THE EFFECTS OF EVENING BRIGHT-LIGHT ON HUMAN BODY TEMPERATURE AND SLEEP ARCHITECTURE

by

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ABSTRACT

A number of influential theories of sleep function argue for a close relationship between body temperature and sleep architecture. The energy conservation theory and thermoregulatory theories of sleep, including the central nervous system restoration and protection theories, each predict increased Slow Wave Sleep (SWS) following elevations in body temperature at sleep onset and during sleep. It has recently become apparent that appropriately timed evening bright-light (BL) (>2500 lux) may suppress melatonin, elevate core temperature, and produce delays of the human Core Temperature Rhythm (CTR). While these effects are being investigated for their potential within industry and to treat various affective and sleep related disorders, the effects of evening BL on sleep are unclear as the literature is small and differing results are reported. The effects of BL on temperature suggest that enhanced SWS might follow evening BL, as increased SWS has been empirically associated with elevations in temperature at sleep onset and, to a lesser extent, with a phase-delay of the CTR. However, the suppression of melatonin associated with evening BL suggests sleep might be disrupted, as melatonin has been proposed to be a hypnotic agent.

In the present thesis three experiments are reported which were designed to investigate the effects of evening BL on rectal temperature and sleep. In the first experiment 11 male subjects were twice exposed to BL or Dim-Light (DL) (normal room illumination) for 2hrs prior to habitual bedtime for two consecutive nights in a crossover design. Rectal temperature was significantly elevated during the first and second hours following BL, and significantly more Stage 3 sleep and SWS occurred with a trend for increased SWS in the fourth sleep cycle.

The second experiment was designed to assess the immediate effects of evening BL on core temperature and sleep, independent from potential CTR phase-shifting effects produced after multiple exposures to evening BL on

consecutive evenings. 11 male subjects were run in two conditions. In the BL condition Ss were exposed to BL for three consecutive evenings and to DL on the fourth. In the dim-light condition Ss were exposed to DL on all four evenings. It was anticipated that three consecutive exposures to evening BL would phase-delay the CTR such that the effects of a temperature rhythm delay on sleep could be assessed independent of BL itself on night 4. On night 1 no significant elevation in rectal temperature was found but SWS was increased in the fourth sleep cycle. On night 3 rectal temperature was significantly elevated during the first two hours following BL, and SWS and Slow Wave Activity (SWA) (.25-3 Hz EEG activity) were significantly increased across the night, most noticeably in the third sleep cycle. No differences in the position of the CTR were evident on night 4, but temperature in the BL condition was significantly lower than in the DL condition during the first and fifth hours following light exposure. In addition, sleep onset latency (SOL) and amounts of Wake were increased in the BL condition on this night. The results indicated that BL administered until habitual bedtime over three consecutive nights may produce immediate effects on core temperature without necessarily delaying the CTR. The SWS enhancing effects of evening BL were found when, and only when, core temperature was significantly elevated around the time of sleep onset. This experiment also suggested that these effects are found more robustly following more than one exposure to BL.

The third experiment was designed to test this hypothesis. A between-subjects design was utilised in which three groups of 12 male subjects were run in three conditions. In the Dim-Dim (DD) condition subjects were exposed to DL for two consecutive nights. In the Dim-Bright (DB) condition subjects were exposed to DL on night 1 and BL on night 2 over consecutive nights. In the Bright-Bright (BB) condition subjects were exposed to BL on both nights. Rectal temperature during the first hour following light treatment was significantly elevated in the BB condition and non-significantly elevated in the DB condition compared to the DD condition. SWA and Total EEG Power (TP) (0.25 Hz to 50 Hz EEG activity) were enhanced in both the DB and BB

conditions. In addition, significantly more SWS was found to occur in the fourth sleep cycle in the DB and BB conditions compared with the DD condition. Thus, evening BL elevated rectal temperature and enhanced SWS upon a single exposure, but these effects were enhanced by exposure to the light on the previous night.

Taken together these experiments indicate that evening bright light elevates rectal temperature and SWS/SWA increases during subsequent sleep, particularly late in the night. These results are consistent with other experimental paradigms in which temperature is raised (e.g. exercise and passive heating) and SWS is observed to increase. Interpreted this way the results add to the body of evidence that suggests SWS and thermoregulation are intimately linked. Another possible interpretation is that a rebound in melatonin following early suppression by bright-light produced increased SWS later the same night. It is also possible that both thermal and melatonin rebound effects occurred following evening bright-light; the thermal effects maintained SWS levels under conditions of melatonin suppression early in the sleep period while melatonin rebound later in the sleep period resulted in the most prominent increases in SWS. Further research might examine this possibility by monitoring plasma melatonin levels, temperature and SWS continuously following evening bright-light. The major finding of this thesis is that bright-light administered until habitual bedtime produces immediate elevations in temperature and increased SWS/SWA, especially late in the night.

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CHAPTER ONE

INTRODUCTION

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INTRODUCTION

This thesis is concerned with the effects on sleep of changes in body temperature produced by evening bright-light. Evening bright-light has been found to produce both "immediate" and "delayed" effects on temperature and, in turn, temperature regulation and alterations in temperature around sleep onset have been found to affect sleep. This thesis seeks to investigate these temperature effects on sleep with a view to commenting on the role of sleep, and especially Slow Wave Sleep (SWS)[1], in thermoregulation.

The thesis has both practical and theoretical importance. With regard to the former, bright-light is being increasingly investigated for application within industry and to treat various chronobiological disorders. Nevertheless, the effects of evening bright-light on sleep remain unclear as differing results have been reported in the few published studies.

With regard to its theoretical importance, the thesis addresses the relationships between thermoregulation and SWS. The immediate effect of bright-light is an elevation in temperature produced, perhaps, by the suppression of melatonin which appears to lower temperature. It will be seen in Chapter 2 that similar elevations in temperature around bedtime have been empirically associated with enhanced SWS. This literature suggests that a major function of SWS may be to downregulate temperature for purposes including energy conservation (e.g. Berger & Phillips, 1988, 1990), central nervous system (CNS) restoration (e.g. Horne, 1983, 1988) or cerebral protection against the neurotoxic effects of brain overheating (Szymusiak & McGinty, 1990). According to this literature bright-light induced elevations in temperature around sleep onset might be expected to result in increases in SWS and slow wave activity of the EEG (SWA). Such increases would be consistent with notions of SWS/SWA as a thermoregulatory mechanism.

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[1] For a complete list of abbreviations see Appendix B

However, it will be seen in Chapter 3 that elevation of temperature by evening bright-light appears to result from suppression of melatonin, a naturally occurring agent which may act as a hypnotic that promotes sleep. Exogenous administration of melatonin has sometimes been found to result in hypnotic effects (e.g. Arendt, 1984; Tzischinsky & Lavie, 1994), and the temporal coincidence between melatonin secretion, sleep onset and lowering of temperature suggest that the normal secretion of melatonin may serve to downregulate temperature and promote sleep onset (Badia, Myers, Boecker, Culpepper & Harsh, 1991). This literature suggests that evening bright-light sufficient to suppress melatonin may result in longer sleep onset latency and diminished sleep quality. Chapter 4 reports Experiment 1 of the current thesis in which the immediate effects of evening bright-light on sleep were assessed.

Chapter 5 will review evidence that in addition to an immediate effect, evening bright-light exposure may result in a delay of the core temperature rhythm (CTR) assumed to reflect an underlying circadian pacemaker (e.g. Czeisler et al., 1989). The effects of such a delay in the CTR on sleep will be considered. In particular it will be suggested that while SWS is generally not assumed to vary with circadian phase, some studies have indicated that SWS propensity increases as sleep onset time temporarily approaches the CTR acrophase (Campbell & Zulley, 1989). This literature suggests the possibility that a CTR delay might result in increased SWS if sleep onset time is held constant. In addition to this literature, the positive correlation found between temperature at sleep onset and SWS (Berger & Phillips, 1988) suggests a similar potential for SWS elevation following CTR delay. Chapter 6 reports Experiment 2 which was designed to assess the possible contribution of a CTR delay to increases in SWS.

The results of Experiments 1 and 2 and the small literature (Bunnell, Treiber, Phillips, & Berger, 1992; Cajochen, Dijk, & Borbely, 1992; Dijk, Cajochen, & Borbely, 1991) suggested the possibility that evening bright-light might affect sleep differently depending on whether or not the subject had received a pre-exposure to evening bright-light. This possibility was assessed in Experiment 3 and is reported in Chapter 7.

Chapter 8 is devoted to a discussion of the findings and implications of these three experiments for practical applications of bright-light and for the theoretical status of SWS as a mechanism for thermodownregulation.

CHAPTER TWO

TEMPERATURE REGULATION AND SWS

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Sleep and thermoregulation have long been associated one with the other. The process of falling asleep itself produces a lowering of body temperature at all phases of the daily Core Temperature Rhythm (CTR) (Gillberg & Ackerstedt, 1982) independently of behavioural activity levels (Barrett, Lack & Morris, 1993). The sleep evoked reduction in temperature is greatest near the maximum of the CTR where it typically produces a reduction in body temperature of 1-2°C (Berger & Phillips, 1988). Lowering of body temperature during sleep has been especially associated with the SWS component of non-REM sleep (NREM sleep) in man. It appears that during SWS the hypothalamic set-point for heat-loss is lowered resulting in lowering of body temperature, predominantly via peripheral heat-loss mechanisms (vasodilation, sweating) (Glotzbach & Heller, 1976). This chapter will present evidence relevant to the relationship between SWS and downregulation of temperature and, in particular, the evidence relating to the effects of thermal loads close to sleep onset. Following this will be a consideration of current theoretical positions on the function of SWS in reducing temperature.

2.1 Thermoregulation During NREM sleep vs REM sleep

Before reviewing the effects of temperature elevation on SWS, the more general question of thermoregulation during NREM sleep vs Rapid Eye Movement sleep (REM sleep) warrants some discussion, as there appear to be robust differences between these types of sleep. It has been noted in both animal and human studies that thermoregulatory responses to peripheral heating or cooling appear present in NREM sleep but greatly diminished or absent in REM. For instance, panting in cats and pigeons exposed to high ambient temperatures occurs during NREM sleep but ceases with REM onset and during

REM sleep (Glotzbatch & Heller, 1989). In addition, polypnea and vasomotion in the ear pinna in cats exposed to high ambient temperatures are present in NREM sleep but absent in REM (Parmiggiani, 1977). Similarly, shivering in cats exposed to low ambient temperatures occurs during NREM sleep but is absent during REM sleep (Glotzbatch & Heller, 1989; Parmiggiani, 1977). These findings have led some authors to conclude that during REM sleep all thermoregulatory functions become absent and a poiklothermic state exists in some species (Parmiggiani, 1977). Azzaroni and Parmiggiani (1993) have recently shown that the downregulation of hypothalamic temperature during NREM sleep in mammals is mediated by peripheral heat loss mechanisms (e.g. via heat loss through the ear pinna).

A similar set of findings has been reported in human studies. For instance, sweating is present during NREM sleep in man exposed to high ambient temperatures, but is absent during REM sleep (Parmiggiani, 1977), and shivering in low ambient temperatures has been found to occur only in NREM stages 1 and 2 in man (Glotzbatch & Heller, 1989). Shapiro et al. (1984) found heat production was significantly lower in stage 4 sleep than in any other sleep stage in man, and 14.4% lower than during resting wakefulness. A gradation of heat production during NREM sleep was reported in which heat production became progressively diminished from stage 2 to stage 4 sleep. Heat production was also found to be least variable in stage 4 sleep. These results suggest that in humans, as in animals, NREM or SWS is specifically associated with thermodownregulation. Reduction of rectal temperature and elevation of rectal temperature have recently been shown to occur following SWS and REM sleep respectively in human subjects (Waterhouse, et al., 1995). Similarly, temporal covariation of SWS and rectal temperature has been observed in normal sleeping subjects such that periods of high SWA are associated with reductions in temperature (Eder, Vitiello, Avery, & Smith, 1993).

However, the absence of thermoregulation during REM sleep in humans is not as pronounced as in some other species (Haskell, Palca, Walker, Berger, & Heller, 1981). In this regard Horne (1988) has argued that in human REM sleep thermoregulation reverts to that employed by the foetus where little thermoregulation occurs (as the mother's own thermoregulation is operative), and it occurs by physiological mechanisms not used during adulthood. Thus, Horne (1988) argues that most studies of thermoregulation during sleep only examine mechanisms for heat loss or gain used in the adult and thus neglect to study other potential mechanisms.

To summarise, in many animal species thermoregulatory functions appear enhanced during NREM sleep compared with REM sleep. NREM sleep in humans is also clearly associated with thermoregulatory function, but the absence of thermoregulation during human REM sleep is less pronounced compared with REM sleep of many animals. Thermoregulation during sleep is most clearly to be seen during NREM sleep in man. The following section will review evidence relating to the effects on NREM sleep (especially SWS) of thermal loads close to the time of sleep onset.

2.2 Ambient Temperature and SWS

Studies of the effects of high and low ambient temperatures on SWS have indicated that temperatures outside thermoneutrality during the sleep period have a suppressive effect on SWS. However, studies in which *pre-sleep* ambient temperature has been used to elevate body/brain temperature have generally reported increases in SWS during the subsequent sleep period (De Nisi, Ehrhart, Galeou, & Libert, 1989; Putkonen, Eloman, & Kotilnen, 1976; Shapiro, Allen, Driver, & Mitchell, 1989). In the latter study total SWS and sleep times were significantly increased by exposure to ambient temperatures of 35 °C and 45°C for the four hours prior to bedtime. These findings have been recently replicated in rats (Moriarty, Szymusiak, Thomson, &

McGinty, 1993). Exposure of the rats to high ambient temperature (33-35°C) before sleep produced a greater drive to sleep and increase in NREM sleep than did a period of sleep deprivation. Thus pre-sleep heating of the body/brain by exposure to high ambient temperatures has been associated with significant increases in SWS in man and increased NREM sleep in rats.

2.3 Exercise, Temperature and SWS

Under some conditions physical exercise results in increased amounts of SWS and longer sleep durations, both after discrete episodes of daytime exercise (exercise effect) and in fit subjects who exercise habitually (fitness effect). Such increases in sleep intensity and duration have been interpreted by some as compensatory to heightened energy expenditure (Berger, 1984), or bodily (Adam & Oswald, 1983) or central nervous system (Horne, 1983, 1988) restoration demands consequent to the exercise.

However, a number of findings suggest the need for alternative explanations. First, the exercise and fitness effects appear to occur only under certain circumstances and have not been robustly replicated across a variety of experimental conditions. In a review of the literature, Trinder, Montgomery, and Paxton (1988) reported that only 8 of 33 published studies found an unambiguous exercise effect on SWS (i.e. increases in SWS or either of its components (Stage 3 and 4) across the whole night or any part of the night). Further, while increases in SWS and sleep duration are found in endurance athletes (Montgomery, Trinder, Paxton, & Fraser, 1987; Trinder, Paxton, Montgomery, & Fraser, 1985) they are not found in power athletes who expend similar amounts of energy (Trinder et al., 1985). The most popular alternative explanations for the exercise and fitness effects have proposed that changes to body or brain temperature mediate exercise effects on SWS.

2.3.1 CNS Restoration

One theory of SWS (to be outlined later in this chapter) is that it serves to downregulate cerebral metabolic rate for purposes of cerebral restoration (Horne, 1988). Thus Horne (1981) argued that for the exercise effect to occur, the day-time activity must be sufficiently intense to produce elevations in brain temperature which increase cerebral metabolic rate. According to this view, the *rate* of energy expenditure during the day may be determinate of the exercise effect, rather than the *amount* of daytime expenditure per se. This explanation grew from the observation (Horne, 1981) that studies reporting SWS increases following exercise had tended to be carried out in warm climates (Shapiro, Griesel, Bartel, & Jooste, 1975; Shapiro & Verschoor, 1979; Shapiro et al., 1981) and under conditions of intense exercise. These factors, Horne argued, were conducive to the production of high cerebral temperatures which are a necessary precondition for the SWS exercise effect to occur.

This hypothesis was supported by Horne and Moore (1985) who found the exercise effect on SWS was minimised if subjects were cooled during exercise (wearing minimal clothing kept artificially damp and an airstream to the body and head). They reported significant increases in SWS and Stage 4 sleep in the uncooled condition compared with the baseline condition. The results were interpreted as indicating that the exercise effect on SWS is dependent on the extent to which the exercise elevated brain temperature.

Consistent with this study is that under normal outdoor exercise conditions (as opposed to treadmill) brain temperature does not increase due to evaporative mechanisms and cool inward venous blood flow (Cabanac, 1985). It is suggested by Trinder, Montgomery, Jordan, and Croft (1993) that a discernible trend exists for the exercise effect on sleep to occur in studies using a treadmill (Horne & Staff, 1983;

Horne & Moore, 1985; Shapiro et al., 1975) but not in studies in which subjects exercise out-of-doors (Montgomery, Trinder, Paxton, Fraser, Meany, & Koerbin, 1985; Montgomery, Trinder, Paxton, & Fraser, 1987; Torsvall, Akerstedt & Lindbeck, 1984). This evidence suggests that SWS is only enhanced by exercise conducted under circumstances which result in increased brain temperature.

2.3.2 Body temperature at Sleep Onset

A second explanation for the exercise effect on SWS is that it occurs as a result of elevated body/brain temperatures at sleep onset itself and during the early parts of sleep. It is hypothesised in this view that SWS serves a thermoregulatory (Obal, 1984; Horne, 1988; Szymusiak & McGinty, 1990) or energy conserving (Berger et al., 1988) role in downregulating temperature following small temperature elevations (within physiological variation) caused by exercise and still evident at sleep or SWS onset. There is little direct evidence to support this view as only one published study has reported temperature at sleep onset following exercise (Montgomery, Trinder, Paxton & Fraser, 1985). In this study rectal temperature was increased following a marathon but SWS was not enhanced. No study has reported tympanic temperatures following exercise at sleep onset.

However, indirect support for the hypothesis that SWS increases following exercise are mediated by elevations in body temperature at sleep onset has been provided by study of temperature characteristics of athletes. The failure to find the exercise effect in athlete groups other than endurance athletes lead to the investigation of temperature characteristics of this group by Jordan, Montgomery, Trinder and Hedges (1993, unpublished manuscript). Although endurance athletes were found to have equivalent temperature profiles during the evening and early sleep period, the athlete group initiated sleep at an earlier time than the sedentary group, resulting in higher

temperatures at sleep onset. These results were replicated in a second study in which the athletes were assessed following no exercise, thus confirming that the temperature elevations at sleep onset in athletes resulted from earlier bedtimes, rather than daytime exercise. This evidence appears to confirm that sleep differences in endurance athletes are due to elevated temperatures at sleep onset. However, if temperature at sleep onset is held constant between endurance athletes and sedentary individuals by holding sleep onset at a constant time, SWS and longer sleep durations are still found in the athlete group (Jordan et al., 1993). Thus it is argued by Trinder et al., (1993) that the exercise effect cannot be attributed to body temperature elevation at sleep onset alone, and the explanation for the exercise effect remains unknown. However, in general terms the literature is consistent with the view that exercise is associated with elevated SWS via a thermoregulatory or energy conserving response to elevated brain or body temperature.

2.4 Passive Body Heating and SWS

Following the observation by Horne (1981) that the exercise effect on SWS appeared to be dependent upon elevation of body or brain temperature, a number of studies have been conducted in which subjects have had body/brain temperature elevated passively by immersion in warm water. Horne and Staff (1983) first found increases in SWS following a warm bath in fit subjects independent of amount of exercise per se. These results were replicated with unfit subjects in whom similar enhancement of SWS was found following a hot bath compared with either a cool bath or a baseline condition (Horne & Reid, 1984).

Consistent with the notion that SWS amounts positively correlate with temperature at sleep onset (Berger et al., 1988), it has been found that passive heating effects on SWS are most pronounced when the heating occurs in the late subjective evening, as opposed to early evening, afternoon or morning (Bunnell, Agnew, Horvarth,

Jopson, & Wills, 1988; Horne & Shackell, 1987). In addition, it has been shown that while absolute temperature is elevated following passive heating, the rate of fall of temperature following heating is equivalent to that following a no-bath control condition (Jordan, Montgomery, & Trinder, 1990), thus negating the hypothesis that SWS amounts are most directly correlated with rate of fall of body temperature (Sewitch, 1987). These results suggest that body/brain temperature at sleep onset is a critical factor determining SWS amounts, and that SWS may be enhanced following discrete elevations in temperature at sleep onset.

