purpose of the study, they were told that the study was designed to examine the effects of visual patterns and intensities of light on performance during sleep deprivation. In order to conceal the experimentally relevant stimulus dimension from the subjects, diffusing screens covering each light fixture were marked with horizontal, vertical, or diagonal lines (1 cm wide, separated by 2 to 2.5 cm). These lines had no effect on the individually adjusted illumination level of the lights. Because variations in spatial patterns are more perceptually salient than changes in illumination, subjects believed the pattern was the independent variable being tested. The line patterns were varied to counterbalance illumination level and test day. Throughout the study, the subjects questioned the investigators concerning the anticipated effects of the lines on the lights. They were asked to defer their questions until the study was completed.

The subjects participated in three 13.5-h (1630–0800 h) testing sessions, separated by at least 10 days, at the MIT Clinical Research Center. Upon admission, each subject was assigned to an individually illuminated computer workstation that was maintained throughout the night at approximately 300, 1500, or 3000 lux. The amount of luminous flux that each subject experienced was measured using a Tektronix J16 digital photometer with a J6511 illuminance probe. Frequent measurements were made to ensure illumination at the appropriate level. These measurements were made by holding the illuminance probe normal to the subject's line of vision at eye level. The light fixtures (Spectrum Industries, East Woodstock, CT) contained Philips FB40/CW/3 cool white fluorescent tubes. The light intensity emitted by each fixture was adjusted by varying the number of fluorescent tubes activated and by adjusting a rheostat that did not affect the spectral composition of the light.

On admission, a catheter with a heparin lock was established in a forearm vein for blood sample withdrawal. Blood samples were taken from each volunteer at 1900, 2100, 2300, and at hourly intervals thereafter until 0800 h. Serum was separated by centrifugation and stored at −20°C until assayed for melatonin concentration. Oral temperature, blood pressure, heart rate, and sleepiness were assessed hourly.

Throughout the night subjects were required to sit at their computer workstation, with eyes open, and to complete interactive computer tasks. They were not required to look directly at the lights and were allowed to vary their posture for comfort so long as this did not interfere with task performance. Two 20-min snack breaks (at 2400 and at 0400 h) and hourly toilet breaks (<5 min) were allowed. Subjects did not encounter light intensities greater than 300 lux during these breaks. The task order and times were held constant across test nights (see Table 1 for detailed schedule).

Melatonin Assay

Melatonin concentrations were measured in duplicate 1 ml samples of serum by radioimmunoassay (RIA) using CIDtech Ultraspecific Melatonin Antiserum (CID-tech Research Inc., Hamilton, Ontario) (7). The assay procedure is described in detail elsewhere (9). Briefly, 1 ml samples of serum were extracted into 5 ml of chloroform, the organic extracts were evaporated under a stream of nitrogen, and resulting residues were dissolved in phosphate buffer. Samples of the buffered extracts of serum were then analyzed by RIA. The sensitivity of the assay (defined as 3× the standard deviation of maximum binding) in the present study was 8 pg/ml.

Performance Test Battery

We selected performance tasks and mood inventories that previous studies have shown to be sensitive to the effects of melatonin, various hypnotics, other pharmacologic agents, and sleep loss (5,22,23,25,26). All performance tasks were administered on AT-class microcomputers equipped with hard drives and color VGA monitors. The computers were modified to port the speaker output to an audio amplifier (Realistic model: SA-150) equipped with stereo headphones (Realistic model: NOVA'40). To reduce the possibility of experimenter-induced bias, all tasks and instructions were automated by using a sequence of menus.

Mood and Sleepiness Measures

The Profile of Mood States [POMS; (28)] and Stanford Sleepiness Scale [SSS; (19)] were adapted to computer administration so the subjects could indicate choices by moving a cursor instead of using a pencil and paper. The SSS is a self-rated 7-point scale designed to quantify the progressive stages of the sleep–alertness continuum. The POMS is a self-report scale that consists of 65 adjectives, each of which is rated on a 5-point scale. Factor analysis yields the following scales: Tension–Anxiety, Depression–Dejection, Anger–Hostility, Vigor–Activity, Fatigue–Inertia, and Confusion–Bewilderment.