Finally, it has been shown that SWS may be enhanced following heating during the sleep period itself. In one study (Bunnell & Hovarth, 1985) subjects received a tepid-water (34°C), hot-water (41°C) or no-water immersion condition for 20min immediately following completion of the second REM period. Significant elevations in SWS were found during the fourth NREM period following the hot-water condition. Thus increases in SWS following temperature elevations were found late in the subjective night, where little or no SWS would normally be expected.

2.5 Brain Heating and SWS

Some theories of sleep (to be outlined presently) argue that the primary function of sleep, and particularly SWS, is regulation of cerebral temperature. Afferent projections from thermosensitive neurons in the skin, body core and spinal cord provide feedforward information to the preoptic and anterior nuclei of the hypothalamus (POAH). A dominant source of feedback information in the mammalian central nervous thermoregulatory system is the temperature of the POAH (Glotzbatch & Heller, 1989). It appears that both thermoregulatory and hypnagogic functions are associated with the POAH, as stimulation of the POAH induces sleep (Szymusiak, Satinoff, Schallert, & Wishaw, 1980). These effects have been reported in both freely moving

animals (Roberts and Robinson, 1969) and immobilised animals (Benedek, Obal, Szekeres, & Obal, 1976).

Experimental manipulation of POAH temperature has usually been achieved using chronically implanted water-perfused thermodes placed around the POAH site. In a series of studies using this technique (Glotbach & Heller, 1976) it was found that the gain and threshold of the heat production response were decreased in NREM sleep when compared with wakefulness. These results suggest that the changes in thermoregulation toward heat loss in NREM sleep described earlier in this chapter are centrally driven.

The role of the SWS component of NREM sleep in thermoregulation has also been examined in studies of POAH stimulation (Szymusiak & McGinty, 1990). In this study insomnia was reported in cats at ambient temperatures of 23°C but not at 33°C following lesion of the POAH. These results were interpreted as illustrating that POAH lesions damaged heat sensing mechanisms, raising the threshold for heat-provoked sleep, and indicating that thermoregulatory and hypnogenic responses are closely associated. It was also reported that EEG sleep was more than doubled in warm conditions in the chronic cerveau isole cat. This was interpreted as showing that SWS is centrally driven (as peripheral input connections were severed) by elevations in brain temperature.

In humans, it has been shown that SWS may be enhanced during sleep following heating of the face/head (Moriarty, Phillips, & Berger, 1988). They report two experiments. In the first it was shown that SWS was enhanced across the 7hr sleep period following pre-sleep heating of the head by the wearing of warm-water perfused tygon facial coils. In the second study SWS was enhanced during the last three hours of the night (where REM usually predominates) concomitant with facial heating, but not facial cooling.

2.6 Menopausal Hot Flashes and SWS

Menopausal hot flashes are episodes of heat-loss under conditions of *normal* core body temperature and appear to be caused by a disorder of thermoregulation centrally driven by the hypothalamus (Woodward & Freedman, 1994). Hot flash episodes are characterised by sensations of internal heat loss, peripheral vasodilation, sweating and tachycardia. A recent study has shown that when menopausal hot flashes occurred during the two hours prior to sleep, significantly longer Stage 4 sleep and shorter first REM episodes occurred (Woodward & Freedman, 1994). These results further suggest a close association between heat-loss and SWS, as the effects occurred even in the absence of a thermal load.

2.7 Sleep Deprivation, Temperature and Sleep

Extensive studies by Rechtschaffen and collegues have shown that sleep deprived rats exhibit thermoregulatory changes eventually leading to death (Bergmann, Everson, Kushida et al., 1989; Everson, Gilliland, Kushida et al., 1989; Rechtschaffen, Bergmann, Everson, Kushida, & Gilliland, 1989). Sleep deprivation by the disk-over-water method (Bergmann et al., 1989; Rechtschaffen & Bergmann, 1995) results in an initial increase in intraperitoneal temperature followed by a decrease to below baseline levels (eg. Bergmann, Everson, Kushida et al, 1989). The initial increase appears to result from a centrally driven elevation in temperature set-point, while the fall in temperature results from excessive heat-loss via peripheral mechanisms (skin, tail) (eg. Rechtschaffen & Bergmann, 1995). While intraperitoneal temperature falls rapidly after the initial increase, hypothalamic temperature is usually maintained above baseline values in totally sleep deprived rats. It has been suggested that this is because hypothalamic temperature is protected closer to the elevated set-point than intraperitoneal temperature (Feng et al., 1995). These studies suggest a close

relationship between sleep and temperature regulation such that complete lack of sleep may result in excessive heat-loss and death.

Not all studies of sleep deprivation have suggested a close link between SWS and temperature regulation though. Beersma & Dijk (1992) reported that selective suppression of SWS did not alter the time course of body temperature compared with a control condition. However this study has been criticised by Berger & Phillips (1995) on two counts. First, it is argued that the body temperature comparisons made were confounded by differences in the reported timing of sleep onset (ranging from 1hr during baseline to more than 3hrs during SWS suppression). Given these differences, they suggested comparing body temperatures at equivalent elapsed times following sleep onset, rather than clock hour. Second, the significantly higher levels of intermittent wakefulness during the SWS suppression condition could have reduced body temperature (by peripheral vasodilation) and countered any elevations in body temperature produced by SWS suppression.

In addition, to this study, two other recent studies examining the recovery from sleep deprivation have claimed a dissociation between SWS and down-regulation of temperature. In the first study the normal rebound of SWS following 40hrs sleep deprivation in humans was not associated with an immediate lowering of body temperature (Dijk & Czeisler, 1993). Temperature was equivalent to a control condition before lights-out, but somewhat *higher* from lights-out to the end of the first NREM sleep episode. It was concluded by the authors that SWS/SWA is not necessarily accompanied by lower values of core temperature. However, examination of the data indicate that the slightly higher initial temperature at sleep onset in the rebound condition fell below that of the baseline condition after the first two NREM periods in which SWA was enhanced. Another interpretation of the data might thus be that elevations in temperature produced by sleep deprivation and noticeable at sleep onset

were associated with enhanced SWA which reduced temperature to below control values. Interpreted this way the results are consistent with elevated SWS as being associated with elevated temperature, and with SWS as a mechanism by which heat-loss can be effected. Similar findings to this study have recently been found in sleep deprived rats (Feng et al., 1995). These rats showed a *reduction* in sleep-wake temperature differences in recovery sleep following long and short periods of total sleep deprivation. On this occasion it appears that SWS/SWA was not associated with a reduction in hypothalamic temperature. These results suggest that under some conditions SWS may not drive temperature down as found in many other experimental paradigms.

2.8 General Conclusions

During NREM sleep in animals and humans thermoregulatory mechanisms are operational and the hypothalamic set point for heat loss appears to be lower than during wakefulness. Thus NREM sleep is associated with thermodownregulation. In many animals REM is associated with a pronounced loss of thermoregulatory function. In man this loss appears to be less pronounced. High pre-sleep ambient temperature, exercise and passive heating of the body and head have been empirically associated with increases in the Slow Wave component of NREM sleep in humans. Menopausal hot flashes in which heat is lost via peripheral mechanisms (e.g. sweating) are also associated with increased SWS, though this relationship does not appear to hold under conditions of sleep deprivation. Thus, while not always the case, in many experimental paradigms SWS appears to be associated with downregulation of temperature such that increases in temperature around sleep onset enhance SWS.

2.9 Theories of Sleep Function and Thermoregulation

In the literature described so far, increases in body temperature within normal physiological variation at sleep onset have generally been associated with enhanced SWS. The functions ascribed to such lowering of MR and temperature are still the subject of debate, but the literature is dominated by three central hypotheses: 1) that SWS lowers MR and temperature to conserve energy, 2) that SWS lowers cerebral MR and temperature to allow for CNS restoration, and 3) that SWS lowers cerebral temperature to protect against the neurotoxic effects of brain overheating. The remainder of this chapter is devoted to discussion of each of these hypotheses.

2.9.1 The Energy Conservation Theory

This hypothesis has been most extensively developed by Berger and his colleagues (Berger, 1975, 1984; Berger & Phillips, 1988; Berger, Palca, Walker & Phillips, 1988;Walker & Berger, 1980). The central tenet of the hypothesis is that sleep primarily exists to conserve energy by downregulating metabolic rate (MR) and body temperature. The evidence for this theory is wide-ranging and a complete review is beyond the scope of the present thesis. Instead what follows is a summary of the major lines of argument as they apply to the relationship between temperature and sleep.

2.9.1a Metabolic Rate (MR) and Sleep across Species

Studies across a wide range of species have indicated a positive correlation between total sleep time (TST) and MR (Alison & Van Twyver, 1970; Zeplin & Rechtscaffen, 1974). Thus high metabolic rates, expensive in energy expenditure, are associated with long periods of sleep presumably for the purpose of lowering MR (and thus temperature). One criticism of this general point has been made by Horne (1988)

who argues that the energy savings gained by sleep vary considerably from species to species. He argues that sleep is likely to play a more prominent role in energy conservation in small mammals than large mammals. Small mammals have high MR's, surface area/volume ratios which render them prone to lose much heat through the skin. In addition, they do not conserve energy behaviourally by spending long periods of time in relaxed wakefulness. For these animals sleep appears to primarily serve to conserve energy. However, Horne (1988) argues that sleep has a lower energy conserving value for large mammals with more developed cerebrums and ability to remain in wakeful relaxation.

2.9.1b Metabolic Rate across the Human Lifespan

Studies of sleep over the life span also indicate that it may serve an energy conserving role. Infants exhibit large amounts of sleep (Williams, Karacan & Hursch, 1974) suggesting its importance in energy conservation during periods of rapid growth. Individuals with high metabolic rates also show longer sleep durations than those with lower rates (Walker & Berger, 1980). More recently it has been shown that SWS in adults and children decrease in amounts across the night but that in infants amounts of SWS are maintained at a constant level following the second sleep cycle (Bes, Schultz, Navelet, & Salzarulu, 1991). It is argued that these differences in sleep and SWS distribution reflect the differing needs for energy conservation throughout the lifetime; much energy is needed as infants grow rapidly, while ageing adults become more sedentary and metabolic rate slows down.

2.9.1c Sleep, Torpor and Hibernation

A number of continuities have been noted between sleep and the associated states of torpor and hibernation, which are clearly energy conserving mechanisms. Small

mammals and birds that enter circadian torpor or hibernation do so via sleep. During these periods body temperatures drop by up to 20°C and low frequency activity dominates the EEG (Berger & Phillips, 1988; Berger, 1993). As in torpor, entrance into hibernation appears to be via sleep (e.g. Walker & Berger, 1980). Circannual study of ground squirrels (Walker, Haskell, Berger, & Heller, 1980) showed amount of time asleep varied as a function of seasonal temperature; it was minimal in the warm summer months and maximal during the cold winter months. These findings, and others, suggest that torpor and hibernation are on a continuum with sleep. As torpor and hibernation appear to serve an energy conserving role, it is argued that sleep also serves this purpose.

However, three recent articles (Daan, Barnes, & Strijkstra, 1991; Kilduff, Krilowicz, Milsom, Trachsel, & Wang, 1993; Trachsel, Edgar, & Heller, 1991) have argued that a) cellular neurophysiological studies suggest hibernation does not consist entirely of NREM sleep, but is characterised by short episodes of wakefulness, and b) sleep immediately following these short wakefulness periods is dominated by SWS, a feature normally associated with long periods of wakefulness and, in the energy conservation hypothesis, a relatively large need for energy conservation. These observations were interpreted by the authors as posing some difficulty for the hypothesis that SWS is on a continuum with hibernation for purposes of energy conservation. In a reply to these interpretations, Berger (1993) argued that the evidence cited by the previous authors was somewhat unsubstantiated on a number of grounds, and that factors including the mode of arousal from hibernation allow alternative interpretations in which arousal to sleep from hibernation is not necessarily incompatible with the notion that sleep serves "an energy conserving preadaptation for subsequent evolution of deeper forms of torpor such as hibernation" (Berger, 1993. p. 215). In addition, it might be argued that the SWS observed to occur in sleep immediately following hibernation represents a response to the current thermal/environmental stimuli (i.e. cold

ambient temperatures and a correspondingly high need for energy conservation) than a

compensation for prior hibernation. Thus, while there appear to be similarities between

sleep and the associated states of torpor and hibernation, there is some controversy

surrounding episodes of euthermia during hibernation as consistent with the energy

conservation theory of sleep.

2.9.1d The Evolution of Sleep and Homeothermy

It appears from a wide ranging analysis of sleep across species that homeothermy

and sleep may have evolved in parallel (Berger, 1975). The complete behavioural and

physiological manifestations of sleep including REM and Slow Wave Sleep (SWS)

appear to occur exclusively in homeotherms (Allison & Van Twyver, 1970). Further, if

as suggested by the evidence, SWS is continuous with shallow torpor and hibernation as

an energy conserving mechanism, then one would expect SWS to be present in

endotherms and absent in ectotherms. This largely appears to be the case. SWS is

usually defined as having: an elevated threshold of sensory arousal; a stereotypic relaxed

posture; increased amplitude and slowing of the EEG. According to these criteria only

endotherms (mammals and birds) show unambiguous SWS (Berger, 1984). It has been

claimed (Megalson & Huggins, 1979) that various reptilians show an analog of SWS but

EEG characteristics are inconsistent from one species to another, do not necessarily

resemble those of endotherms and are not necessarily associated with increased sensory

arousal thresholds (Walker & Berger, 1980).

In summary, evidence from across species and in man suggest a close

association between SWS and lowering of MR/thermodownregulation, and energy

conservation has been proposed as the primary reason for this process. Specifically, it is

argued that body temperature at SWS onset correlates positively with subsequent

amounts of SWS in man (Berger, Palca, Walker, & Phillips, 1988).

2.9.2 Restorative Theories

Nevertheless, other authors suggest that though energy conservation appears to be an important function, it may be consequent to some other more fundamental role. Restoration of the body and/or central nervous system has been suggested as another possible function of sleep. Restorative theories of sleep can be divided into those that contend that sleep restores general body/brain processes (e.g. Adam & Oswald, 1983) and those that argue that sleep serves to restore only the brain or Central Nervous System (CNS) (e.g. Horne, 1988; Szymusick & McGinty, 1990). Of more interest to this thesis are the brain or CNS restorative theories as they specifically address the relationship between sleep and temperature.

2.9.2a Horne

Horne argues that sleep comprises two main processes which fulfil CNS restoration and energy conservation purposes. The first process serves a CNS restoration role, occupies the first part of the night and in humans consists mainly of SWS (particularly Stage 4). Horne (1983, 1988) calls this sleep "core sleep" and ascribes to it the function of compensatory repair and restoration of CNS processes decayed or diminished during the course of waking brain activity. According to Horne, elevated cerebral metabolism (which may be produced by elevated temperature) during daytime activity may accelerate cerebral "wear and tear" processes. This "wear and tear" is compensated for by the downregulating effects of SWS on CNS metabolic rate and thus of cerebral temperature. This notion has received empirical support from experimental manipulations of cerebral MR and temperature discussed earlier in this chapter (Horne, 1981; Horne & Moore, 1985; Horne & Reid, 1985; Horne & Staff, 1983). Perhaps the most convincing experimental data for Horne's position is the observation that SWS may increase in response to prolonged increases in daytime brain

activity through raised sensory stimulation (Horne & Minard, 1985). Although Horne includes REM sleep in the CNS restoration process, it is SWS, when cerebral MR and temperature are driven down, that is obligatory in this process.

To summarise, according to Horne's theory elevations in brain temperature may increase cerebral metabolism and accelerate "wear and tear", resulting in increased SWS during subsequent sleep for purposes of cerebral restitution. Thus Horne's theory, like the energy conservation theory, predicts that elevations in body/brain temperature may result in enhanced SWS, though for the SWS effect to occur following body heating the body temperature would have to be sufficiently high to elevate brain temperature.

2.9.2b Szymusiak and McGinty

Unlike Horne, some authors have concluded that a lowering of brain temperature is not a means to any other function, but an end in itself. Szymusiak and McGinty (1990) have recently proposed that the primary role of SWS is to downregulate cerebral temperature for purposes of protection against the neurotoxic effects of cerebral overheating. They propose that the primary purpose of SWS in mammals is to effect CNS heat loss, compensatory to waking CNS heat gain, through a regulated drop in the hypothalamic set point for temperature. Various findings are used to support this notion. First, a number of animal and human studies (as discussed earlier in this chapter) show that localised warming of the forebrain and especially the preoptic area of the anterior hypothalamus (POAH) may augment SWS (Bunnell et al., 1988;Horne et al., 1985; Szymusiak & Mc Ginty, 1990). This effect has been noted even in a surgically isolated forebrain in which peripheral and lower brain stem thermoresponsive processes are eliminated (Szymusiak & McGinty, 1990). These results suggest that the POAH may control both thresholds for heat loss, and SWS regulation. Thus a close neuroanatomical relationship exists between thermoregulatory and hypnagogic function; they appear to

occupy overlapping brain sites. It is thus thought that the POAH contains heat sensitive elements which normally control SWS.

Second, subjects in time-free environments may sometimes exhibit "internal desyncronisation" of sleep/wake and body temperature rhythms such that sleep is initiated at any/all points on the CTR (Czeisler, Weitzman, Moore-Ede, Zimmerman, & Knauer, 1980). These experiments (to be discussed more fully in Chapter 5) indicate that the longest sleep episodes occur when sleep is initiated at or near the circadian peak of temperature, and sleep usually spontaneously ceases at or near the circadian minimum of temperature. Szymusiak and McGinty (1990) interpret these findings as indicating that sleep exists primarily to downregulate temperature.

Third, Szymusiak and McGinty (1990) argue that the high correlations between a) psychomotor performance and body temperature, and b) aerobic activity and basal metabolic rate, constitute an evolutionary advantage and drive toward extended periods of high MR and body temperature. It is suggested by the authors that these high body and brain temperatures cannot be sustained indefinitely without some tissue or brain dysfunction. For instance, loss of consciousness is an initial effect of heat stroke. Sleep, and especially SWS, is proposed to be a compensatory mechanism whereby body temperature is regularly lowered such that the benefits of high awake temperatures can be enjoyed during the day (when activity will be most productive) without wasting energy and incurring possible tissue damage at night (when activity is less adaptive).

It is noted by Szymusiak and McGinty (1990) that the thermodownregulatory functions associated with SWS do not appear to be operational during REM sleep. Szymusiak and McGinty (1990) suggest that REM sleep affords regular periods during which cerebral MR is elevated, rendering the organism more likely to be able to initiate successful fight/flight responses if required. In summary, the theory proposed by

Szymusiak & McGinty (1990) specifically predicts that elevations in brain temperature will be followed by compensatory increases in SWS which will drive temperature down.

2.9.3 Summary

The energy conservation and CNS restorative/protective theories each argue that there is a close association between sleep and thermoregulation. SWS is seen as a mechanism by which heat-loss can be effected for reasons of energy conservation and/or tissue restoration/ protection. Each theory predicts that increases in body and/or brain temperatures should be followed by compensatory increases in sleep, and particularly SWS.

2.10 General Summary and Conclusions

The evidence reviewed in this chapter has pointed to the SWS component of NREM sleep as most closely associated with thermoregulation. During SWS in humans the hypothalamic set-point for heat-loss is lowered, resulting in lowering of core temperature via peripheral heat-loss mechanisms (e.g. sweating, vasodilation). Thus enhanced SWS has been found immediately following thermal loads imposed via exercise, high ambient temperatures, passive body heating and heating of the head sufficient to elevate temperature at sleep onset. The functional significance of SWS as a mechanism by which heat-loss is effected remains a subject of contention. However energy conservation, restoration of the CNS and protection of the brain from the effects of overheating remain popular explanations. The evidence reviewed in this chapter, and each of the theories of SWS outlined, largely suggests that elevation of body and/or brain temperature at around sleep onset will result in enhanced SWS.