Dual Task

In this test, the subjects must simultaneously perform two tasks: a modified version of the Bakan Vigilance task (20) and the "estimation of two classes of events in a signal stream" (PROP) test (33). The Bakan Vigilance task presents, on the CRT screen, a sequence of three-digit numbers every 1.5 s for

TABLE 1

TIME LINE OF TESTING

1830	Subject Arrives
	Insert venous catheter
	Blood sample #1
1900	Begin baseline testing
	Profile of mood states
	Stanford Sleepiness Scale
	Simple Auditory RT
	Four-Choice RT
2000	Initiate Light Treatment
	Dual Task
	Digit symbol substitution
	Stanford Sleepiness Scale
2100	Blood sample #2
	Four-Choice RT
	Profile of mood states
	Stanford Sleepiness Scale
	Simple Auditory RT
2200	Dual task
	Digit symbol substitution
	Stanford Sleepiness Scale
2300	Blood sample #3
	Wilkinson Auditory Vigilance
	Stanford Sleepiness Scale
	Profile of mood states
2400	Blood sample #4
	Snack (20 min)
	Simple Auditory RT
	Stanford Sleepiness Scale
	Four-Choice RT
0100	Blood sample #5
	Digit symbol substitution
	Dual task
	Profile of mood states
	Stanford Sleepiness Scale
0200	Blood sample #6
	Wilkinson Auditory Vigilance
	Stanford Sleepiness Scale
0300	Blood sample #7
	Simple Auditory RT
	Dual task
	Four-Choice RT
	Profile of mood states
	Stanford Sleepiness Scale
0400	Blood sample #8
	Snack (20 min)
	Digit symbol substitution
	Stanford Sleepiness Scale
0500	Blood sample #9
	Wilkinson Auditory Vigilance
	Profile of mood states
	Stanford Sleepiness Scale
0600	Blood sample #10
	Simple Auditory RT
	Dual task
	Four-Choice RT
	Stanford Sleepiness Scale
0700	Blood sample #11
	Digit symbol substitution
	Profile of mood states
	Stanford Sleepiness Scale
0800	Blood sample #12
	Remove catheter
	Release subject

Task Name	Approximate Duration (min)	Number of Repetitions
Stanford Sleepiness Scale	1	13
Profile of mood states	5	7
Dual task	30	5
Wilkinson Auditory Vigilance Task	60	3
Four-Choice Reaction Time	5	5
Simple Auditory Reaction Time	5	5
Digit symbol substitution task	3	5

30 min. Usually, each successive number differs from the previous number by one digit. Occasionally, however, all three digits are repeated. The subjects' task is to detect the occurrence of these repeated sequences and to respond by pressing a key on the computer keyboard. Six blocks of 200 trials are presented during each test. Twenty-two three-digit number sequences are repeated during each block of trials. A single digit or letter is presented to the right of and simultaneously with the three digit number of the Bakan series. At the end of each block of trials, the subjects are required to estimate the proportion of letters (versus numbers) occurring in the last block of PROP stimuli. Subjects respond by moving a cursor on the computer screen to select a choice. The actual proportion varies randomly between 0.2 and 0.8, in increments of 0.1, for each block of 200 stimuli. The number of true positive and true negative responses as well as the proportions estimated and actually presented throughout each block of trials are retained in a computer file.

Wilkinson Auditory Vigilance Task

The Wilkinson Auditory Vigilance task is a computer adaptation of the task described by R. T. Wilkinson (38), with two modifications. Throughout the task, subjects must listen to a series of 500 Hz 70 dB (SPL) tones, presented at a rate of one tone every 2 s. The tones are of two lengths, long (500 ms) and short (variable ms). The subjects' task is to press a key when the short tone is heard. This version of the task is similar to Wilkinson's original version in that the tones were presented for 1 h

(1,800 tones) and 40 (2.2%) of the tones were short. Because the subjects were tested in a quiet room using headphones, no masking noise was used. In addition, the difficulty of short tone detection was evaluated and adjusted individually for each subject during training so each subject detected a short tone approximately 50% of the time (26). The length of the short tones ranged from 350 to 450 ms (mean and mode = 400 ms). Investigators monitored the subjects throughout administration of this task to ensure that they did not sleep or close their eyes. The number of true positive, true negative, and premature responses are retained in a data file.