CHAPTER THREE

THE IMMEDIATE EFFECTS OF BRIGHT-LIGHT ON HUMAN PSYCHOPHYSIOLOGY

CHAPTER THREE

THE IMMEDIATE EFFECTS OF BRIGHT-LIGHT ON HUMAN PSYCHOPHYSIOLOGY

Bright evening light (>2500 lux) has been shown to produce a variety of psychophysiological effects. In this discussion a distinction will be made between the "chronic" effects and the "immediate" effects of evening bright-light. It is the purpose of this chapter to review the immediate effects of evening bright-light and their potential to affect subsequent sleep.

3.1 Evening Bright-Light May Affect Sleep via its Immediate Effects on Melatonin and Temperature

The immediate effects of evening bright-light of interest to the present thesis are suppression of the normal release of melatonin by the pineal gland and subsequent elevation of body temperature and enhanced alertness. This constellation of effects usually occur together, as melatonin appears to downregulate body temperature and may also act as a hypnotic. This thesis is concerned with the effects on sleep of temperature changes following evening bright-light. Melatonin is therefore of interest in as much as changes in temperature following evening bright-light appear to be primarily mediated via a suppression of melatonin. The following section will briefly review bright-light suppression of melatonin and consider evidence for melatonin as a downregulator of temperature and as a hypnotic agent.

3.1.1 Evening Bright-Light Suppression of Melatonin

Melatonin is a hormone secreted by the pineal gland from approximately 21:00-07:00hrs in a normal subject. For a long time it was thought that human melatonin secretion was unaffected by light. This finding was in contrast with animal studies in which moderate intensities of light suppressed night-time melatonin secretion. Lewy, Wehr, Goodwin, Newsome, & Markey, (1980) first

reported that considerably more intense light (>2500 lux) suppressed night-time melatonin secretion in humans within 10-20min. Low daytime levels of melatonin were obtained after an hour of exposure to the bright-light and melatonin levels rose to normal night-time levels within 40min once subjects were returned to dim-light conditions. Suppression of night-time melatonin secretion by bright-light has since been replicated many times (e.g. Bunnell et al., 1992; Horne, Donlon, & Arendt, 1991; Myers, Badia, Murphy, Plenzer, & Hakel, 1995; Strassman, Qualls, Lisansky, & Peake, 1991). A dose-dependent effect of bright-light on melatonin release has also been demonstrated such that, up to a point, melatonin suppression is more pronounced with increasing levels of bright-light intensity (McIntyre, Norman, Burrows, & Armstrong, 1989).

3.1.2 Melatonin and Thermodownregulation

A number of studies suggest that melatonin may directly downregulaute temperature. Exogenous administration of pharmacological doses of melatonin during the day-time hours has been shown to lower temperature in the mouse (Arutyunyan, Mashdovskii, & Roshchina, 1964), rat (Barchas, Da Costa, & Spector, 1966) and in humans (Carman, Post, Buswell, & Goodwin, 1976). Similar reduction in body temperature has been shown in humans given exogenous administration of melatonin in pharmacological doses during both the day (Dollins, Zhdanova, Wurtman, Lynch, & Deng, 1994) and at night (Strassman et al., 1991). In the latter study exogenous melatonin reduced temperature in men which had been elevated by evening bright-light suppression of melatonin. The same relationship between bright-light, temperature elevation and suppressed melatonin has recently been shown to occur in women also (Cagnacci, Solandi, & Yen, 1993). It has been suggested (Dawson & Encel, 1993) that if melatonin does directly downregulate temperature, then much of the circadian variation in core temperature may be directly related to the circadian variation of melatonin excretion. Indeed exogenous melatonin administration has been found to restore rhythms of body temperature in pigeons kept in constant light (Phillips & Berger, 1992).

In humans evening bright-light sufficient to suppress melatonin has reliably increased rectal temperature by 0.2-0.3°C (Badia et al., 1991; Strassman et al., 1991; Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991). These elevations have lasted into the subsequent sleep period for durations from two hours (following an administration period of two hours) (Bunnell et al., 1992), to four hours (following an administration period of three hours) (Cajochen et al., 1992).

Similar evening bright-light has also typically (e.g. Badia et al., 1991; Myers et al., 1995) increased tympanic temperature. However one study found no elevation in tympanic temperature following evening bright-light, even in the in the presence of an elevation in rectal temperature (Bunnell et al., 1992). The discrepancy in findings between these studies may be due to a difference in methodology. In the former cases bright-light was administered throughout the period from 00:00-09:00hrs whereas in the latter study administration was only until habitual bedtime. As plasma melatonin peaks at around 04:00hrs, bright-light administered at this time is likely to produce more dramatic suppressant effects than bright-light administered much earlier. Bunnell et al. (1992) further suggest that fine homeostatic thermoregulation of cerebral temperature may have countered such an effect. The similarity of the time period required to observe temperature effects and melatonin suppression following evening bright-light prompted Badia et al. (1991) to speculate that the two effects were related i.e. that is, that bright-light suppression of melatonin resulted in increased temperature as melatonin exerts a downward thermoregulatory effect. These temperature elevations induced via evening bright-light are of interest in the current thesis as SWS has been shown to be enhanced under conditions of evening temperature elevation (Chapter 2).

Taken together these studies suggest that the normal rise in melatonin levels during the evening and early morning hours may act to downregulate body temperature.

3.1.3 Melatonin as a Hypnotic Agent

Suppression of melatonin by evening bright-light is of interest as there is a growing literature suggesting melatonin may act as a hypnotic agent, perhaps via its effect on temperature. Sleep propensity is known to vary approximately inversely with body temperature such that sleep propensity is highest when temperature is lowest (the sleep propensity rhythm will be discussed in greater detail in Chapter 5). Consistent with this, a number of studies have reported that exogenous administration of melatonin given via intravenous injection (Cramer, 1980), orally (Arendt, Borbely, Franey, & Wright, 1984; Lieberman, 1986; Tzischinsky & Lavie, 1994) and by nasal spray (Vollrath, Semm, & Gammel, 1981) may increase sleep propensity. Exogenous administration of melatonin, both in large pharmacological quantities (Lieberman, 1986; Waldhausser, 1990) and normal physiological quantities (Arendt et al., 1984; Vollrath et al., 1981) has typically produced measurable increases in sleepiness and reductions in vigilance, though this has not always been the case (James, Sack, Rosenthal, & Mendelson, 1990). In the latter study insomniacs reported greater quality of sleep, though no changes were noticed in the standard polysomnographic record. Hypnotic effects have been found for both day-time (Lieberman et al., 1984) and night-time (Waldhausser et al., 1990) administration of melatonin. Recently it has been shown that daytime administration of melatonin in physiological quantities produced measurable increases in sleep length and sleepiness while reducing sleep onset latency and performance on a vigilance task (Dollins et al., 1994). These results suggest that the normal nocturnal rise in melatonin levels may act to promote sleep onset. Ferrini-Strambi et al. (1993) have reported improved sleep following exogenous melatonin administration while Berger and Phillips (1991) found exogenous administration of melatonin restored sleep to pigeons kept in constant bright-light. Tzischinsky and Lavie (1994) have recently reported a time dependent hypnotic effect of melatonin such that the maximal hypnotic effects of melatonin occurred more quickly following exogenous administration in the evening than during the afternoon. For instance it was found that the maximal hypnotic effect occurred after 3hrs 40min following melatonin administration at 12:00hrs, but occurred only 1hr after melatonin administration at

21:00hrs. Following such administration of melatonin Tzischinsky and Lavie (1994) found increased sleep propensity and enhanced EEG sleep in the theta, delta and spindle bandwidths.

Further evidence for melatonin as a hypnotic agent comes from experiments in which increased vigilance is found following *suppression* of night-time melatonin by bright-light. For instance Horne et al. (1991) reported that bright green light administered from 00:00-6:00hrs suppressed salivary melatonin levels, reduced subjective sleepiness and improved vigilance as measured by the Wilkinson Auditory Vigilance Test (Wilkinson, 1968). Similarly, Badia et al. (1991) reported reduced sleepiness, improved performance on behavioural tasks and increased EEG beta activity during periods of bright-light sufficient to suppress melatonin from 00:00-06:00hrs. Of most interest to the present thesis, evening bright-light sufficient to suppress melatonin has sometimes been associated with increased sleep onset latency in the sleep period immediately following exposure (Cajochen et al., 1992; Dijk et al., 1991; Drennen et al., 1989). These findings are consistent with the notion that bright-light suppression of melatonin has an "energising" effect sufficient to reduce sleep propensity and increase sleep onset latency. However, one exception to this finding has been reported by Bunnell et al. (1992) who found evening bright-light suppressed melatonin but did not produce significant disturbance to sleep onset.

3.1.4 Ageing, sleep and melatonin

Evidence for melatonin as a hypnotic agent which acts via its influence on temperature also comes from studies of ageing and sleep. It is well documented that sleep in the elderly is disturbed. In particular it has been shown that the elderly have more Stage 1 sleep, decreased SWS and decreased amplitude of delta wave sleep (Bliwise, 1993). It is also apparent that temperature remains somewhat elevated during the sleep period in some elderly people compared with a young population (e.g. Monk, 1991). As melatonin production in the elderly has also been found to be reduced (Sack, Lewy, Erb, Vollmer, & Singer, 1986; Waldhausser & Steger, 1986) there has been speculation that sleep disturbance in the elderly may be caused by

insufficient melatonin production and relatively elevated temperature. For instance, Haimov et al. (1994) found significant correlations between disturbances of melatonin secretion and poor sleep in the elderly. Consistent with this hypothesis, it has been shown that exogenous administration of melatonin reduced temperature and sleep onset latency in elderly subjects (Haimov et al., 1995; Pollard, Lushington, & Dawson, 1996).

Despite these trends a simple relationship between melatonin production, temperature drop and sleep propensity in the elderly has not always been found. Cagnacci, Solandi, and Yen, (1995) found normal concentrations of melatonin, but reduced effectiveness of the melatonin to reduce temperature in elderly women. While Pollard et al. (1996) found exogenous administration of melatonin reduced temperature and sleep onset latency in the elderly, they did not find significant correlations between amounts of temperature reduction and decrease in sleep onset latency. It was concluded that melatonin produced hypothermic and hypnotic effects, but that the effects may be dissociated. Lushington, Lack, & Dawson (1995) found that melatonin production in the healthy elderly did not differentiate between good and poor sleepers. However when analysed separately a sex difference appeared such that melatonin production was associated with sleep in elderly women but not elderly men. Thus while the wider literature suggests a direct link between melatonin production, temperature regulation and sleep in the elderly, other studies suggest the hypothermic and hypnotic effects of melatonin in the elderly may dissociate.

3.1.5 Summary

The evidence reviewed above suggests that melatonin may produce hypothermic and hypnotic effects. Much of the evidence suggests that the hypnotic effects are causally related to the thermic effects; that the lowering of temperature results in increased sleep propensity. These results thus suggest that the normal rise in melatonin levels during the subjective evening reduces temperature and may promote sleep onset. The corollary of this is that suppression of melatonin by

evening bright-light tends to result in increased alertness and vigilance via increased body temperature. These effects are of interest as the present thesis is concerned with the effects of evening bright-light on subsequent sleep. On one hand elevation of temperature following evening bright-light might be expected to enhance sleep quality as elevations in temperature around sleep onset have been associated with increased SWS (Chapter 2). On the other hand suppression of melatonin might be expected to disrupt sleep as melatonin suppression has been associated with increased vigilance and reduced sleepiness.

3.2 The Effects of Evening Bright-Light on Subsequent Sleep

While the effects of evening bright-light on melatonin, temperature and alertness are becoming well-documented, the effects of suppressed melatonin and elevated temperature on sleep variables are not as well investigated. The following section will comprise a review of the empirical findings on the effects of evening bright-light on sleep to date.

3.2.1 Sleep Onset Latency

SOL has sometimes been found to increase following bright-light induced temperature elevation (Cajochen et al., 1992; Dijk et al., 1991; Drennen et al., 1989). This result is consistent with melatonin as a hypnotic and suggest that the suppression of melatonin and/or elevation in temperature produced immediately by evening bright-light is sufficient to delay sleep onset. However, bright-light induced melatonin suppression and temperature elevation have not always produced significant increases in SOL (Bunnell et al., 1992). This maybe because of a difference in methodology. Bunnell et al. (1992) administered bright-light until habitual bedtime, whereas Dijk et al. (1991) and Cajochen et al. (1992) exposed subjects to bright-light until 00:00hrs. No indication of subjects' habitual bedtime is given in these studies and it is possible that some or all subjects in the latter studies had habitual bedtimes earlier than 00:00hrs. It is possible that exposure to bright-

light after habitual bedtime might produce greater "energising" effects than exposure before habitual bedtime. In another study no effects of evening bright-light on temperature or SOL were found (Carrier, Dumont, Guillemette, Lafrance, & Hebert, 1995).

3.2.2 REM Sleep

The immediate effects of evening bright-light on REM are ambiguous. No study has reported changes to overall amounts of REM (Bunnell et al., 1992; Cajochen et al., 1992; Carrier et al., 1995; Dijk et al., 1991; Drennen et al., 1989). One study has reported that a moderate dose of evening bright-light resulted in significantly delayed REM latency (REMLAT) (Bunnell et al., 1992) and another has reported an advance in REMLAT immediately following three exposures to bright-light (Drennen et al., 1989). On other occasions no difference in REMLAT has occurred (Cajochen et al., 1992; Dijk et al., 1991). Considerable variation therefore exists in reports of REMLAT following evening bright-light and the reasons for this variation are unclear.

3.2.3 Slow Wave Sleep (SWS) and Slow Wave Activity (SWA)

Of most interest to the present thesis are the findings relating to SWS following evening bright-light. Few studies have been reported of sleep immediately following evening bright-light, and of these two have not included NREM measures (Drennen et al., 1989; Sack et al., 1986). Of the four published studies to report SWS data none found significant differences following evening bright-light, though three found weak trends in this direction (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991). SWA in the first sleep cycle following evening bright-light has been found to increase (Bunnell et al., 1992), decrease non-significantly (Cajochen et al., 1992) and show no variation (Carrier et al., 1995; Dijk et al., 1991). Increased SWA has been found following evening bright-light in the fourth sleep cycle (Cajochen et al., 1992) and in the eighth hour of sleep (Carrier et al., 1995). This increase was accounted for by Cajochen et al. (1992) as compensatory for disturbed

sleep onset and decreased SWA in the first cycle, and as indicating a weak relationship between temperature and sleep. However no such disturbance to the early sleep period was found by Carrier et al. (1995) and the reason for a late increase in SWA remains unclear. In contrast, Bunnell et al. (1992) attributed enhancement of SWA in the first sleep cycle to concurrent elevations in temperature. It was concluded in this study that the thermic effects of evening bright-light exerted a stronger effect on sleep than the potentially arousing effects of suppressed melatonin. Table 3.1 outlines the studies to date that have investigated sleep immediately after exposure to evening bright-light.

3.3 Summary and Conclusions

Evening bright-light may delay the onset of melatonin, and produce immediate elevations in rectal temperature, tympanic temperature and alertness. Sleep architecture following evening bright-light is not yet well documented, and results are ambiguous. There is a trend for longer SOL's following bright-light, possibly due to arousing effects of suppressed melatonin. The immediate effects of evening bright-light on REM sleep remain unclear. Of most interest to the present thesis are the effects of evening bright-light on SWS. Elevated temperature at sleep onset is associated with enhanced SWS. Some theories of sleep specifically predict increased SWS following temperature elevations. Increases in SWS might thus be expected to follow evening bright-light sufficient to suppress melatonin and elevate temperature. Such a pattern of results has been reported by Bunnell et al. (1992). However, suppression of melatonin is also associated with increased vigilance, and in some studies has resulted in longer sleep onset latency and disturbance to early SWS/SWA (Cajochen at al., 1992; Dijk et al., 1991). In addition SWA has sometimes been found to increase late in the sleep period following bright-light (Cajochen et al., 1991; Carrier et al., 1995). The reasons for this are also unclear. It is the purpose of the present thesis to further examine the thermic effects of evening bright-light on sleep architecture, with particular emphasis on SWS.

Table 1. Studies reporting sleep and temperature immediately following evening bright-light.

Study	Exposure	Temperature	Sleep Onset	REM Sleep	Slow Wave Sleep
Bunnell et al. (1992)	2500 lux during 2 hrs prior to habitual bedtime	Rectal temp. elevated approx. 0.25°C for 3 hrs. No change in tympanic temp.	No effect	REM latency delayed	Increased low-frequency EEG activity during first 2 sleep cycles.
Cajochen et al. (1992)	2500 lux from 21:00-00:00hrs	Rectal temp. elevated by approx. .0.3°C for 4 hours	SOL delayed	No effect	Slight suppression during the first NREM period, and enhanced SWA in the fourth NREM period.
Carrier et al. (1995)	Five hours of 6000-11000 lux from 18:30-23:30hrs	No elevation in rectal temp.	Not reported	Not reported	Increased SWA in 8th hour of sleep.
Dijk et al. (1991)	2500 lux from 21:00-00:00hrs	Rectal temp. elevated by approx. 0.3°C for 4 hours	SOL delayed	No effect	No effect
Drennen et al. (1989).	3000-6000 lux from 18:00-21:00hrs	Immediate effects not reported	SOL delayed.	REM latency advanced.	Not reported.

CHAPTER FOUR

EXPERIMENT 1

THE IMMEDIATE EFFECTS OF EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP

CHAPTER FOUR

EXPERIMENT 1

THE IMMEDIATE EFFECTS OF EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP

The aim of Experiment 1 was to assess the immediate effects of evening bright-light on temperature and sleep architecture. As reviewed in the previous chapter, it has become clear that appropriately timed bright-light (>2500 lux) may suppress nightime melatonin secretion (Bunnell et al., 1992; Lewy et al., 1980), produce immediate elevations in temperature (Badia et al., 1991; Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991; Myers et al., 1995; Strassman et al., 1991), and increase nightime alertness (Badia et al., 1991; Myers et al., 1995). These effects are being investigated for possible application within industry to improve nightime performance and adjustment to shift-work (e.g. Czeisler et al., 1990; Dawson & Campbell, 1991; Dawson, Encel, & Lushington, 1995; Eastman, Liu, & Fogg, 1995; Thessing, Anch, Muchlbach, Schweitzer, & Walsh, 1994). However, the effects of evening bright-light on nightime sleep immediately following exposure remain unclear.

On one hand, the elevating effects of evening bright-light on core temperature might be expected to enhance sleep. Similar temperature elevations produced by exercise (Horne, 1981; Horne & Moore, 1985), pre-sleep exposure to high ambient temperatures (Shapiro et al., 1989), warm baths (Horne & Staff, 1983; Horne & Reid, 1984; Jordan et al., 1990) and passive heating of the head (Moriarty et al., 1988) have resulted in increased SWS during the sleep period immediately following the heating. Some theories of sleep assume a close relationship between sleep and temperature, and predict that elevations in temperature around bedtime will result in enhanced SWS (e.g. Berger et al., 1988; Szymusiak & McGinty, 1990; Horne, 1988).

On the other hand suppression of melatonin by evening bright-light might be expected to result in diminished sleep, as melatonin has been suggested to be a hypnotic

agent. For example, exogenous infusion of melatonin has been shown to lower core temperature in humans exposed to all-night bright-light (Strassman et al., 1991; Cagnacci et al., 1995) and has been empirically associated with reduced sleep onset latency (Dollins et al., 1994; Tzischinsky & Lavie, 1994) and enhanced NREM sleep (Ferini-Strambi et al., 1993; Tzischinsky & Lavie, 1994; Waldhauser et al., 1990). Similar infusions have been shown to restore sleep in pigeons kept in constant bright-light (Berger & Phillips, 1991). Increased alertness and performance on psychomotor tasks are also associated with evening bright-light melatonin suppression (Badia et al., 1991). Together these findings suggest sleep following bright-light sufficient to suppress melatonin might be diminished.

Only a few studies have examined the immediate effects of evening bright-light on subsequent sleep (Bunnell et al., 1992; Cajochen et al., 1992; Carrier et al., 1995; Dijk et al., 1991; Drennen et al., 1989). Two of these studies reported no alteration to any sleep stage but sleep onset latency which was found to be increased following bright light (Cajochen et al., 1992; Dijk et al., 1991). The latter study also reported a slight suppression of SWA in the first sleep cycle followed by increased SWA in the fourth cycle. The authors of these studies suggested only a weak association between temperature and SWS/SWA. In contrast, another study found elevated rectal temperature and suppressed melatonin following evening bright-light, but found no disturbance to sleep early in the night (Bunnell et al., 1992). Instead they reported elevated temperature and SWA levels extending to the end of the second sleep cycle. These authors argued for a close association between temperature and SWS/SWA, as it appeared that the thermic effects of bright-light on sleep had outweighed any diminishing effects associated with melatonin suppression. In contrast again, Carrier et al. (1995) reported an increase in SWA late in the night despite no increase in temperature. Thus, despite the theoretical and practical significance, the effects of evening bright-light on sleep data remain unclear. Experiment 1 was designed to assess the immediate effects of evening bright-light on temperature and sleep architecture. It was hypothesised that evening bright-light would be associated with elevations in both rectal temperature and SWS.

Method

Subjects. Eleven male subjects aged between 18 and 25 were recruited from the University community. Females were not used as subjects because of the effects of gonadal hormones on core temperature. Subjects were required to be non-smokers and free of medication and respiratory/sleep pathology. In addition they were required to abstain from caffeine and alcohol during participation. All subjects were paid for their participation and the project was approved by the University ethics committee.

Design and General Laboratory Procedure. Table 2 outlines the experimental procedure. There were two conditions in the experiment; evening bright-light exposure (BL) or evening dim-light exposure (DL). Subjects were each run in the BL and DL condition twice. The order of presentation of conditions was counterbalanced across subjects; five subjects were run on a DL BL BL DL schedule and six on a BL DL DL BL schedule. Each subject spent one adaptation night in the laboratory during the week leading up to the start of the experimental schedule. Each session comprised a 48hr period during which the subjects spent both nights in the sleep laboratory and sleep was recorded on the second night of each session. While continuous ambulatory rectal temperature was recorded over the 48hrs, each session within the schedule was separated by exactly one week such that each subject took four weeks to complete the schedule.

The dependent variables were rectal temperature and sleep architecture variables which were reported for the second night of each experimental session. Subjects initially reported to the sleep laboratory in the morning of the first day of each 2 day run. Here they were given instruction in the fitting and use of the Mini-logger and rectal thermisters. Following fitting of the equipment, recording of ambulatory rectal temperature began. Subjects reported to the sleep laboratory 2hrs prior to habitual bedtime on both nights of each condition run. Upon arrival each night they were seated and watched television or viewed videos for the 2hr period before bedtime, during which either BL or DL was administered. Thus subjects received two consecutive nights of either bright or dim light during each session. Electrodes for sleep recordings were attached during the BL or DL administration period. Subjects prepared for and

retired to bed immediately following the exposure period and arose at their habitual times in the morning. Subjects were required to maintain exercise and diet constant across experimental conditions, and to keep a diary of daily activities. The reports of two subjects (DA and PJ) indicated unusually strenuous activity (a long walk up a hill, and an aerobics session) associated with elevated rectal temperature approaching the scheduled time for light administration. These session were re-run on the equivalent days of the next week. Constant diet and exercise conditions held for all other subjects to the extent that their self reported activity diaries correctly reflected actual activities.

Bright-Light. The laboratory set-up for administration of bright-light is shown in diagramatic form in Figure 1. Bright-Light was provided by two 1000 watt quartz halogen lamps, and a light-box consisting of 10 standard 100 watt globes situated behind a diffusion screen. The lamps were directed onto a white backing board surrounding the television screen which reflected the light toward the subject seated approximately 2m from the screen. The light-box was placed directly beneath the screen. Thus the entire area surrounding the television screen directed light toward the subject. The light measured at the subject's forehead was approximately 3,200lux. In the dim-light condition normal room illumination was used measuring approximately 100lux.

Rectal Temperature Recording. Ambulatory rectal temperature was continuously recorded using a Mini-Mitter Mini-Logger coupled with a YSI 400 series disposable rectal thermister. The indwelling thermister was inserted 10cm into the rectum and taped in place to the small of the back. Temperature was sampled every 16 seconds. At the completion of each experimental session temperature data was downloaded to a 386 IBM compatible PC for storage and analysis.

Sleep Recording and Scoring. Standard sleep recording procedures were followed in which Electroencephlagram (EEG), Electrooculogram (EOG) and Electromyogram (EMG) signals were recorded using gold disk electrodes. The EEG was measured from positions C3/A2 (International 10-20 system). The EEG signal was recorded using a GRASS 7P511 amplifier with the low-frequency filter set at set at .3Hz, the high-frequency filter set at .3KHz and the sensitivity set at 7.5μv/mm. A

single EOG was recorded from vertically displaced electrodes applied to the outer canthi of the eyes. The EOG signal was recorded using a GRASS 7P3 pre-amplifier with the low-frequency filter was set at .15Hz and sensitivity set at 5µv/mm, connected to a GRASS 7DA driver-amplifier with the high-frequency filter set at 35khz. EMG was measured from two electrodes applied bilaterally to the submentalis muscles. The EMG signal was recorded with a GRASS 7P3 pre-amplifier with low-frequency filter set at 10Hz and sensitivity set at 5µv/mm, connected to a GRASS 7P3 driver-amplifier with the high-frequency filter set at 3KHz. All signals had 50 Hz activity filtered out on-line and were recorded onto paper using a GRASS Model 7 PCM 12C polysomnograph at a speed of 10mm per sec. Sleep records were scored according to the standard Rechtchaffen and Kales (1968) guidelines. The records were scored in 30sec epochs by two scorers who were blind to the condition of the recording and who had an inter-rater agreement of over 90%. Disagreements were either adjudicated by discussion or resolved by a third scorer.

Determination of sleep cycles was accomplished using the guidelines adopted by Trinder, Stevenson, Paxton, & Montgomery (1983). These guidelines consist of seven rules: 1) A cycle was defined as the time from the beginning of the NREM period to the end of the following REM period. 2) The beginning of NREM sleep, and thus of a cycle, at both sleep onset and following a REM period was defined as Stage 2. 3) With the exception of the first NREM period, 5 minutes of REM sleep was required to score a REM period (5min within a 7min period). 4) The end of a REM period was retrospectively indicated by a lapse in REM sleep of more than 15min. However, once the end of a REM period was identified, the new period began at the first Stage 2 following the last REM epoch. 5) The first REM period was deemed to have occurred if any indication of REM sleep characteristics could be observed around the period during which it might be expected to occur. This method was adopted because of the well known characteristic of young subjects to have rudimentary first REM periods. 6) The final cycle in the night was considered to have been completed if greater than 5min of NREM sleep followed the last REM period. 7) Any cycle which contained more than 5min of Stage 1, movement time (MT) or Wake combined was classified as a disrupted cycle and excluded from analysis.
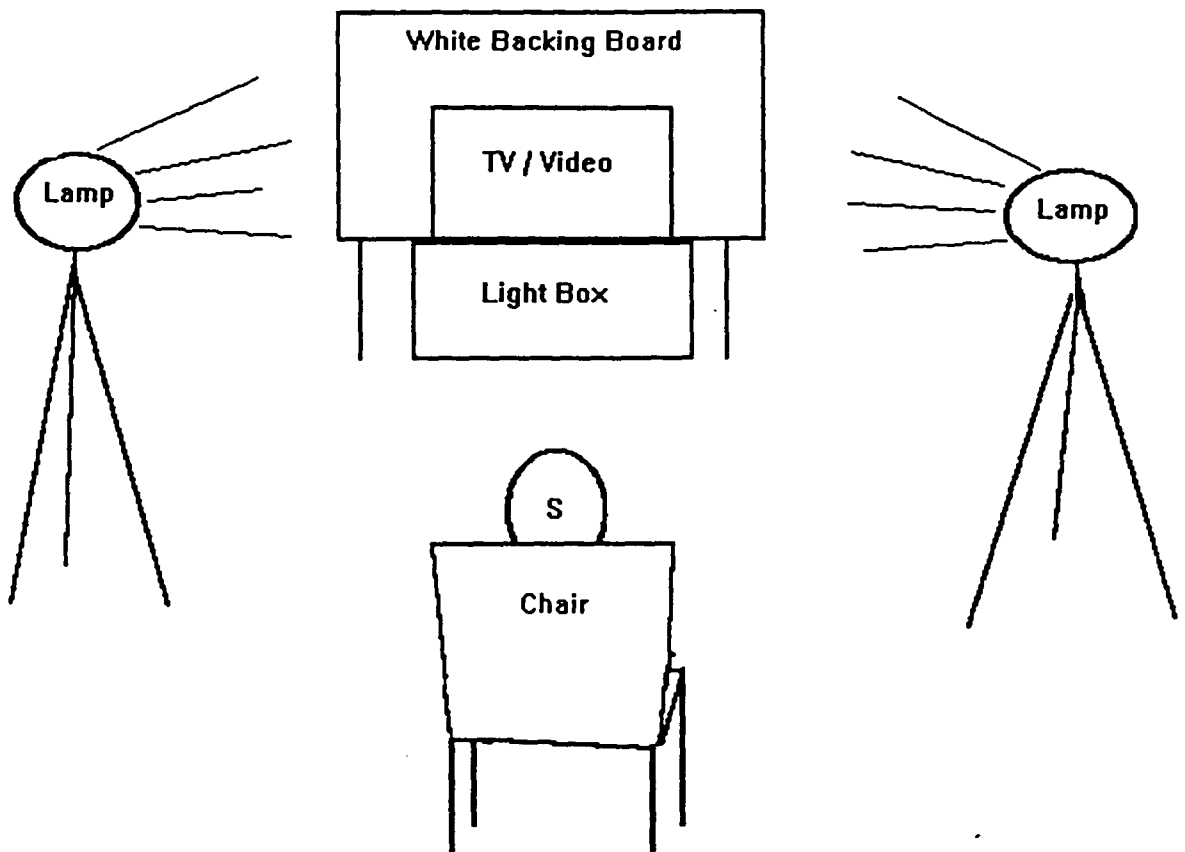
Figure 1: *Bright-Light set-up used in Experiment 1 and subsequent experiments. Lamps were 1000watt full spectrum. The light-box consisted of 10 full spectrum 100watt bulbs mounted behind a 5mm diffusion screen. Illumination measured at subject eye level was approximately 3200lux.*

Table 2. Schedule of events in the Experiment 1 procedure. The details of these events are described in the text. This experimental session commences within a week of an adaptation night in the sleep laboratory. Each subject was run in the schedule four times (twice in each of BL and DL conditions in a counterbalanced ABBA design).

DAY 1

TIME	ACTIVITY/EVENT
08:00 - 10:00	Subject arrives at sleep laboratory for fitting of the rectal thermister and Mini-Logger.
Daytime hours	Subject engages in normal daytime activities keeping diet and exercise constant across conditions and noting activity in a short diary. Ambulatory rectal temperature is continuously recorded.
2hrs prior to habitual bedtime	Subject arrives at the sleep laboratory. BL/DL administration commences and continues according to Condition for the 2hrs prior to habitual bedtime.
1hr prior to habitual bedtime	Mock wire-up is completed with electrodes attached as if for recording of sleep.
habitual bedtime	Subject retires to bed, electrode jacks are attached to recording board above pillow. Subject sleeps until spontaneous awakening at habitual wake time.

DAY 2

TIME	ACTIVITY/EVENT
Daytime hours	Subject engages in normal daytime activities keeping diet and exercise constant across conditions and noting activity in a short diary. Ambulatory rectal temperature is continuously recorded.
2hrs prior to habitual bedtime	Subject arrives at the sleep laboratory. BL/DL administration commences and continues according to Condition for the 2 hrs prior to habitual bedtime.
1hr prior to habitual bedtime	Electrodes are attached in preparation for assessment of sleep.
Habitual bedtime	Subject retires to bed and sleep recordings begin upon lights-out.
Habitual wake-time	Subject rises, sleep recordings are terminated and temperature data are down-loaded from Mini-Logger to PC.

Results

Data for the two sessions within each condition were collapsed within subjects for all analyses.

Temperature. One subject's data (CW) was unusable as consistent slippage of the temperature thermister made readings unreliable. Average temperatures were calculated for the period of BL or DL administration and for each of five hours following administration. These means are shown in Table 3. A 2 X 6 Condition (DL/BL) x Time (light exposure period + the following 5hrs) ANOVA revealed no effect of Condition [$F(1,18) = .992$, $p > .1$][1], but a significant effect of Time [$F(4,72) = 98.00$, $p < .001$] indicating a decline in temperature and a significant Condition x Time interaction [$F(4,72) = 8.304$, $p < .001$]. Post-hoc dependent groups t-tests indicated that temperature following BL was significantly elevated during the hour following light administration compared with the DL condition (BL = 36.75 °C, DL = 36.48 °C) [$t(9) = -4.54$, $p < .001$] and during the second hour following light administration compared with the DL condition (BL = 36.4 °C, DL = 36.19 °C) [$t(9) = 2.92$, $p < .05$]. Figure 2 illustrates the elevation in temperature following evening BL.

Rectal temperature at the time of sleep onset was also calculated (sleep onset was defined as the first full minute of Stage 2 sleep). Nine of the ten subjects analysed had higher temperatures at sleep onset in the BL condition (see Table 5) and temperature at sleep onset was found to be significantly elevated in the BL condition compared with the DL condition (BL = 36.68 °C, DL = 36.49 °C) [$t(9) = 2.39$, $p < .05$].

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[1] All ANOVA tables cited are contained in Appendix C.

Table 3. Experiment 1 mean rectal temperatures during the five hours immediately following bright and dim light.

HOUR	MEAN RECTAL TEMPERATURES (°C) (SDs in Parentheses)	
	DIM-LIGHT	**BRIGHT-LIGHT**
HOUR 1	36.48 (.19)	36.75 (.24)**
HOUR 2	36.19 (.16)	36.4 (.20)*
HOUR 3	36.08 (.18)	36.13 (.21)
HOUR 4	36.01 (.24)	35.98 (.21)
HOUR 5	35.99 (.26)	35.87 (.24)

* p<.05
** p<.001

Asterisks indicates significant differences between conditions. Statistical analyses are described in the text.
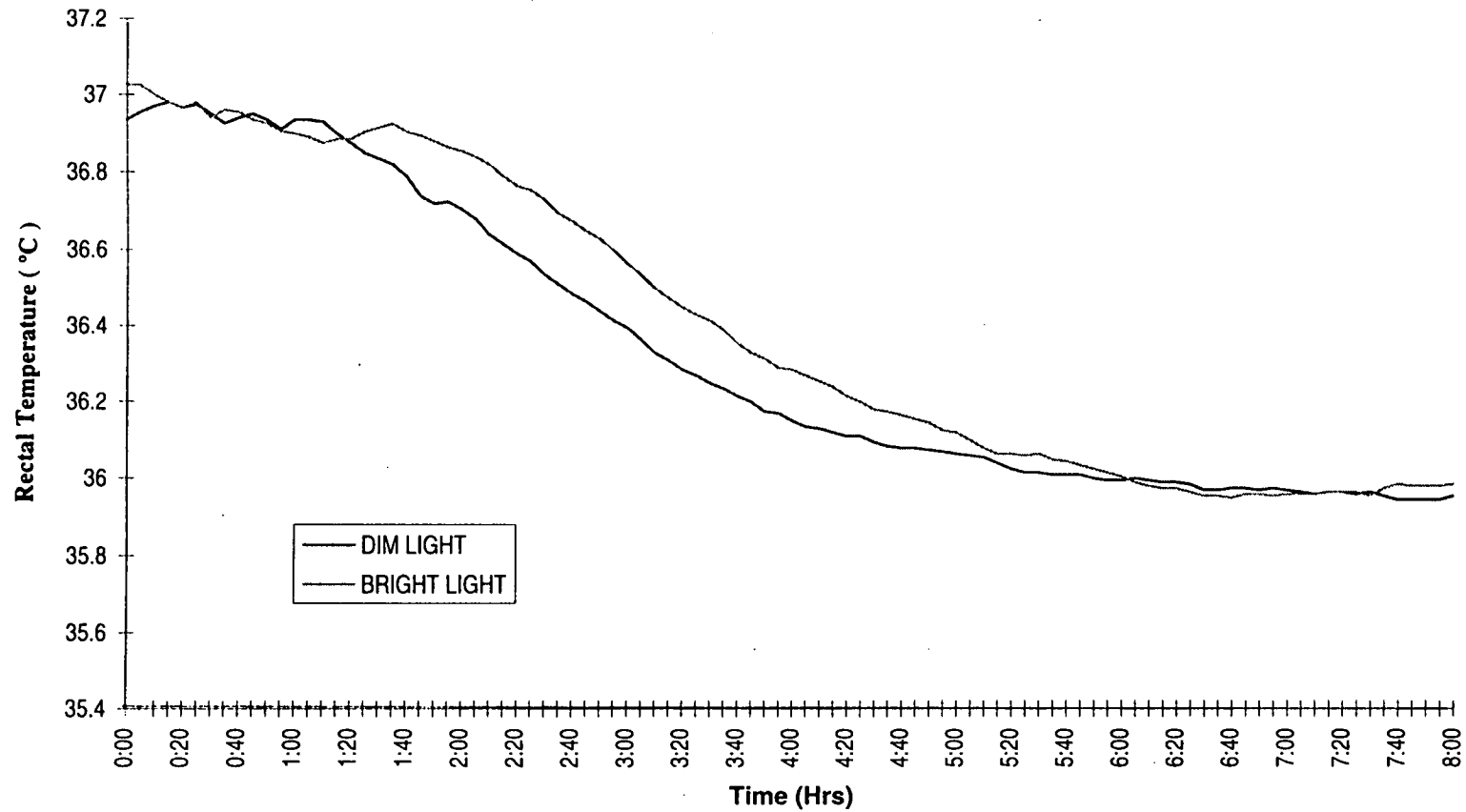
Figure 2: *Experiment 1 mean rectal temperatures following bright and dim light. Light exposure commenced at 0:00hrs and ceased at 2:00hrs at which point subjects retired to bed.*

Sleep. Table 4 shows the means and standard deviations of sleep variables. Statistical analyses of sleep variables were conducted by t-tests. No significant differences were found following BL for Sleep Onset Latency (SOL), Movement Time (MT), wakefulness, Stage 1 sleep, Stage 2 sleep, Stage 4 sleep, REM sleep or REM sleep latency. However, significantly more Stage 3 sleep [t(10) = 2.76 , p<.05] and SWS (stages 3 and 4 sleep added together) were found following BL than DL [t(10) = 2.38, p<.05]. Table 4 shows individual subject scores for Stage 3 and SWS. Examination of this table reveals that ten of the eleven subjects recorded more Stage 3 sleep in the BL condition (31.4min) than the DL condition (25.2min) and nine of the eleven subjects recorded more SWS following BL (93.1min) than following DL (82.9min).

Amounts of SWS occurring within each of the first four sleep cycles were summed and assessed in a 2 x 4 Condition (DL/BL) x Cycle (1-4) ANOVA . This analysis indicated that significantly more SWS occurred in the BL condition across the night [F(1,10 = 8.9, p<.05] and that SWS amounts diminished significantly from sleep cycles 1 to 4 [F(3,30) = 20.43, p<.001]. No significant differences in SWS amounts were found between the conditions on any single sleep cycle, but a trend existed for more SWS in the fourth cycle in the BL condition (12.0min) compared with the DL condition (6.7min) [t(10) = 1.9, p<.09]. Figure 3 illustrates these effects.

Amounts of SWS occurring during the first seven hours of sleep (all subject records extended for 7 hours) were also summed and assessed in a 2 x 7 Condition (DL/BL) x Hour (1-7) ANOVA which again indicated significantly more SWS in the BL condition [F(1,10) = 5.37, p<.05] though SWS amounts within any single hour were not found to differ between conditions. This data was also used for a cumulative analysis of SWS per hour across the seven hours of sleep. This analysis also indicated more SWS in the BL condition [F(1,10) = 6.34, p<.05], diminishing amounts of SWS over time [F(6,60) = 73.5, p<.001] and a significant Group x Time interaction [F(6, 60) =6.35, p<.01] such that more SWS had accumulated by the end of hours 5, 6 and 7 in the BL condition (hour 5 = 85.86min, hour 6 = 90.72min, hour 7 = 93.1min) compared with the DL condition (hour 5 = 72.9 min, hour 6 = 75.9min, hour 7 = 76.8min) [t(10) = 2.5, p<.05, t(10) = 2.95,   p<.05 and t(10) = 3.45, p<.01 respectively]. These elevations are illustrated in Figure 4.