Four-Choice Reaction Time (RT)

This test resembles the Wilkinson four-choice RT task and is a measure of visual vigilance (39). Subjects are presented with a series of visual stimuli at one of four adjacent spatial locations on a CRT screen. The subject must correctly indicate, by striking one of four corresponding adjacent keys on a microcomputer keyboard, the correct location of each stimulus. Four hundred trials were administered. The mean response latency and variances, as well as the number of true positive and true negative responses, are registered and retained. The number of premature responses (responses made during the 400 ms pause between stimuli) and time-out errors (failure to respond within 2000 ms of stimulus presentation) are also retained. Five warm-up stimuli and the response errors are not included in the total number of trials presented.

Simple Auditory Reaction Time

In this task, the subject responds, as rapidly as possible, to the onset of an auditory signal. The test trials are presented in rapid succession following five warm-up trials. A 300 ms 360 Hz tone warns the subject that a trial is about to begin. After a random delay of 100 to 900 ms, a 1000 Hz tone signals the subject to respond. Subjects are instructed to respond as quickly as possible after the onset of the 1000 Hz tone. The subjects' response latency appears on the computer screen for 300 ms between each trial. A warning message accompanied by an oscillating error tone occurs if the subject responds prematurely (prior to or within 50 ms of the onset of the stimulus tone) or fails to respond within 2000 ms. The subject must acknowledge premature and time-out errors by pressing the Enter key. A 1000 ms delay occurs between error acknowledgement and the next trial to allow time for the subject to reposition his hand. The response latency and variance, as well as the number of premature and time-out errors are retained in a data file. The task continued until 200 reaction times were recorded.

Digit Symbol Substitution Task

This task is a microcomputer implementation of the Digit-Symbol Substitution task of the WAIS-R Intelligence scale (14). It consists of a display of nine symbols in a row of boxes at the top of the screen, a display of nine corresponding numbers (i.e., 1 through 9) in a row of boxes below the symbols, a cue box and an answer box. The subject must use the numerical keypad to enter the number corresponding to the symbol that appears in the cue box, using the symbols and numbers at the top of the screen as a guide. The task is timed and the subject is instructed to enter as many answers as possible within 90 s. The first five symbols presented are considered practice trials and are not counted in the final output or in the timed portion of the test. The symbol associated with a given digit does not change within a 90-s set of trials but does change (randomly) each time the task is activated to prevent subjects from memorizing response keys. No response feedback is given to the subject, but a warning tone occurs if the subject presses a nonnumerical key on the keyboard.

Data Analysis

A repeated measures, within-subjects, 3 × 3 Latin square design analysis was used for all measures except serum melatonin levels. Repeated measures factorial analysis was used for serum melatonin levels because complete data was available for only 21 subjects. Group means were substituted for the performance data of one subject, who completed only one test session, in order to maintain the integrity of the study design for analysis purposes.

RESULTS

Serum Melatonin Levels

The mean serum melatonin levels of 21 of the subjects are illustrated in Fig. 1. The mean (±SEM) areas under the time-melatonin-concentration curve (AUC) between 1900 and 0800 h were 398.8 (±197.2), 288.5 (±121.4), and 247.6 (±125.2) under the 300, 1,500, and 3,000 lux conditions, respectively. Repeated measures factorial analyses of these values shows a significant light treatment effect, $F(2, 36) = 12.77$, $p < 0.001$. Contrasts indicated that the serum melatonin secretion under medium and high intensity lights was significantly lower than that under low intensity light ($p < 0.002$), and that serum melatonin secretion under high intensity light was significantly lower than that under medium intensity light ($p < 0.006$). A significant intraclass correlation (41), $F(2), 20, 42 = 3.741$, $p < 0.001$, $r_1 = 0.477$, was found among the subject serum melatonin AUC measures, indicating reproducibility of melatonin response to light within subjects. The light treatment order and light treatment by light intensity effects were not significant.