Table 4. Experiment 1 sleep stage means and standard deviations (minutes) for dim-light and bright-light conditions.

SLEEP VARIABLES	MEAN TIMES (min) (SDs in Parentheses)	
	DIM-LIGHT	BRIGHT-LIGHT
MT	2.6 (2.3)	3.0 (2.7)
WAKE	37.1 (24.8)	37.2 (25.2)
STAGE 1	27.1 (10.7)	27.3 (9.2)
STAGE 2	215.4 (22.4)	216.6 (25.5)
STAGE 3	25.2 (8.9)	31.4 (8.5)*
STAGE 4	57.7 (21.6)	64.7 (27.9)
SWS	82.9 (19.6)	93.1 (20.8)*
SWS CYC 1	44.6 (21.4)	51.0 (22.8)
SWS CYC 2	22.6 (17.3)	21.6 (18.5)
SWS CYC 3	9.2 (9.0)	10.5 (10.3)
SWS CYC 4	6.7 (8.1)	12.9 (12.4)
REM	108.7 (21.7)	101.6 (16.6)
SOL	31.3 (25.3)	27.1 (20.9)
REM LATENCY	87.3 (40.9)	92.3 (44.8)

* p<.05

Asterisks indicates significant differences between conditions. Statistical analyses are described in the text.

Note: SOL = Time from lights out to first minute of Stage 2 sleep.
REM LATENCY = Time from first Stage 2 to the first REM epoch.

Table 5. Individual subject scores recorded for sleep onset temperature (SOT), Stage 3 sleep and Slow Wave Sleep (SWS) following DL and BL conditions

Subject	SOT (°C)		Stage 3 (min)		SWS (min)	
	DL	BL	DL	BL	DL	BL
MP	36.78	36.99	25.5	36.75	71.75	81.25
SC	36.79	37.04	28.5	39.75	56.12	60.25
PJ	36.3	36.41	37	29.75	55	94
DA	36.86	36.94	22.5	23.25	83.5	113.75
MK	36.43	36.59	37.75	51	105.75	110.25
LE	36.27	36.42	32.5	32.75	83.75	82.75
SP	36.31	37.17	30	27	100.75	105.75
CG	36.17	36.27	13	27	78.75	63.25
CW	-	-	15.25	28.75	96	104.25
TB	36.38	36.3	12.5	20.5	66.75	90.25
BP	36.64	36.67	22.5	28.5	114	126.25
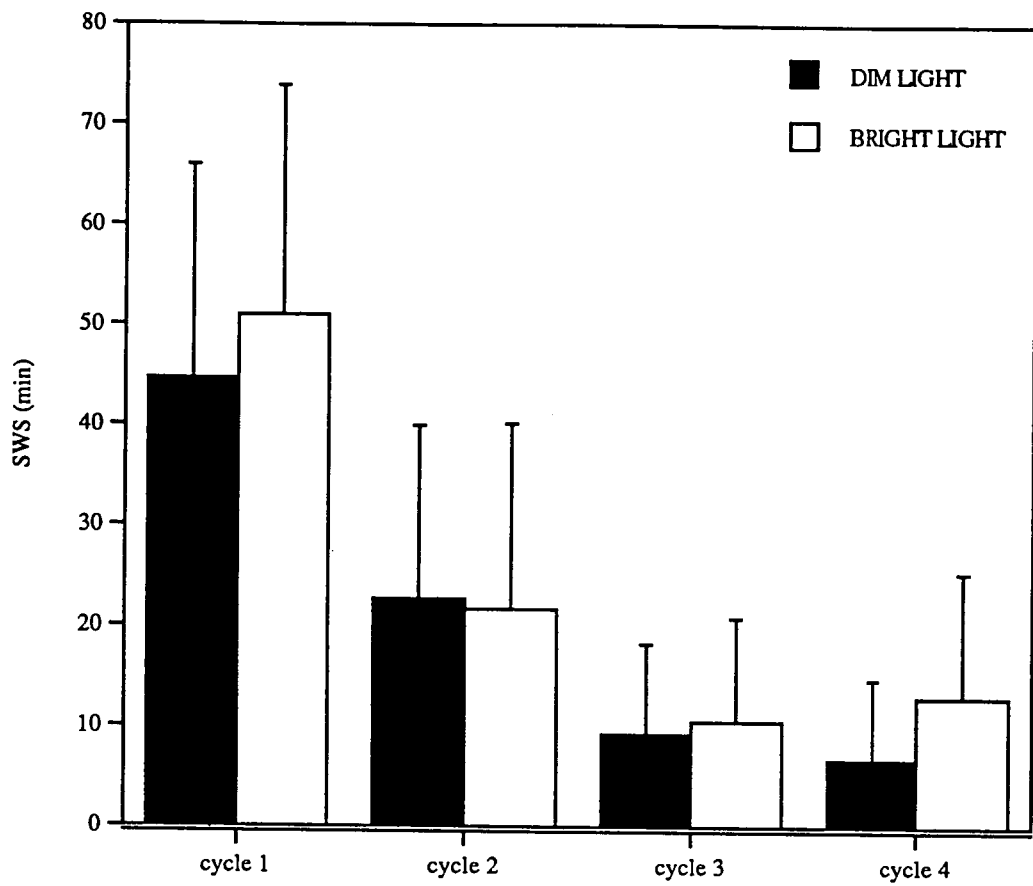
Figure 3: *Experiment 1 SWS amounts and standard deviations occuring during each of the first four sleep cycles in the bright-light and dim-light conditions.*
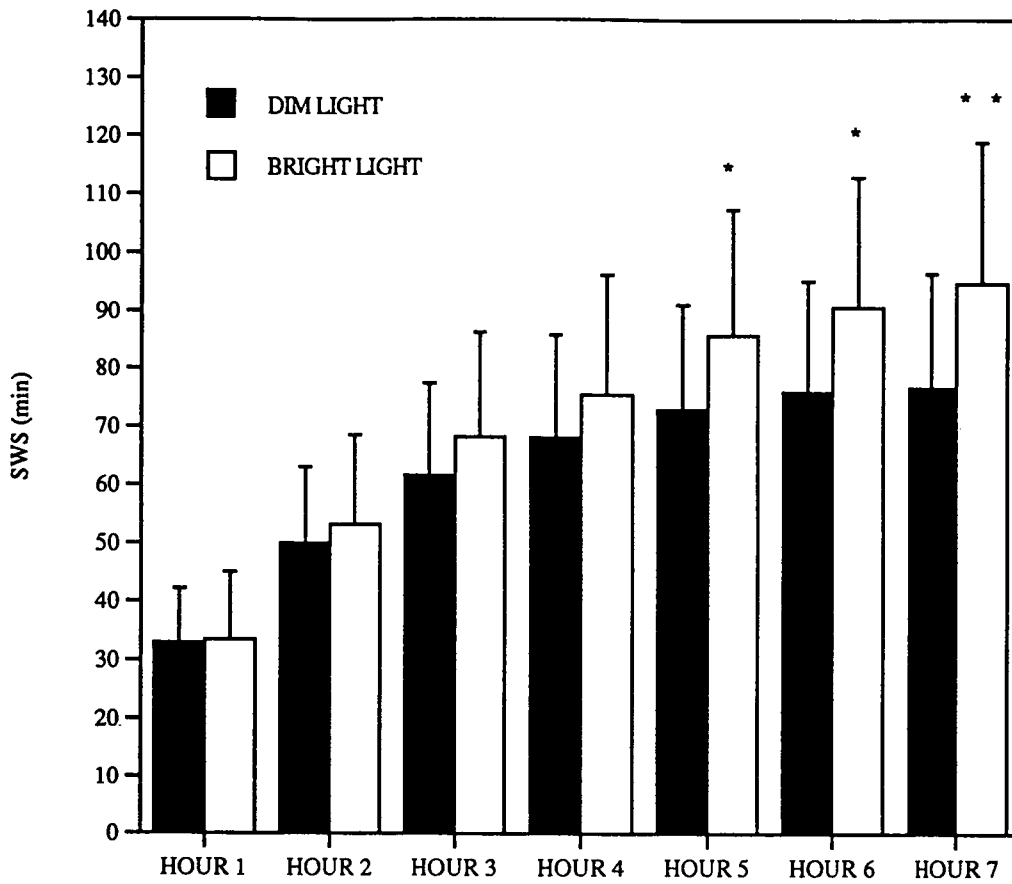
Figure 4: *Experiment 1 levels of SWS accumulated per hour of sleep following dim-light and bright-light.*

* *p<.05*
** *p<.01*

Statistical analyses are described in the text.

Discussion

Two hours of bright-light before habitual bedtime significantly elevated rectal temperature and increased amounts of Stage 3 and SWS. An increase in rectal temperature of 0.2 to 0.3 °C following bright-light administration at this time was consistent with most previous studies (Badia et al., 1991; Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991; Strassman et al., 1991) but not with Carrier et al. (1995) who reported no increase in temperature. The finding that the temperature elevation lasted for the first two hours following bright-light administration is consistent with Bunnell et al. (1992) who also used a 2hr exposure time. Cajochen et al. (1992) reported rectal temperature elevations up to 4hrs following bright-light administration. This is consistent with the suggestion of Bunnell et al. (1992) who found a similar result and can be best accounted for by the longer exposure period (3hrs) used in that study.

The significant increase in SWS observed in the present study was also consistent with another report in which enhanced low frequency EEG activity was found (Bunnell et al., 1992). Similar increases in SWS (approximately 15min) were found by Bunnell et al. (1992), though these differences fell short of statistical significance. The larger number of subjects used in the present study (n=11) compared with Bunnell et al. (1992) (n=5) may account for this difference.

The failure to find any disturbance to sleep onset is in contrast to some studies (Cajochen et al., 1992; Dijk et al., 1991; Drennen et al., 1989) but not others (Bunnell et al., 1992). Indeed there was no evidence in the present data of any sleep disruption following pre-sleep bright-light administration, either to sleep onset latency or SWS. In Bunnell et al., (1992) and the present study DL was considerably brighter (100lux) than the very low light levels (6lux) used in the other studies. It is possible that subjects in the latter studies became excessively drowsy under these conditions. If so, this would explain why SOL was found to be increased in these studies and not in the Bunnell et al., (1992) or the present study.

However, the trend toward increased SWS in the fourth sleep cycle was

consistent with two other studies reporting sleep immediately following evening bright-light (Cajochen et al., 1992 and Carrier et al., 1995). Cajochen et al. (1992) interpreted the effect as owing to a greater sleep debt incurred in the bright-light group who showed increased SOL and diminished SWA during the first NREM period. As there was no evidence of either of these effects in the present data, (in fact SWS was non-significantly elevated in the first NREM period), or in that of Carrier et al. (1995), the trends toward increased SWS in the fourth sleep cycle appear to be due to some other factor. Although preferring an explanation based on "sleep pressure", Cajochen et al. (1992) did not rule out the possibility that the increase in SWA seen in the fourth NREM period was due to a delayed thermic effect. Similarly, it is possible in the present experiment that the thermic effect on SWS usually seen early in the sleep period was delayed until later cycles by potentially arousing effects of bright-light.

In summary the higher levels of SWS in association with increased body temperature are consistent with other studies which have reported a similar relationship following physical exercise (Horne & Moore, 1985) and passive heating (Horne & Staff, 1983; Jordan et al., 1990). The finding is also consistent with one other study to report enhanced sleep following evening bright-light (Bunnell et al., 1992). In addition to the direct thermal effects of bright-light, it is possible that a CTR phase-shifting effect might also have accounted for the present results. The evidence for this possibility will be examined in the following chapter and Experiment 2 was designed to empirically test this hypothesis.

CHAPTER FIVE

BRIGHT-LIGHT CIRCADIAN RHYTHMS AND SLEEP

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5.1 Human Circadian Rhythms

De Maiaran (1729) first reported that a plant would continue to have approximately 24 hr rhythms of activity when light and dark stimuli were absent. Since then a variety of circadian rhythms have been identified in plants, animals and humans which persist in the absence of entraining "zeitgebers" (time givers). Circadian rhythms may be most easily identified in a "free-running" environment, in which the absence of external time cues allows the rhythm to be measured independently of masking or confounding variables (Weitzman, Czeisler, Zimmerman, Moore-Ede, & Ronda, 1983). In humans, circadian rhythms of body temperature (Strogatz, Kronauer, & Czeisler, 1986), melatonin excretion (eg. Cagnacci, Solandi, & Yen, 1993) and alertness (e.g. Lavie, 1991) have been found to exist. These rhythms are thought to be controlled by one or more inner biological clocks or oscillators, assumed to be anatomically associated with the suprachiasmic nuclei of the hypothalamus (Rusak & Groos, 1982). Under normal circumstances in which environmental zeitgebers are operating, these rhythms are synchronised with each other. However, under free running conditions where subjects are isolated from time cues "internal desynchronisation" of one rhythm from another may occur (Kronauer et al, 1980; Wever, 1975, 1977). For instance, desynchronisation of the sleep-wake and Core Temperature Rhythm (CTR) has frequently been observed in free-running experiments, such that subjects retire to sleep at progressively later points of the CTR (e.g. Czeisler, Weitzman, Moore-Ede, Zimmerman, & Kronauer, 1980).

5.2 Bright Light and Human Circadian Rhythms

Until recently it was thought that in humans, unlike animals, the circadian phase-shifting effects of light were modest (Drennen, Kripke, & Gillan, 1989). However, the findings that some blind subjects showed abnormal or free-running rhythms (Lewy & Newsome, 1983), that physiological adjustment to jet-lag may be augmented by light treatment (Daan & Lewy, 1984) and that night-time melatonin onset may be delayed by bright-light (Lewy et al., 1980) suggested that bright-light might be a more powerful entrainer of human circadian rhythms than thought previously. Most noticeably, the finding that night-time melatonin onset is suppressed by bright evening light (>2500 lux) (Lewy et al., 1980) suggested that human circadian rhythms might be strongly affected by daylight intensities, but unaffected by indoor illumination levels (Lewy, Sack, Miller, & Hoban, 1987). Subsequently it has been shown that bright-light is a powerful human zeitgeber and can shift circadian rhythms of melatonin (Lewy et al., 1980; Lewy et al., 1987), alertness (Dawson & Campbell, 1991), REM sleep (Sack, Lewy, Miller, & Singer, 1986) and core temperature (Czeisler et al., 1986; Czeisler et al., 1989; Dawson & Campbell, 1991; Drennen et al., 1989; Rosenthal, Joseph-Vanderpool et al., 1990).

While some studies indicate that only duration and brightness of the light are critical to phase shifting (James, Wehr, Sack, Parry, & Rosenthal, 1985), most studies indicate that the timing of the light relative to the endogenous circadian rhythm determines both the direction and magnitude of bright-light induced phase shifts (Czeisler et al., 1986; Czeisler et al., 1989; Daan & Lewy, 1984; Drennen et al., 1989; Lewy et al., 1983; Lewy, Sack, & Singer, 1984; Lewy et al., 1987; Rosenthal, Levendosky et al., 1990; Sack et al., 1986). A human Phase Response Curve (PRC) to the entraining effect of light similar to that reported in primates (Lewy et al., 1983) has thus been proposed for humans (Czeisler et al., 1986; Czeisler et al., 1989; Lewy et al., 1983; Lewy et al., 1984). When bright-light is administered before the CTR nadir, the CTR is phase delayed such that the nadir occurs at a later clock time. When bright-light is administered after the CTR nadir, the CTR is phase advanced such that the nadir occurs at an earlier clock time. Phase

shift magnitude also varies with temporal proximity of bright-light to the CTR nadir; phase shift magnitudes increase as the timing of bright-light temporally approaches the CTR nadir, and decrease as bright-light periods move temporally further from the CTR nadir. Thus maximal phase delays and phase advances of the CTR occur when bright-light is administered immediately prior to, and following the CTR nadir respectively. The position of the circadian pacemaker can be shifted by appropriately timed bright-light to any other chosen phase position from 1 to 3 days (Czeisler et al., 1989).

Of most interest in the current thesis are possible phase-shifting effects of evening bright-light administered until habitual bedtime. There is some variation in the literature reporting the effects of such administrations. Two studies have reported phase-delays of up to 3hrs following three consecutive evening exposures to bright-light (Carrier & Dumont, 1995; Drennen et al., 1989) and another study (Czeisler et al., 1986) reported a 6hr delay of the CTR following a week of exposure to bright-light before bedtime. Phase-delays of the CTR have even been found after only a single pulse of bright-light administered until habitual bedtime (Dawson, Lack, & Morris, 1993). Lack and Wright (1993) found delayed CTRs following BL administration prior to habitual bedtime, though their subjects were early morning insomniacs with "earlier than normal" temperature rhythms prior to BL treatment. Under these conditions exposure to BL prior to habitual bedtime would result in exposure unusually close to the CTR nadir producing correspondingly unusually large delays of the CTR. On the basis of these results one might expect a delay of the CTR following light exposure as administered in Experiment 1 of the present thesis.

However other studies have found no CTR delay after evening bright-light. The failure to find CTR delays in these studies may be explicable in terms of the somewhat unusual methodologies employed; continuous light during a constant routine (Daurat et al., 1993), 10min pulses of bright-light each hour (Horne et al., 1991) and permission to sleep during light exposure in free-running subjects (Honma, Honma, & Wada, 1987). Rosenthal, Joseph-Vanderpool et al., (1990)

found only four of ten subjects had delayed CTR's following 9 consecutive nights of BL exposure until 21:00hrs though bright-light was also administered in the early morning; a manipulation likely to minimise evening light effects. Other studies of temperature following a single exposure to bright-light have not formally assessed CTR, though visual examination of the data suggests no phase-delay took place (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991).   In conclusion, while the wider literature suggests that exposure to evening bright-light should delay the phase of the CTR, the literature in which bright-light is administered before the normal sleep period suggests that it is possible, but not necessarily the case, that such exposure will delay the CTR.

5.3 Current Applications

The phase-shifting effects of bright-light are currently being investigated and trialed for application to circadian rhythm alertness and sleep problems associated with mis-alignment between the circadian pacemaker and the sleep-wake cycle. While a complete review of this work is beyond the scope of the present thesis, it should be noted that bright-light induced shifts of the circadian pacemaker have been successfully employed in improving night-time alertness and day-time sleep in simulated night-shifts (Czeisler et al., 1990; Dawson & Campbell, 1991; Dawson, Encel, & Lushington, 1995; Eastman, Liu, & Fogg, 1995; Thessing, Anch, Muehlbach, Schweitzer, & Walsh, 1994; for a review see Czeisler & Dijk, 1995), in treating delayed sleep phase syndrome (e.g. Lack & Wright, 1993; Rosenthal, Joseph-Vanderpool, et al., 1990), and in treating seasonal affective disorder (e.g. Rosenthal, Alytia, et al., 1990).

5.4 Melatonin and Circadian Rhythms

The section above has outlined the potential for evening bright-light to shift the CTR. In addition it should be noted that melatonin rhythms are also shifted by

bright-light. It has been shown that bright-light produces equivalent phase-shifts of the CTR and circulating plasma melatonin such that the maximum of the melatonin rhythm precedes the CTR nadir by approximately 1.8hrs before and after bright-light exposure (Shanahan & Czeisler, 1991). It has also been shown that the CTR and melatonin rhythms free-ran together with the sleep-propensity rhythm in a blind man (Nakagawa, Sack, & Lewy 1992). These results suggest that temperature and melatonin rhythms are governed by a single circadian pacemaker and accordingly are shifted together by bright-light.

Further, while not directly relevant to the present thesis, it is of some interest to note that in addition to bright-light, melatonin itself may be a regulator of human circadian rhythms (Arendt, Deacon, English, Hampton, & Morgan, 1995; Lewy, Ahmed, Jackson, & Sack, 1992). The PRC for melatonin appears to be 180°C out of phase with that of bright-light (Lewy et al., 1992). Thus melatonin administration in the late evening will produce a phase advance of the circadian pacemaker while melatonin administration in the morning will delay the circadian pacemaker. Exogenous administration of melatonin is being used to treat circadian rhythm disorders found in jet-lag, blind people and shift-workers (see Arendt et al., 1995 for a full review).

5.5 Circadian Influences on Sleep

Of most interest to the present thesis are the possible effects of a bright-light induced CTR delay on sleep. In the following section consideration will be given to how circadian phase interacts with sleep variables and how shifts of the CTR by bright-light may impact on these sleep variables.

5.5.1 Sleep Onset

Lay notions of sleep often assume a simple linear relationship in which amount of prior wakefulness predicts sleepiness and the ability to resist or initiate

sleep. However, it has been shown in a number experimental paradigms that sleep onset is much more affected by circadian phase than by prior wakefulness. In free-running studies, in which sleep onset choices are made independent of time cues or social requirements, internally synchronised subjects have repeatedly been shown to initiate sleep at or close to (within one hour of) the CTR nadir (Czeisler et al, 1980; Monk & Moline, 1989; Wever, 1985). A similar pattern has been noted in internally desynchronised subjects (Czeisler et al., 1980; Wever, 1985). It appears that in free running subjects sleep onset and temperature are inversely related such that the likelihood of sleep onset is greatest at the temperature nadir, and least at the temperature acrophase (Czeisler et al., 1980). In addition, a secondary peak in sleep propensity appears to occur during before the temperature acrophase (Strogatz, Kronauer, & Czeisler, 1986).

Moreover, there does not appear to be an even simple linear relation between circadian phase and ability to resist/initiate sleep. It has been shown that there are phases of the 24hr period associated with a very slight probability of initiating sleep, even under conditions of sleep deprivation (Lavie, 1986, 1991; Lavie & Zvulini, 1992). It appears that two "forbidden zones" or "wake maintenance zones" occur during the periods before the primary and secondary sleep propensity peaks.

The "ultra-short" sleep-wake cycle has been used to investigate sleep propensity with a finer temporal resolution than previously used (e.g. Lavie, 1986, 1991). In this schedule 20min periods are divided into two sections; a 7min period for sleep, and the remaining 13min period for sustained wakefulness. Using an ultra-short sleep-wake cycle across a 24hr period it has been shown that the wake maintenance zone ends abruptly, not gradually, with an almost immediate rise to asymptote of the ability to initiate sleep, (Lavie, 1986, 1991). The transition point from wake maintenance to high sleep propensity has been termed the "sleep gate" (Lavie, 1986, 1991). The phenomena of wake maintenance zones and sleep gates appear robust within individuals and under conditions of sleep deprivation (Lavie, 1986, 1991; Lavie & Segal, 1989). A primary nocturnal sleep gate has been found to occur reliably within individuals at times between 21:00hrs and 4:00hrs in normal

entrained subjects (Lavie, 1986). A secondary mid-afternoon sleep gate has also been reported to occur at approximately 14:00hrs (Lavie, 1986, 1989). Thus sleep propensity appears to have a primary peak around the CTR nadir and a secondary peak during the mid-afternoon. Between these peaks lie wake-maintenance zones in which sleep propensity is very low.

This underlying sleep-propensity rhythm (as determined by an ultrashort sleep-wake protocol) has also been found to be synchronised with the temperature and melatonin rhythms in a single case study of a blind man (Nakagawa, Sack, & Lewy, 1992). Thus the sleep propensity rhythm may free-run with the CTR and melatonin rhythm out of synchrony with the actual sleep-wake rhythm. Although this man did not complain of clinical insomnia the desyncrony of rhythms apparently understandably resulted in some loss of sleep efficiency. The implication of this is that sleep propensity appears to be temporarily (if not causally) linked with the CTR and melatonin rhythms.

In accordance with the literature cited above, CTR delays following evening bright-light have been found to reduce sleepiness on simulated night-shifts both on the night following the bright-light pulse (Thessing et al., 1994), and on the second night following the light pulse (Dawson & Campbell, 1991). Possible explanations for this include suppression of melatonin and increased temperature (discussed in Chapter 3). Another explanation is that moderate delays of the CTR result in sleep onset occurring higher on the falling limb of the CTR, or even during a "wake maintenance zone"; both associated with relatively reduced sleep propensity. Indeed one study has reported increased SOL following bright-light induced delays of the CTR (Carrier & Dumont, 1995). However, shifts of the CTR by bright-light sufficient to place normal sleep onset time into the wake maintenance zone have not always resulted in greatly increased SOL (Drennen et al., 1989). SOL's in this study were increased with bright-light administration, but not to the extent predicted by the forbidden zone hypothesis. In general though, delays of the CTR via evening bright light might be expected to increase SOL as sleep propensity decreases as sleep onset time approaches the CTR acrophase.

5.5.2 Sleep Duration

Sleep duration is also primarily affected by circadian phase. Sleep durations are longest when sleep is initiated near the CTR acrophase and shortest when initiated near the nadir. This has been shown in entrained subjects (Gillberg & Akerstedt, 1982; Weitzman, Czeisler, & Moore-Ede, 1979; Weitzman et al, 1983), in subjects with displaced sleep onset times (Akerstedt & Gillberg, 1981) and in subjects under free-running conditions (Czeisler et al., 1980; Weitzman et al., 1979; Weitzman et al., 1983; Wever, 1985). For instance, in one study it was reported that free-running subjects averaged 7.8hrs of sleep when it was initiated at the CTR nadir, and 14hrs of sleep when initiated at the CTR maximum (Czeisler et al., 1980). As some studies have reported no correlation between sleep length and prior wakefulness (Czeisler et al., 1980) circadian influences have been viewed as the chief determinants of sleep length (Strogatz et al., 1986). Accordingly, it has been reported that sleep length can be predicted according to where sleep is initiated relative to either absolute body temperature (Zulley, 1976) or an educed 24hr curve (Czeisler, 1980). The dependence of sleep length on circadian phase might be interpreted as indicating that sleep length varies according to thermoregulatory need; when temperature is high (as at the CTR acrophase) relatively more sleep is needed to down-regulate temperature than if sleep is initiated at lower temperatures. Alternatively, it has been argued that it is the rise in the CTR that terminates sleep, and thus sleep length will vary according to how many hours it was initiated prior to the circadian rise (Gillberg & Akerstedt, 1982). Accordingly, delays of the CTR produced by evening bright light might be expected to result in longer sleep durations, as sleep onset would be initiated closer to the acrophase of the CTR and further from the CTR nadir.

5.5.3 REM Sleep

REM sleep too shows a distinctive circadian periodicity in a variety of experimental paradigms. REM amounts have been shown to be largely affected by circadian factors in studies of naps at varying times (eg. Dinges, 1986), during free-

running studies (eg. Weitzman et al., 1979; Zulley, 1980), under conditions of internal desynchronisation (eg. Czeisler, 1980) and in studies of temporally displaced sleep (Akerstedt & Gillberg, 1981). In general it is found that increasing body temperature is correlated with decreasing REM sleep propensity and vice versa, such that REM sleep amounts are greatest at the nadir of the CTR and least at the acrophase of the CTR (Wever, 1985). Under free-running conditions REM sleep propensity and core body temperature remain synchronised, while SWS and the sleep-wake cycle itself may oscillate independently (Czeisler et al, 1980; Weitzman et al, 1979). It has even been observed that under free-running conditions subjects will occasionally go from wakefulness directly to REM sleep, if sleep is initiated just after the CTR nadir (Weitzman et al., 1983). Further, the dependence of REM amounts on circadian phase continues to exist under conditions of sleep deprivation (Dinges, 1986; Knowles, Coulter, Wahnon, Reitz, & MacLean, 1990). These results have been interpreted by some as indicating that certain sleep processes in the brain are endogenous biological rhythms (Weitzman et al., 1983). However, it remains to be seen if the correspondence between REM sleep and the CTR is coincidental or intrinsic (Wever, 1985).

As REM propensity is maximal at the nadir of the CTR, shifting of the CTR by bright-light might be expected to produce changes in REMLAT. Endo, Honma, Honma, and Suenaga (1993) found a lengthened first REM sleep period following a 1hr advance of the CTR/melatonin rhythm induced by morning bright-light. These results were interpreted as consistent with REM propensity being linked with the CTR/melatonin rhythm. This has result has not always been obtained though. Carrier and Dumont (1995) reported no effect of a CTR phase-delay on REM latency, another study reported a slight *advance* in REM latency under phase-delayed conditions (Drennen et al., 1989) and a third study reported only trends for increased REMLAT following evening bright-light and decreased REMLAT following morning bright-light (Sack et al., 1986). In a final study Dawson and Lack (1988) reported REM disturbance in a subject whose CTR was not delayed by evening bright-light. These results suggest that REM propensity and timing following bright-

light may not reflect the typically found relationship between REM sleep and temperature.

5.5.4 Slow Wave Sleep

It is suggested that a delay of the CTR via evening bright-light may increase SWS in one or both of two possible ways; either by placing SWS onset at a higher phase of the CTR, or by a shift in the SWS propensity rhythm which may be linked to the CTR.

5.5.4a Higher temperature at sleep onset

If sleep onset time is held constant, a delay of the CTR in a normally entrained subject will result in sleep onset occurring higher on the falling limb of the CTR. The evidence reviewed in Chapter 2 suggests that temperature at sleep onset may be correlated with SWS (Berger & Phillips, 1988) such that temperature elevation around sleep onset enhances SWS. Thus one mechanism by which a delay of the CTR might increase SWS is via increased temperature at sleep onset.

5.5.4b A circadian variation in SWS

Unlike sleep onset, duration and REM sleep, SWS amounts have typically been reported to vary little according to circadian phase. However, some studies have suggested a distinct circadian variation in SWS linked with the CTR. What follows is a discussion of the popular position that SWS varies strictly with amounts of prior wakefulness, and a review of the evidence that an additional circadian influence may exist.

Careful monitoring of the effects of full or partial SWS deprivation has led some authors to believe that SWS is primarily under homeostatic control; that a given amount of SWS is required per day, and that homeostatic mechanisms operate to maintain this set-point. Thus SWS debt incurred following selective or total sleep

deprivation is substantially reclaimed if the following sleep period is uninterrupted (Borbely, Baumann, Brandeis, Strauch, & Lehmann, 1981), and may be fully reclaimed over 2 uninterrupted recovery nights (Borbely et al., 1981). SWS amounts are also preserved in studies of restricted sleep, indicating its physiological priority over other stages (Carskadon, Harvey, & Dement, 1981; Taub & Berger, 1976; Tilley & Wilkinson, 1984; Tilley, 1985). The same reclamation of SWS debt occurs in nap recovery sleep such that the SWS debt on the recovery night is minimised or eliminated by afternoon nap sleep (Tilley, Donohoe, & Hensby, 1987).

Given that homeostatic requirements for SWS amount are met, it has typically been found that SWS amounts vary according to duration of prior wakefulness (Akerstedt & Gillberg, 1981; Borbely, 1981, 1982; Czeisler et al., 1980; Dinges, 1986; Hume & Mills, 1977; Hume, 1983) or duration of elapsed time since termination of the last sleep episode (Webb & Agnew, 1967). SWS amounts have been observed to increase linearly with increases in amounts of prior wakefulness time up to approximately 30hrs (Dinges, 1986), or up to 16hrs of sleep deprivation (Akerstedt & Gillberg, 1981) beyond which little more SWS is observed to occur. The relationship between amount of prior wakefulness and subsequent SWS has been demonstrated in studies of sleep displaced to progressively later times (Akerstedt & Gillberg, 1981; Dinges, 1986; Hume & Mills, 1977; Webb & Agnew, 1967), in studies of nap sleep (Tilley et al., 1987) in free-running studies (Czeisler et al., 1980), and at opposite phases of the circadian cycle (Dinges, 1986).

The relationship between sleep need and prior wakefulness is the basis for the popular two-process model of sleep (Borbely, 1982; Daan, Beersma & Borbely, 1984). This model assumes that sleep need ("Process S") accumulates during waking hours and decreases exponentially during sleep. Sleep onset occurs when the level of Process-S reaches a critical high threshold (H), and waking occurs when Process-S falls below a critical low threshold (L). A circadian process (Process-C), assumed to be controlled by a single circadian pacemaker, modulates the levels of the sleep and wake thresholds. Thus sleep propensity, intensity and duration may be predicted by

the model according to the combined effects of Process-S and C on the sleep and wake thresholds.

As SWS/SWA is seen as the electrophysiological correlate of Process-S (Tilley et al., 1987), the model predicts that following sleep onset at H, SWS will decline exponentially across the sleep period and reappear only after a rise in Process-S associated with wakefulness. The model does not predict that SWS will vary according to the circadian phase of sleep if prior wakefulness is held constant, as Process-S itself is not assumed to vary directly with Process-C, or with any other factor than prior wakefulness. Recently EEG delta activity has been reported to exhibit only "minor circadian modulation" as compared with Stage 2 spindle sleep (Dijk & Czeisler, 1995). The association between SWS amounts and durations of prior wakefulness are consistent with the CNS restoration theory offered by Horne (1988) in that cerebral wear and tear processes are incurred during wakefulness, and countered during SWS.

Despite this emphasis in the literature for SWS amounts to be determined by prior wakefulness a number of studies have reported a circadian influence on SWS propensity. The temporal coincidence at approximately 13:00hrs-14:00hrs between high SWS propensity and poor psychomotor performance (Broughton, 1968) propelled the hypothesis that the post lunch dip in psychomotor performance (Blake, 1967) might also be associated with high SWS propensity (Broughton, 1975), especially given that the mid-afternoon period is also a preferred time for napping. The most direct supportive evidence for such a 12hr ultradian rhythm in NREM sleep has been the reporting of a reappearance in SWS approximately 12hrs following initial occurrence in extended sleep (Gagnon & De Konick, 1984; Gagnon, De Konick & Broughton, 1985; Webb, 1986; Weitzman et al., 1980). This effect has been shown to occur in entrained subjects with displaced sleep times (Gagnon & De Konick, 1984; Gagnon et al., 1985; Webb, 1986) such that the 12hr rhythm in SWS propensity may even be phase shifted with habituation to the altered sleep onset time (Gagnon et al., 1985). The reappearance of SWS in extended sleep has also been found to occur under free-running conditions (Webb & Agnew, 1974; Weitzman et

al., 1980) and does not appear to be compensatory to SWS debt occurring in the major nocturnal SWS period (Webb, 1986). However, studies of extended sleep which have assessed EEG by period amplitude analysis (Feinberg, Fein, & Floyd, 1980) or spectral analysis using Fast Fourier Transform (FFT) (Dijk, Brunner, & Borbely, 1990) have failed to find evidence of a 12hr rhythm in SWS. Further, Horne (1988) has attempted to explain the reappearance of SWS as a consequence of accumulated periods of wakefulness during the extended sleep period, and not as related to a circadian influence. Even given this SWS debt it remains that SWS reappears following 12hrs as opposed to occurring indiscriminately at various points during the extended sleep, or being carried over to the next night.

A small mid-afternoon peak in SWS propensity, consistent with a 12hr rhythm in SWS propensity, has also been reported in subjects using ultra-short sleep-wake schedules across a 24hr period (Lavie, 1991). In addition, the high propensity for SWS at its usual time, which is evident in the ultra-short sleep-wake protocol, suggests a circadian influence as its occurrence at this time would not be predicted solely according to amounts of prior wakefulness. A similar 12hr rhythm of SWS propensity has also been reported following observations of uninterrupted sleep experimentally displaced across the 24hr day (Hume & Mills, 1977).

Of most interest to the present thesis, it has also been reported that the amount of SWS obtained during spontaneous naps by free running subjects is largely dependent on circadian phase (Campbell & Zulley, 1989). In this study SWS was maximal in naps initiated within 4 hrs of either the absolute temperature maximum, or the 24hr fitted curve acrophase. After partialling out the effect of prior wakefulness, regression analysis indicated a significant positive correlation between SWS amount and temperature.

On the basis of these findings one may speculate that a delay of the CTR via bright-light might enhance SWS propensity. Indeed Bunnell et al. (1992) suggested this possibility as explaining the enhanced low frequency EEG activity found following a single pulse of evening bright-light. Only one published study has

directly tested this possibility; Carrier and Dumont (1995) reported that SWS was
unaffected by a bright-light induced CTR delay of 1.62 hrs. Nevertheless, some
evidence exists to suggest that the timing of SWS with respect to the CTR may
influence amounts of SWS independently of durations of prior wakefulness, and it
remains a possibility that the increases in SWS found in Experiment 1 of the current
thesis were a consequence of a phase-delay of the CTR.

5.6 General Conclusions

In conclusion, the dependence of sleep onset, duration and REM sleep
propensity on circadian phase is well documented. SWS has typically been reported
as varying according to duration of wakefulness prior to the sleep period. However,
other evidence suggests the existence of a 12hr ultradian rhythm in SWS propensity.
Most importantly to the present thesis, this rhythm may be linked with the daily
temperature rhythm (Campbell & Zulley, 1989). SWS might be affected in at least
two ways by phase shifting of the CTR. Firstly, a delay of the CTR relative to sleep
onset in a normally entrained subject would result in higher sleep onset temperature,
a condition reported to be associated with enhanced SWS (see Chapter 3). Secondly,
if the SWS propensity rhythm coincides temporally with the CTR, it might be
expected that sleep begun closer to the acrophase of the CTR would contain more
SWS. Thus while SWS has generally not been reported as dependent on circadian
factors, there is some basis for hypothesising delays of the CTR might increase SWS
amounts.

CHAPTER SIX

EXPERIMENT 2

THE IMMEDIATE vs DELAYED EFFECTS OF EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP

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THE IMMEDIATE vs DELAYED EFFECTS OF EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP

The increases in SWS following evening bright-light found in Experiment 1 were associated with elevations in rectal temperature early in the subjective night. This association is consistent with other literature in which elevated SWS in humans is found following exercise (Horne & Moore, 1985), pre-sleep exposure to high ambient temperatures (Shapiro et al., 1989), menopausal hot flashes prior to sleep (Woodward & Freedman, 1994) and passive heating of the body (eg. Horne & Staff, 1983; Jordan et al., 1990) and head (Moriarty et al., 1988).

In addition to producing immediate elevations in temperature, evening bright-light has been shown to phase-delay the CTR. The extent to which the increases in SWS observed in Experiment 1 were causally related to such a delay is not known as no attempt to separate the two possible effects was made in Experiment 1, nor have the effects been separated in previous studies. It has been seen in the previous chapter that although the wider literature has emphasised a dependence of SWS amounts primarily on durations of prior wakefulness (e.g. Daan et al., 1984; Dijk, Cajochen, Tobler, & Borbely, 1991; Dinges, 1986; Tilley et al., 1987), there are also empirical findings which suggest that SWS amounts vary according to a circadian factor. The reappearance of SWS in some studies of extended sleep (Gagnon et al., 1984; Gagnon et al., 1985; Webb, 1986), the timing of the major nocturnal SWS episodes, a small mid-afternoon peak in SWS propensity found using the ultra short sleep-wake schedule (Lavie, 1991) and a correlation found between circadian body temperature and SWS amounts in naps of free-running subjects (Campbell & Zulley, 1989) all suggest a circadian influence on SWS. These findings suggest that SWS propensity increases as sleep onset time temporally approaches the CTR acrophase. Assuming sleep onset time is held constant, a delay in the CTR produced by evening bright-light would result in

sleep initiated closer to the CTR acrophase. The findings reviewed above and in Chapter 5 therefore suggest the possibility that SWS would be enhanced under these conditions.

The effects of bright-light induced CTR delays on sleep have been reported in few studies, and these have typically not reported SWS results. The most reliable finding appears to be that SOL is increased following delay of the CTR either immediately following bright-light exposure (Drennen et al., 1989) or on the night following multiple exposures to bright-light (Carrier & Dumont, 1995). Lack & Wright (1993) reported greater sleep durations in early morning insomniacs following delay of the CTR and Sack et al. (1986) reported delayed REM latency following multiple exposures to evening bright-light. Carrier and Dumont (1995) reported no change to SWS following a 1-2hr shift of the CTR by evening bright-light. None of the remaining studies reported NREM sleep effects. However, in a study of the immediate effects of bright-light on sleep, Bunnell et al. (1992) suggested the possibility the enhanced Slow Wave Activity (SWA) found was due to delay in circadian rhythms.

In Experiment 1 the immediate and phase-shifting effects of bright-light on sleep were confounded as no assessment of sleep was taken other than immediately following bright-light. Experiment 2 was designed to assess the immediate effect of evening bright-light on temperature and sleep independently of possible temperature and sleep effects associated delay of the CTR.