Light Effects

There were no significant differences in performance associated with the three light treatment conditions. The Four-Choice RT correct response reaction time variance and number of time-out errors changed significantly with light treatment, $F(2, 42) = 4.162$, $p < 0.05$, and $F(2, 42) = 5.795$, $p < 0.01$, respectively. The mean correct response variances were 12895.7, 10471.3,

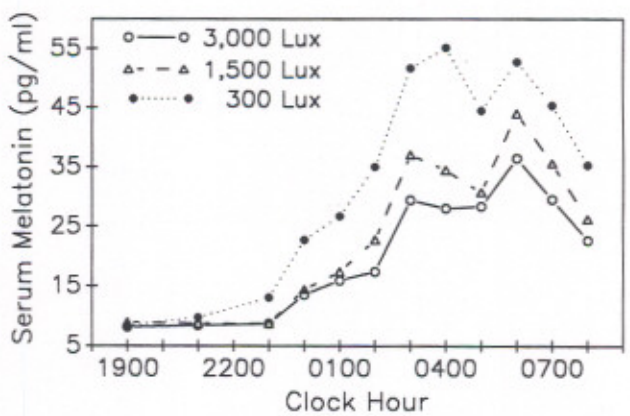

FIG. 1. Mean serum melatonin profiles of 21 subjects exposed to different light intensities and sampled at intervals throughout the night.

and 12609.7, and the number of time-out errors were 0.84, 0.37, and 0.60 for the 300, 1500, and 3,000 lux conditions, respectively. The greatest performance improvement in both measures was observed under the medium (1500 lux) light condition with the low- and high-light conditions being approximately equal. Initial analysis indicated a significant light treatment effect on the POMS Depression/Dejection scale. Examination of the data indicated, however, that the effect could be due to a baseline offset under the low light condition. Analysis of the data after removal of this offset (by subtracting the 1900 h value from subsequent scores) indicated that there was no significant light treatment effect on the POMS Depression/Dejection scale. There were no other significant light effects or light by time interactions on the performance or physiological measures. Results of a second analysis of the performance data from a subgroup of subjects with 3000/300 lux condition serum melatonin ratios of 0.6 or greater did not differ from those of the complete group.

Fatigue Effects

Overnight decreases in oral temperature (Δ, −1.29°F; Fig. 2) and heart rate (Δ, −8.66 bpm) were significant ($p < 0.01$). As illustrated in Fig. 3, mean responses to the SSS increased significantly from 2.28 at 2000 h to 5.29 at 0700 h, $F(2, 42) = 54.76$, $p < 0.001$, indicating an increase in sleepiness throughout the testing period. Similarly, all of the POMS scales showed significant (maximum $p < 0.02$) changes with time that are consistent with effects of circadian variation. Mean scores on the Tension–Anxiety, Depression–Dejection, Anger–Hostility, Fatigue–Inertia, and Confusion–Bewilderment scales increased by 1.43, 1.75, 2.39, 8.41, and 3.54 points, respectively, during the night. Mean responses on the POMS Vigor–Activity scale decreased from 16.99 at 1900 h to 8.49 at 0700 h. The average number of correctly identified Dual task target stimuli decreased significantly from 100.42 at 2200 h to 82.15 at 0600 h, $F(4, 84) = 20.671$, $p < 0.001$. Corresponding significant increases were observed, over time, in the number of stimuli incorrectly identified as targets, $F(4, 84) = 4.556$, $p < 0.002$, and estimates of the proportion of numbers versus letters presented, $F(4, 84) = 17.141$, $p < 0.001$. The average number of stimuli incorrectly identified as targets increased from 10.99 to 15.80, and the mean error in proportion estimates increased from 0.45 to 0.67.