Method

Subjects. Subjects were 11 males recruited from the University population. The subject selection criteria adopted and requirements for subject participation imposed were the same as in Experiment 1. All subjects gave informed consent to participation and the project was approved by the University Ethics Committee.

Design. Table 6 outlines the design and procedures adopted in this study. A fully repeated-measures design was employed in which each subject was run once in a

dim-light (DL) and bright-light (BL) condition. Each condition spanned a period of four consecutive days. Subjects slept in the sleep laboratory on each of the four corresponding nights. In the DL condition subjects watched TV/video for the three hours prior to their habitual bedtime in dim-light (approx 100lux) on each of the four nights. In the BL condition subjects were exposed to approximately 3200lux of bright-light for the three hours prior to their habitual bedtimes on nights 1, 2 and 3, but received DL on night 4. Ambulatory rectal temperature was continuously monitored during each condition. Sleep was assessed on nights 1, 3 and 4 of each condition. The order of the conditions was counterbalanced across subjects.

The experiment was designed to assess the effects on temperature and sleep of multiple exposures to BL, and to assess the effects of any resultant phase-shift of the CTR independently of the BL itself. Thus assessment of the immediate effects of BL on temperature and sleep were made on nights 1 (following a single BL exposure) and 3 (following the third consecutive exposure of BL), while night 4 allowed assessment of the effects of any possible CTR phase-shift without the immediate effects of BL (as no BL was administered in either condition on this night). A constant routine procedure (in which constancy in vigilance, activity and food intake is maintained over a 28hr period) was not employed because the primary interest was sleep on the night immediately following a series of bright-light exposures. A constant routine procedure would not have allowed such an assessment. The dependent variables were rectal temperature, CTR characteristics, sleep architecture variables and sleep EEG assessed by fast fourier analysis of sleep EEG.

General Laboratory Procedures. Subjects reported to the laboratory on the morning of day 1 of each condition where they were instructed in the use of the Minni-logger and ambulatory temperature recordings were begun. The subjects returned three hours prior to their habitual bedtime whereupon either dim or bright-light conditions were commenced. During the hour prior to bedtime electrodes were attached in readiness for sleep assessment. Subjects retired to bed immediately following the light exposure period whereupon sleep recordings were commenced. Sleep recordings were stopped upon the subjects awakening at habitual waking times. Following this the

subjects left the laboratory for usual daily activities. This procedure was repeated for nights 2, 3 and 4 during which dim-light or bright-light was administered as described. All-night sleep recordings were made on nights 1, 3 and 4. Subjects were instructed to keep exercise and diet constant across all experimental conditions and a daily log of activities was kept. Although some differences in exercise habits were found between subjects, amounts and timing of exercise recorded by subjects were consistent across conditions and nights within any one subject. Temperature, sleep and fast fourier recordings were made according to the standard procedures described in Experiment 1.

Spectral Analysis. In traditional hand-scoring of sleep records large amplitude EEG activity occurring at approximately 0-2Hz is classified as SWS (Dijk et al., 1991). In addition to the hand scored record it has become customary to submit the EEG record to either period amplitude analysis (e.g. Feinberg, March, Floyd, Walker, & Price, 1978), or frequency analysis by Fast Fourier Transform (FFT) (e.g. Dijk et al., 1991). Analysis of EEG frequency by FFT can provide another index of EEG slow-waves (or any bandwidth desired). It might be expected *a priori* that SWS and SWA should be analagous, but this has not always been shown to be the case. As discussed, for example, several studies have found SWS in the latter portions of extended sleep while other studies have not found SWA at these times.

In the present experiment (and Experiment 3) the EEG signal was converted from analog to digital and recorded on-line to a 386 PC at 100 samples per sec. This data was subjected to FFT analysis of Slow-Wave Activity (SWA) (defined as 0.25-3Hz), and four other band-widths (3-8Hz, 8-12Hz, 12-30Hz and 30-50Hz). Total EEG Power (TP) was calculated for statistical analysis as the sum of all frequencies to 50Hz. Data were divided for analysis into chunks of 5.12sec which were combined into 30sec epochs to correspond with the paper record. Epochs containing noise due to body movement or poor electrode contact were excluded from analysis. Instead, the average value of the epoch immediately prior to and following the excluded epoch was substituted in its place.

Table 6. Day by day schedule of events in the BL and DL conditions during Experiment 2. Details of each event are described in the text. An adaptation night was held for each subject within 1 week prior to commencement of the schedule which was counterbalanced among subjects.

DAY	DIM-LIGHT	BRIGHT-LIGHT
DAY 1	Subjects arrive at the sleep laboratory 08:00-10:00hrs and are fitted with the rectal thermister & Mini-Logger. Continuous ambulatory temperature recordings are begun. Subjects engage in usual daytime activities. 3hrs prior to habitual bedtime subjects arrive at the sleep lab and **DL** is commenced. Subjects are prepared for sleep recordings and retire to bed at habitual bedtimes. All-night sleep recordings are made.	Subjects arrive at the sleep laboratory 08:00-10:00hrs and are fitted with the rectal thermister & Mini-Logger. Continuous ambulatory temperature recordings are begun. Subjects engage in usual daytime activities. 3hrs prior to habitual bedtime subjects arrive at the sleep lab and **BL** is commenced. Subjects are prepared for sleep recordings and retire to bed at habitual bedtimes. All-night sleep recordings are made.
DAY 2	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **DL** until bedtime. Subjects retire following a mock wire-up. No sleep recording is made.	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **BL** until bedtime. Subjects retire following a mock wire-up. No sleep recording is made.
DAY 3	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **DL** until bedtime. Subjects retire following preparation for all-night sleep recording.	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **BL** until bedtime. Subjects retire following preparation for all-night sleep recording.
DAY 4	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **DL** until bedtime. Subjects retire following preparation for all-night sleep recording. Subjects awake at habitual times, sleep recordings are stopped and temperature data is downloaded to PC.	Subjects rise at habitual times and engage in usual daytime activities. Subjects arrive at the sleep laboratory 3hrs prior to habitual bedtime and are exposed to **DL** until bedtime. Subjects retire following preparation for all-night sleep recording. Subjects awake at habitual times, sleep recordings are stopped and temperature data is downloaded to PC.

Results

Temperature. The temperature means and standard deviations across each Condition and Night are presented in Table 7. Two subjects' data on Night 1 were ruled out of temperature analyses because of poor quality sections of recordings (MP's DL condition and SC's BL condition on Night 1). Average rectal temperatures for each of five hours following light administration were calculated for each condition and each night. On the basis of findings from Experiment 1 it was expected that any temperature effects to follow bright-light would occur during the first two hours following exposure. The first two hours and the last three hours were therefore assessed independently using a 2 x 3 x 2 Condition (DL/BL) x Night (Night 1, 3 and 4) x Hour (1 and 2) MANOVA in the former case and a 2 x 3 x 3 Condition (DL/BL) x Night (Night 1, 3 and 4) x Hour (3, 4 and 5) MANOVA in the latter case. It was hoped that if no differences were found in the last 3hrs of sleep, analysis could be confined to the first 2hrs of sleep thus reducing the likelihood of Type 1 errors in post-hoc analysis. As expected, analysis of hours 3, 4 and 5 indicated that temperature declined from hour to hour [F(2, 16) = 8.2, p<.01][1] but no effects of Condition or Night were evident. Thus temperatures in hours 3-5 were equivalent in DL and BL conditions across all three nights. However, analysis of the first two hours following light exposure indicated a significant Condition x Night interaction [F(2, 16) = 4.3, p<.05] as well as an effect of Hour [F(1, 8) = 59.6, p<.001] showing a temperature decline from hour 1 to 2.

Dependent group t-tests indicated no differences on Night 1 but elevated temperature following BL on Night 3 during the second hour following light administration (DL = 36.25 °C, BL = 36.42 °C) [t(10) = -2.35, p<.05]. A similar trend existed for the first hour following light administration (DL = 36.5 °C, BL = 36.7 °C) [t(10) = 2.17, p<.06]. The upper panel of Figure 7 shows the elevation in temperature at this time in the BL Condition on Night 3. t-tests conducted on the Night 4 data indicated elevated temperature in the DL condition (36.62 °C) compared with the BL condition (36.45 °C) during the first hour following light exposure [t(10) = 3.29, p<.01].

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[1] All ANOVA tables cited are contained in Appendix D.

Temperature at sleep onset was also evaluated in a 2 x 3 Condition (DL/BL) x Night (Night 1, 3 and 4) ANOVA following calculation of rectal temperature at sleep onset time determined by the hand scored sleep records. This analysis indicated no effect of Condition [$F(1, 8) = .36$, $p>.05$] or Night [$F(2, 16) = .91$, $p>.05$] but the Condition x Night interaction was significant [$F(2, 16) = 5.2$, $p<.05$]. Dependent group t-tests indicated no difference in temperatures on Night 1 [$t(9) = .33$, $p>.05$], significantly elevated temperature in the BL condition on Night 3 [$t(11) = 2.9$, $p<.05$] and significantly elevated temperature in the DL condition on Night 4 [$t(11) = -4.6$, $p<.01$].

Table 7. Experiment 2 mean rectal temperatures during the five hours immediately following bright and dim light on nights 1, 3 and 4.

MEAN RECTAL TEMPERATURES (°C)
(SDs in Parentheses)

HOUR	NIGHT 1		NIGHT 3		NIGHT 4	
	DL	BL	DL	BL	DL	BL
1	36.49 (.28)	36.61 (.40)	36.50 (.26)	36.70 (.22)	36.62 (.29)	36.45 (.23)**
2	36.22 (.29)	36.31 (.30)	36.25 (.23)	36.42 (.30)*	36.39 (.30)	36.23 (.23)
3	36.07 (.18)	36.14 (.26)	36.14 (.22)	36.20 (.20)	36.29 (.19)	36.16 (.23)
4	36.04 (.19)	36.14 (.40)	36.09 (.17)	36.07 (.23)	36.23 (.17)	36.09 (.18)
5	36.05 (.18)	35.96 (.20)	36.08 (.25)	35.99 (.17)	36.23 (.17)	36.08 (.18)

* **p<.05**
** **p<.01**

Asterisks indicate significant differences between values for each hour within separate nights. Statistical analyses are described in the text.

Table 8. Experiment 2 sleep stage means and standard deviations (minutes) in DL and BL conditions across each Night.

SLEEP STAGE	MEAN TIMES (min) (SDs in Parentheses)					
	NIGHT 1		NIGHT 3		NIGHT 4	
	DL	BL	DL	BL	DL	BL
MT	3.1 (1.6)	4.2 (1.1)	3.3 (1.2)	4.3 (3.2)	3.5 (2.1)	3.2 (1.7)
WAKE	21.0 (15.2)	26.5 (20.3)	21.0 (17.6)	24.9 (14.6)	24.8 (23.2)	45.6 (28.6)*
STAGE 1	26.0 (10.5)	30.8 (16.9)	27.2 (11.5)	23.9 (9.6)	33.5 (15.7)	27.0 (12.0)
STAGE 2	189.2 (31.9)	186.9 (39.6)	196.4 (25.8)	186.8 (45.0)	169.7 (64.3)	182.3 (36.1)
STAGE 3	40.6 (17.8)	41.0 (22.4)	39.5 (15.1)	50.4 (17.6)	37.7 (11.8)	39.8 (11.6)
STAGE 4	77.3 (28.8)	77.5 (16.7)	67.9 (12.7)	85.5 (25.1)*	74.7 (17.0)	77.7 (28.1)
SWS	118.0 (33.8)	118.6 (16.7)	107.6 (24.3)	136.5 (38.1)*	112.4 (26.1)	117.5 (33.5)
SWS CYC 1	35.1 (16.7)	27.6 (8.8)	30.2 (16.4)	30.7 (14.6)	29.1 (14.6)	32.4 (18.0)
SWS CYC 2	22.9 (13.6)	24.9 (13.5)	23.6 (10.3)	28.7 (16.9)	26.8 (11.1)	21.8 (11.4)
SWS CYC 3	8.9 (7.5)	9.0 (11.9)	10.6 (6.8)	14.9 (8.3)	6.1 (5.3)	13.2 (9.9)
SWS CYC 4	4.1 (8.7)	8.1 (8.1)*	5.2 (7.1)	10.2 (9.3)	9.3 (6.9)	5.2 (5.1)
REM	93.9 (32.9)	102.0 (30.1)	103.7 (21.9)	109.5 (20.2)	92.0 (25.2)	94.5 (21.1)
SOL	14.0 (7.9)	25.3 (19.4)	17.5 (11.7)	23.4 (18.0)	18.8 (17.0)	36.6 (25.9)**
REM LATENCY	111.6 (47.2)	88.3 (28.6)	80.6 (21.6)	75.1 (15.6)	82.0 (20.9)	91.5 (34.2)

* p<.05
** p<.01

Asterisks indicate significant differences between conditions within nights. Statistical analyses are described in the text.

Abbreviations: CYC = Sleep Cycle, SOL = Sleep Onset Latency

Note: SOL = Time from lights out to first minute of Stage 2 sleep.
REM LATENCY = Time from first Stage 2 to the first REM epoch.

To assess for possible phase-shifting effects in the BL condition, CTR nadir was established by fitting a cosine wave to the 24hr period immediately preceding the subjects' morning waking times. These times were converted to "minutes following midnight" and assessed in a 2 x 3 Condition (DL/BL) x Night (nights 1, 3 and 4) ANOVA. This analysis indicated no effect of Condition, Night or Condition x Night interaction on either Night 1 [DL = 286.4min (91.2min), BL = 317.7min (109.6min)], Night 3 [DL = 334.4min (187.6min), BL = 309.2min (113.1min)] or Night 4 (DL = 332.7min (121.6min), BL = 328.4min (88.5min)]. Phase angle at sleep onset was also calculated and assessed in a Condition x Night ANOVA. As bedtime was held constant, and assuming there were no differences in sleep onset latency, delays of the CTR by BL would result in smaller phase-angle values at sleep onset. Consistent with the CTR analysis, no Condition or Night effects were found [Night 1 DL = 126.8° (19.2°), BL = 120.2° (20.2°) , Night 3 DL = 115.4° (21.4°), BL = 112.2° (18.1°) and Night 4 DL = 116.7° (12.6°), BL = 121.4° (27.1°)]. As REM propensity shows a clear circadian rhythm in phase with the deep CTR, a delay in REM latency would suggest a delay in the CTR. No such delays in REM latency were found on any night (see Table 8). Thus there was no evidence that evening BL had delayed the CTR.

Sleep. Sleep variable means and standard deviations are given in Table 8. Data was not available for one subject (SK) in the DL condition on Night 3 due to technical difficulties on that night. Each sleep stage variable was analysed in a separate 2 x 3 Condition (DL/BL) x Night (nights 1, 3 and 4) ANOVA. No significant differences were found for SOL, MT, Wake, Stage 1 or REM across Conditions or Nights. However, significantly less Stage 2 sleep, and more Stage 3, 4 and SWS was recorded in the BL Condition across the three nights [$F(1, 8) = 6.59$, $p<.05$; $F(1, 8) = 5.36$, $p<.05$; $F(1, 8) = 7.70$, $p<.05$; and $F(1, 8) = 8.11$, $p<.05$ respectively]. It appears from these results that, taken across the three nights, more Stage 3, 4 and SWS occurred at the expense of Stage 2 sleep following BL compared with DL. Post-hoc dependent group t-tests indicated significantly more Stage 4 and SWS occurred on Night 3 in the BL Condition (85.5min and 136.5min respectively) compared with the DL Condition (67.9 min and 107.6min respectively) [$t(9) = 2.58$, $p<.05$ and $t(9) = 3.16$, $p<.05$ respectively].

Table 9 indicates that nine of ten subjects recorded more Stage 4 sleep and nine of ten subjects recorded more SWS on this night. In addition, trends for increased Stage 3 sleep following BL were also evident on Night 3 (DL = 39.5min, BL = 50.4min) [t(9) = 2.19, p<.06]. Dependent groups t-tests on the Night 4 data revealed significantly longer SOL [t(8) = 3.44, p<.01] and greater amounts of Wake [t(9) = 3.12, p<.05] in the BL Condition (36.6min and 45.6min respectively) compared with the DL condition (18.8min and 24.8min respectively). Thus no differences in sleep stages were found on Night 1, but more SWS was found following BL on Night 3, and on Night 4 Wake and SOL were increased in the BL condition.

Amounts of SWS occurring during the first four sleep cycles of each night were assessed in a 2 x 4 x 3 Condition (DL/BL) x Cycle (cycles 1-4) x Night (nights 1, 3 and 4) ANOVA. SWS diminished in quantity from cycle 1 to 4 [F(3, 24) = 45.69, p<.001] and the Condition effect almost reached significance [F(1,8) = 5.21, p<.052] indicating strong trends for increased SWS in the first four cycles across the three nights in the BL condition compared with the DL condition. In addition, a significant Condition x Night interaction [F(2, 16) = 5.52, p<.05] and a significant Condition x Night x Cycle interaction [F(6, 48) = 2.30, p<.05] indicated different distributions of SWS during the first four cycles across Nights depending on Condition. Further analysis indicated that more SWS was recorded in the BL condition (8.1min) than in the DL condition (4.1min) during the fourth sleep cycle on Night 1 [t(10) = 2.61, p<.05], and trends were found for increased SWS in the third sleep cycle on Nights 3 and 4 following BL [t(9) = 1.97, p<.08 and t(9) = 2.01, p<.08 respectively]. Thus SWS tended to be increased in the latter part of the night following BL exposure. The upper panel of Figure 5 illustrates these trends evident on Night 3.

Of the EEG files for spectral analysis one subject's data (PJ) for all three nights was ruled out of analysis and of the remaining subjects a total of 12 files were excluded from analysis for technical reasons. A further 3 subjects (MW, SK and SB) did not complete four NREM periods on all occasions. The available n for analyses was thus lower than for the sleep and temperature data. Accordingly, spectral analyses were conducted separately for each night rather than across Nights. NREM periods were

determined from the hand scored records according to the guidelines for determination of sleep cycles described in Experiment 1. Separate 2 x 4 Condition (DL/BL) x NREM period (periods 1-4) ANOVAS indicated no differences between conditions on Nights 1 and 4 for any bandwidth. However, a significant Condition x NREM Period interaction was found for SWA and TP on Night 3 [$F_{(3, 15)} = 3.9$, $p < .05$ and $F_{(3, 15)} = 3.9$, $p < .05$ respectively] indicating greater amounts of SWA and TP following BL. Subsequent t-tests on individual NREM periods indicated only weak trends for increased SWA and TP during NREM periods 2,3 and 4 ($p < .15$). No differences in any other bandwidth were found on Night 3. Thus SWA and TP were significantly elevated following BL across Night 3 as a whole, but not within any single NREM period during that night. The lower panel of Figure 5 illustrates the trends for elevated SWA on Night 3 evident in the means of the first four NREM periods. In addition, the lower panel of Figure 7 illustrates these trends evident in a plot of SWA averaged over 5min intervals. Examination of the upper panel of Figure 7 in conjunction with the lower panel reveals that early increases in rectal temperature on Night 3 were followed later in the night by slightly increased SWA in NREM periods 2, 3 and 4. As indicated earlier, although the differences between the DL and BL conditions did not reach significance in any single NREM period, significantly greater amounts of SWA occurred across the night taken as a whole.

Inspection of Table 9 will reveal these significant increases in SWA and TP were found on Night 3 despite the analysis containing only 6 subjects for whom complete EEG data was available. This analysis included the one subject who did not show an increase in SWS and excluded 5 who did. Table 9 shows that 4 of the 6 subjects for whom full data was available recorded elevated SWA following bright-light. However, there were some discrepancies between the SWS and SWA results: the remaining two subjects (ST and DA) showed small decreases in SWA in the BL condition despite recording more SWS, and another subject (MK) recorded slightly more SWA despite having recorded slightly less SWS following BL.

To further examine SWS temporal distribution on Night 3, amounts of SWS accrued during each of the first six hours of sleep were calculated and assessed in a 2 x

6 Condition (DL/BL) x Hour (hours 1 to 6) ANOVA. This analysis indicated significantly more SWS in the BL condition [$F(1, 8) = 6.7$, $p<.05$] and a decline in SWS amounts from hours 1 to 6 [$F(5, 40) = 13.0$, $p<.001$]. Subsequent dependent group t-tests did not indicate significantly increased amounts of SWS in the BL condition during any single hour.