Wilkinson Auditory Vigilance task responses reflected similar circadian effects. The mean number of correctly identified target stimuli decreased significantly, $F(2, 42) = 35.912$, $p < 0.001$, by 3.31 targets, and the mean number of premature responses significantly increased by 1.57 responses, $F(2, 42) = 4.266$, $p < 0.020$, as testing progressed throughout the night. The Simple Auditory RT mean response latency and number of premature responses increased significantly by 5.43 ms, $F(4, 84) = 7.109$, $p < 0.01$, and 2.84 responses, $F(4, 84) = 3.925$, $p < 0.006$, respectively, between the 2400 and 0800 h tests. Increases (maximum $p < 0.001$) were also observed in average latency (Δ +35.91 ms) and variance (Δ +87273.3) of Four-Choice RT task correct responses, as well as in the number of premature responses (Δ +1.76) and time-out errors (Δ +0.96), as testing progressed between 2100 and 0600 h. The mean number of correct responses on the Four-Choice RT task decreased from 375.65 to 361.53, $F(4, 84) = 9.774$, $p < 0.001$, during the same period. Some of the overnight performance decrements observed in the Four-Choice RT, Dual, and Wilkinson Auditory Vigilance tasks are illustrated in Fig. 4.

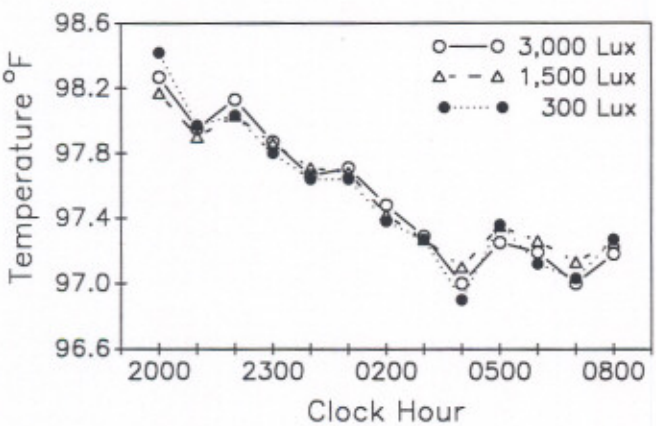

FIG. 2. Mean oral temperatures measured at intervals throughout the night during exposure to different ambient light intensities ($n = 24$).

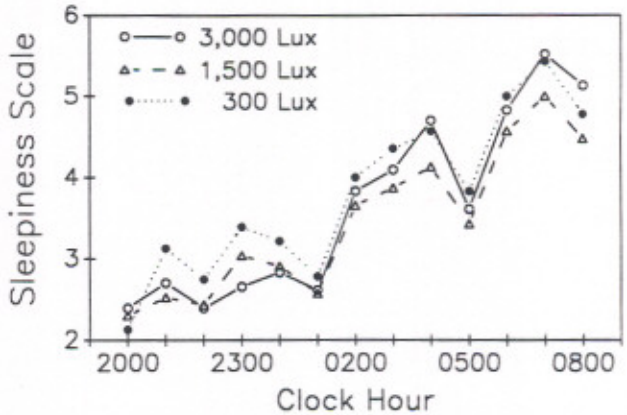

FIG. 3. Mean Stanford Sleepiness Scale responses assessed hourly in 24 subjects exposed to different ambient light intensities throughout the study period.

General performance decrements were observed on successive test days irrespective of light treatment condition. The number of Dual task correct responses decreased from 96.32 to 88.25, $F(2, 42) = 4.647$, $p < 0.015$, between test days 1 and 3. There were significant decreases in the mean number of correct (Δ −3.28), incorrect (Δ −59.57), and premature (Δ −2.57) Wilkinson Auditory Vigilance task responses on successive test days (maximum $p < 0.05$). Simple Auditory RT mean response latency also decreased from 177.04 to 167.67 ms over successive test days, $F(2, 42) = 19.179$, $p < 0.01$. Similar decreases were observed in the Four-Choice RT number (Δ −4.54), latency (Δ −12.46 ms), and variance (Δ −2028.01) of correct responses (maximum $p < 0.03$).

DISCUSSION

These data show that overnight exposure to ambient light intensities of 1,500 lux or 3,000 lux causes a dose-dependent reduction of nocturnal melatonin secretion compared to that observed at 300 lux (Fig. 1). However, parallel changes in the physiological and performance indices measured are not observed, even though some of the latter deteriorate significantly as the number of hours of nocturnal wakefulness increases. The changes observed in oral temperature (Fig. 2), the SSS (Fig. 3), the POMS Depression/Dejection and other mood scales, simple and choice RT and vigilance, are all consistent with previously

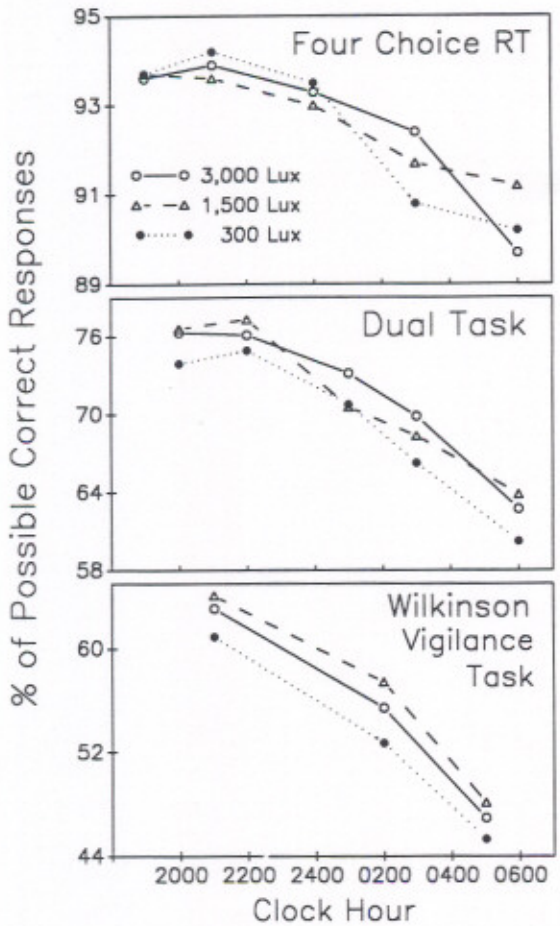

FIG. 4. Overnight performance decrement in the Four-Choice RT task, Dual task, and Wilkinson Auditory Vigilance task. The values plotted are average percent of the potential correct responses for each task under different light intensities (n = 24).

reported circadian variations in these parameters (16,17,19). Results of the current study differ from those reported in similar studies (10,15) which attribute performance changes to alteration in ambient light intensity. Among the factors which might account for this inconsistency are differences in the:

1. extent of melatonin suppression;
2. experimental controls; and
3. performance test batteries.

An interesting, though serendipitous, finding of the present study is the abrupt increase in oral temperature and decrease in circulating melatonin that accompanies a reduction in sleepiness following the 0400 h snack break (Figs. 1, 2, and 3). Decreased POMS Tension/Anxiety scale response levels were also observed between the 0300 and 0500 h test periods. The snack consisted of cheese, crackers, and noncaffeinated beverages. None of these substances are known, nor are they expected, to influence mood or melatonin secretion. It is likely that the observed mood and physiological changes were responses to the break in the testing routine rather than a direct effect of food consumption. It is interesting that the novelty of such a change in stimulation caused concurrent alterations in both mood and physiological measures. This phenomenon merits further investigation.

There were marked interindividual differences in nocturnal melatonin secretion. Total nocturnal melatonin secretion for the 21 men studied ranged from 153 to 1018 pg/ml/13 h (AUC) during exposure to the 300 lux condition. Total suppression of nocturnal melatonin secretion was approached in only a few subjects, even with exposure to 3,000 lux, the greatest light intensity studied. There was, however, a high level of intraindividual consistency in characteristic melatonin production, as evidenced by a significant intraclass correlation among individual serum melatonin AUC measures. This correlation occurred in spite of the systematic variation in total melatonin secretion induced by the light treatments.

The nocturnal melatonin levels observed under the 300 lux condition are approximately equal to those observed by Brainard et al. (6) in a similar study using a light intensity of 100 lux. Others have conducted studies which reported performance enhancement, although they employed the same or lower bright light treatments (10,15) and periods of relief from such exposure (4,10). These results suggest that differences in performance may not be attributable to either the intensity or constancy of light treatment. Suppression of nocturnal serum melatonin levels beyond those achieved in the present study may be necessary before behavioral effects are evident. Brainard et al. (6) found near total suppression of nocturnal melatonin secretion with overnight exposure to a light intensity of 3000 lux, an observation not confirmed in the current study. These inconsistencies indicate that a better measure of the light intensity actually impinging on the retina, or another property of the photic environment, is necessary to permit direct comparisons among studies of this nature (34). Precise quantification of the relationship between ambient light intensity, retinal illumination, and melatonin secretion would greatly facilitate our ability to assess the effects of light on human performance.

It is possible that sample size, experimenter and/or demand characteristic bias contributed to the differences between the findings of the current study and those of other investigators (10,15). For example, Campbell et al. cautioned that their performance results were based on a small subset of their subject population (n = 12; 4 in the 1000 lux condition versus 8 from the pooled 10 and 100 lux conditions) in which each subject was tested only once. In addition, subjects may have been tested by investigators who were aware of the expected results, in groups in which all of the subjects receive the same treatment simultaneously. It is, of course, very difficult to control for unintentional experimenter and demand characteristic bias under such a regimen. The influence of demand characteristics on reading performance and self-reported arousal was demonstrated by Veitch, Gifford, and Hine (36) who found differences in these measures resulting from positive or negative information given subjects regarding full-spectrum lighting effects.

Several controls were incorporated into the design of the present study to reduce the possibility of experimental bias. Lines on the diffusing screen of each light fixture served to confuse the subjects' perception of the independent variable being tested. Simultaneous testing of subjects under more than one condition and the use of menus to automate the testing sequence reduced the possible effect of demand characteristics. Repeated testing of the same, relatively large, group of subjects under all conditions reduced the between-group variance.

Some tasks in the current test battery differed from those used by other investigators (4,10,15). The test battery used in the current study centered primarily around mood, reaction time, and vigilance tasks. These tasks have all been shown to be sensitive to the effects of exogenous melatonin (13,23). All of these tasks proved sensitive to circadian variation but not to significant alterations in nocturnal melatonin levels. Neither French et al.

nor Campbell et al. reported statistically significant changes attributable to circadian variation in performance. The fatigue and circadian variations in performance observed in the present study may have been so large that they masked and/or obscured temperature and performance changes attributable to alterations in serum melatonin concentrations. The relative contribution of sleep loss, work load, and circadian variations in performance parameters (which may involve circulating melatonin levels) is a basic problem which remains to be resolved (3).

In summary, the results of this study indicate that the ambient light intensities tested did differentially suppress nocturnal serum melatonin secretion but did not cause corresponding differential alterations in the physiological measures or performance tasks examined. Changes in the behavioral parameters indicate a significant decrement in performance over time, consistent with previously reported circadian variation (16,17,19). Although our findings differed from those reported in similar studies (4,10,15), there are factors which bear further examination that could account for these conflicts such as differences in experimental controls, light intensities, extent of melatonin suppression, specific performance tests, and subject populations. This approach to testing the effects of diminished endogenous melatonin is necessarily limited to nocturnal investigation. The effects of sleep deprivation are, thus, inescapable concomitants of melatonin suppression. These effects may have masked any behavioral effects caused by suppression of nocturnal pineal melatonin secretion.

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