The values used in the analysis described above were also summed to provide an assessment of hour by hour accumulation of SWS. A 2 x 6 Condition (DL/BL) x Hour (hours 1 to 6) ANOVA indicated significantly more accumulation of SWS in the BL condition [$F(1, 9) = 5.6$, $p<.05$] from hour 1 to 6 [$F(5, 45) = 104.0$, $p<.001$] and a significant Condition x Hour interaction [$F(5, 45) = 4.1$, $p<.01$]. Dependent groups t-tests revealed significantly more SWS had accumulated by hours 5 and 6 in the BL condition (116.3min and 123.3min respectively) on Night 3 compared with the DL condition (97.5min and 104.2 min respectively) [$t(9) = 2.8$, $p<.05$ and $t(9) = 2.7$, $p<.05$ respectively]. The upper panel of Figure 6 illustrates these effects.

For comparison with cumulative SWS, amounts of SWA and TP occurring per hour during the first six hours of sleep were also calculated, summed and assessed in separate 2 x 6 Condition (DL/BL) x Hour (hours 1 to 6) ANOVA's for Night 3. In accordance with the SWS results, a significant SWA Condition x Hour interaction occurred indicating increased SWA in the BL condition [$F(5, 30) = 2.88$, $p<.05$]. t-tests on the Night 3 data indicated only non-significant increases in SWA at each hour in the BL condition compared with the DL condition on this night. These trends are graphed in the lower panel of Figure 6. No effects were found for TP.

Table 9. Night 3 individual subject scores recorded for and total Stage 4 sleep, SWS and SWA in the DL and BL conditions.

Subject	Stage 4 sleep (min)		SWS (min)		SWA (µv/mm)	
	DL	BL	DL	BL	DL	BL
DA	86.5	90.5	114.5	124	176807.00	152524.00
PJ	66.5	81.5	92.5	116.5		
CG	77	139.5	130.5	217.5	184952.00	307678.00
JP	50.5	90.5	88.5	158		
MK	57.5	60.5	104.5	97.5	171617.00	215964.00
MP	80	95	146.5	152.5	189252.00	197048.00
MW	46.5	38	63	77.5		
SC	81	75.5	129	151.5	216474.00	224670.00
SB	67	90	94	133.5		
SK		79.5		111.5		
ST	68.5	100	113.5	137	122560.00	109231.00
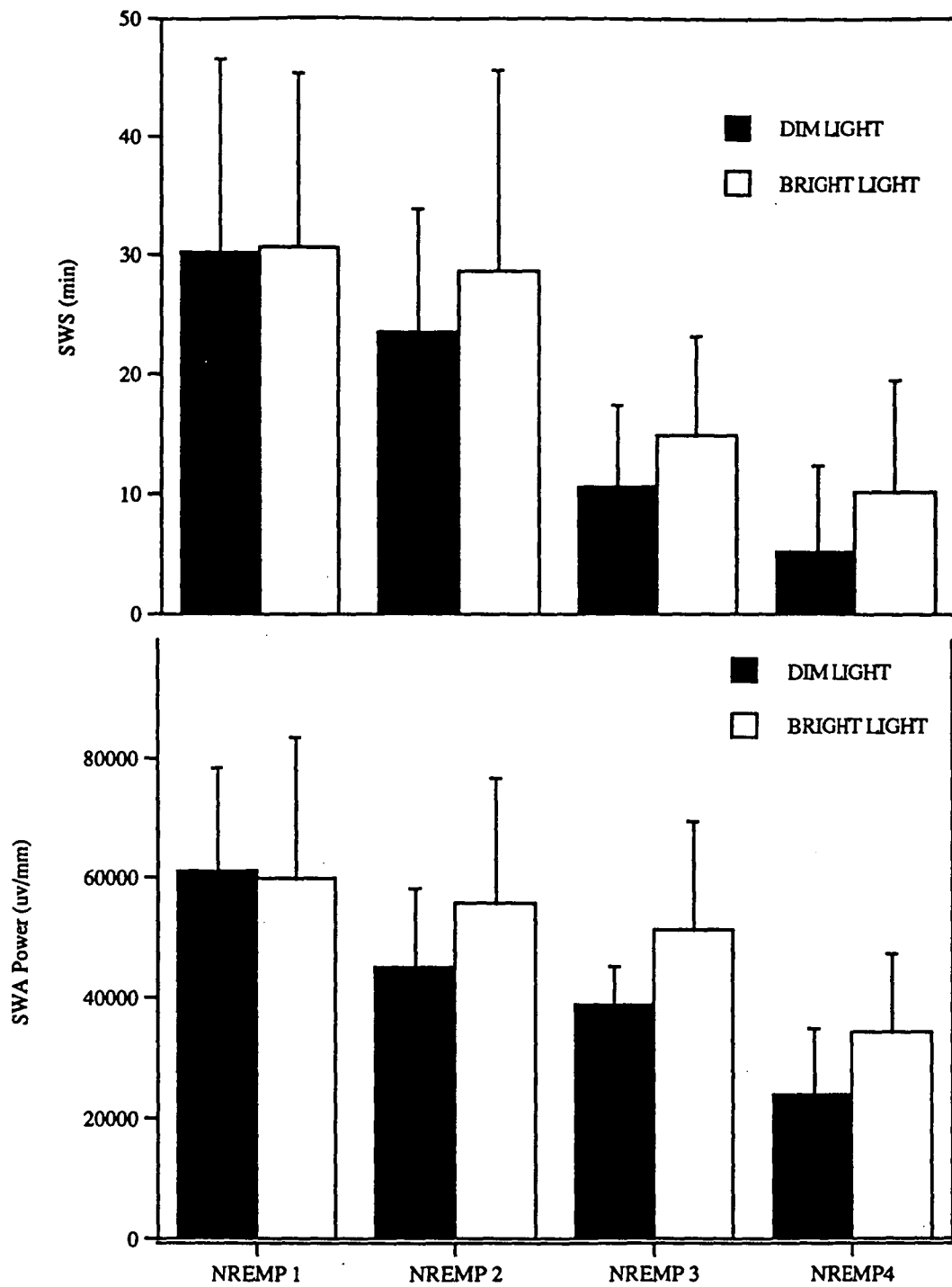
Figure 5: *Experiment 2 Night 3 SWS and SWA amounts and standard deviations occurring in each of the first four NREM periods.*
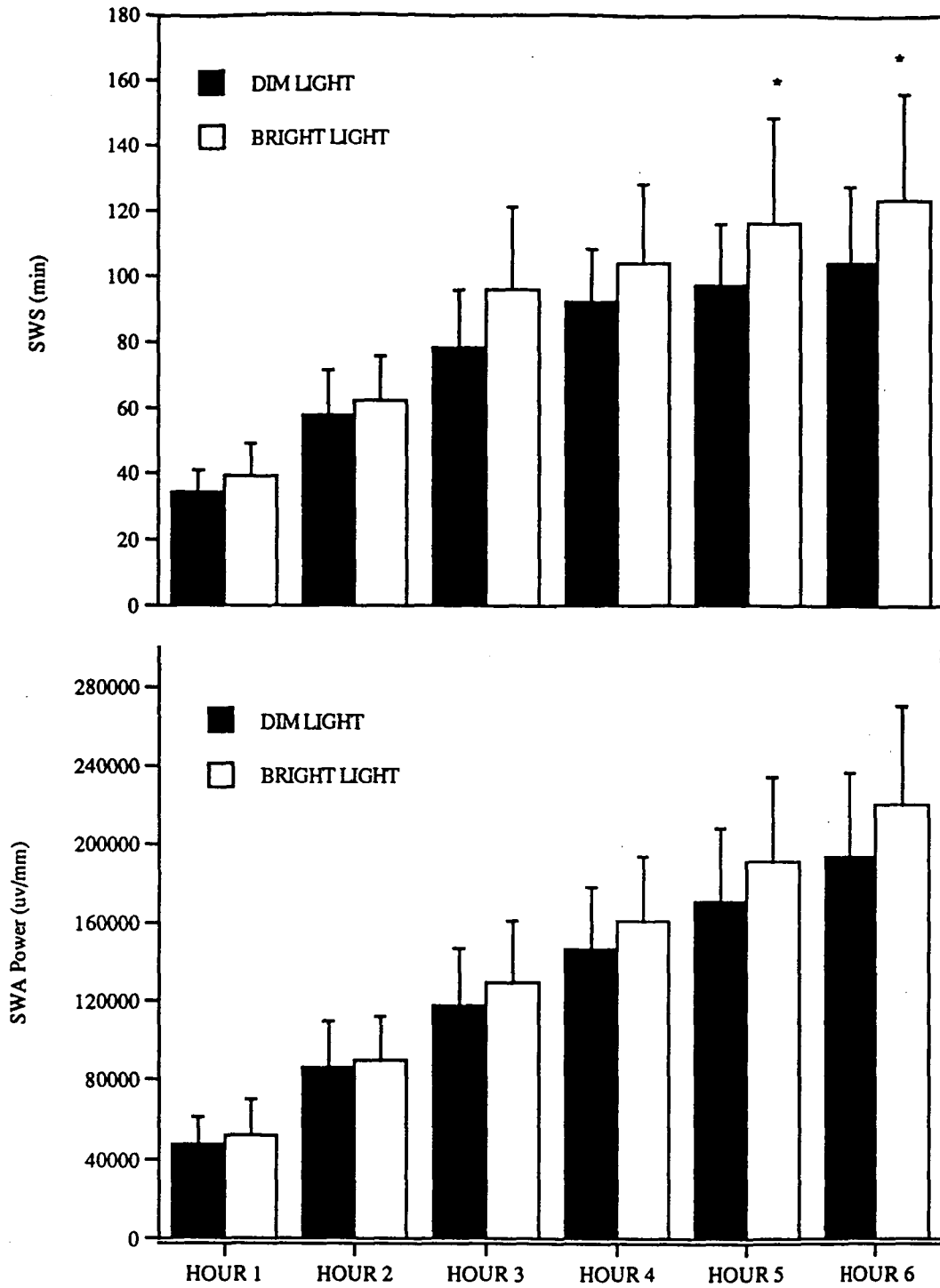
Figure 6: *Experiment 2 Night 3 SWS and SWA accumulation across the first six hours of sleep.*

* *p<.05*

Statistical analyses are described in the text.
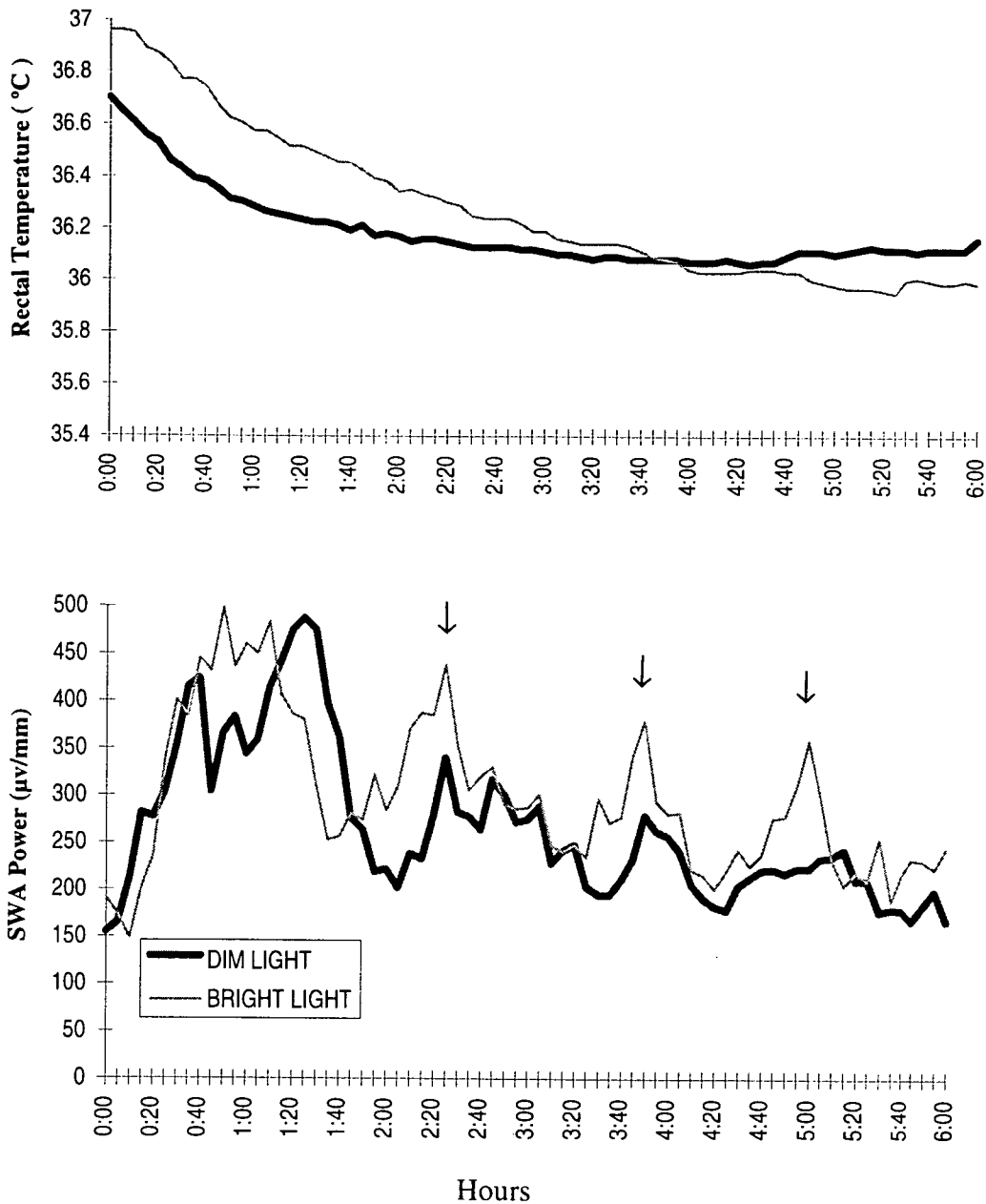
Figure 7: *Night 3 mean rectal temperature and SWA values averaged over 5min epochs from the end of the light-exposure period. Note the early elevation in temperature and elevations in SWA during NREM periods 2, 3, and 4 in the bright-light condition (indicated with arrows). The temperature plot is based on all 11 subjects. The SWA plot is based on the 6 subjects who fully completed all four NREM periods, and whose EEG recordings during these periods were clean. See text for statistical analyses of temperature and SWA.*

Discussion

Exposure to evening bright-light prior to habitual bedtime produced no changes to temperature or sleep on Night 1, elevated temperature and SWS/SWA on Night 3 and increased SOL and wakefulness on Night 4 despite no bright-light administration on this night. These effects were not associated with any delay of the CTR.

The failure to find a delay of the CTR after three consecutive exposures to BL until habitual bedtime was somewhat unexpected and is in contrast to some studies (Carrier & Dumont, 1995; Dawson et al., 1993; Drennen et al., 1989). However, it is possible that the time of exposure was not close enough to the CTR nadir to cause a delay. Previous studies reporting CTR delays following similar durations and intensities of light have typically exposed the bright-light at times temporally closer to the CTR nadir than the present study (e.g. Dawson & Campbell, 1991). Indeed, Bunnell et al. (1992) reported no delay to the CTR following bright-light to habitual bedtime. Lack and Wright (1993) found delayed CTRs following BL administration prior to habitual bedtime, though their subjects were early morning insomniacs who appeared to have "earlier than normal" temperature rhythms prior to BL treatment. If this were so, then exposure to BL prior to habitual bedtime would result in exposure unusually close to the CTR nadir producing correspondingly unusually large delays of the CTR. The failure to find such a delay in the present experiment also suggests the possibility that the delay reported by Drennen et al. (1989) following 3 evenings of BL may have been an artefact of the immediate effect of BL on temperature, as assessments were not made independently of BL administration. This possibility is made more plausible given that no delay in REM latency was reported; in fact REM latency was found to advance in this. No delay in REM latency was found in the present experiment either, further suggesting that no delay of the underlying CTR occurred. This result suggests that the increases in SWS found in Experiment 1 were unlikely to have resulted from a delay of the CTR, as the timing, duration and intensity of the bright-light stimulus were similar in this experiment. It appears from the present results that multiple exposures to evening bright-light administered until habitual bedtime may produce immediate temperature elevations without necessarily delaying the CTR. The failure to find a CTR delay by

Night 4 was disappointing as it ruled out an assessment of the effects of such a delay on sleep without the immediate effects of BL.

The failure to find significantly elevated temperature on Night 1 of the present study is unexpected, as most previous studies have reported such elevations following a single exposure to similar intensities and durations of evening bright-light (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1989). Nevertheless, one study failed to find temperature elevation following three similar exposures (Carrier et al., 1995). It appears in the present case that although trends for elevation were present, larger than usual variance prevented significance as the standard deviations in the BL Condition on this night were somewhat larger than those of either Condition on any other Night or those found in Experiment 1.

However, two additional exposures to BL for 3hrs prior to habitual bedtime over consecutive nights resulted in expected elevations in temperature on Night 3. This result is consistent with other studies in which evening bright-light has elevated rectal temperature by approximately 0.2 to 0.3°C during the first two hours of the subsequent sleep period (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991) however longer durations of temperature elevations have also been reported following 3hrs of BL exposure as used in the present experiment (Cajochen et al., 1992; Dijk et al., 1991). The present findings are also consistent with Experiment 1 in showing that temperature elevation effects continue to occur with multiple consecutive exposures to evening bright-light. The only exception to this finding has been reported by Carrier et al. (1995) who suggested that melatonin onset times in their baseline group occurred too late to be suppressed by bright-light.

An unanticipated result was the recording of reliably higher temperatures during the first hour following light exposure, and at sleep onset, on Night 4 in the dim-light condition. This effect appears to have resulted from alterations to temperatures in the dim-light condition rather than the bright-light condition, as temperatures were somewhat higher in the dim-light condition than previously recorded on either of the other two nights in Experiment 2 or in the dim-light condition in Experiment 1. It is also

possible that exposure to bright-light on three consecutive evenings produced a reduction in the CTR amplitude evident on the fourth night. This hypothesis is based on findings that CTR amplitude may be decreased under dim-light conditions on the night following evening bright-light exposure (Jewet, Kronauer, & Czeisler, 1991).

Increased SOL and Wake have previously been reported on a DL night following previous multiple exposures to evening BL (Carrier & Dumont, 1995) though, unlike the present study, these changes were associated with a delay in the CTR. The present results suggest that some disturbance to sleep may occur upon cessation from multiple exposures to bright-light whether or not the CTR is delayed.

Consistent with Experiment 1 and two other studies (Cajochen et al., 1992; Carrier et al., 1995) was the finding that despite no increase in SOL or decrease in SWS or SWA in the first sleep cycle, sleep immediately following BL (Nights 1 and 3) tended to be enhanced in the latter part of the night. On Night 1 SWS in the fourth cycle was significantly increased, and there were trends for a similar increase in the third cycle on Night 3. These results suggest the possibility that arousing effects of bright-light early in the night, found to be measurable in some studies (Cajochen et al., 1992; Dijk et al., 1991), may delay temperature effects on SWS usually found in the first two sleep cycles till late in the night.

The results suggest further association between temperature and SWS in that SWS was significantly enhanced across the night as a whole when, and only when, temperature was elevated in the early portion of sleep (Night 3). Significantly greater amounts of Stage 4 and SWS resulted under these conditions, and more SWS had accumulated in the BL condition by the fifth and sixth hours of sleep. Nine of ten subjects recorded more total SWS. Similar differences in accumulation of SWA were found, though absolute quantities within any one NREM period or hour of the night were not found to differ between conditions in the way that SWS had. This difference in findings may be due to the lower n available for this analysis (6 as compared with 10). In addition, the analysis contained the one subject who did not show elevated SWS, while all other subjects missing from the SWA analysis showed such elevations.

As no CTR delay or significant sleep disturbance following bright-light was found in the present study, elevated temperature remains a likely explanation for the enhanced sleep found to occur in this study and in Experiment 1. However, the present study also suggests that these results may be more reliably obtained following more than one exposure to bright-light. Experiment 3 was designed to investigate this issue.

CHAPTER SEVEN

EXPERIMENT 3

THE EFFECTS OF A SINGLE EXPOSURE TO EVENING BRIGHT-LIGHT vs PRE-EXPOSURE TO EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP.

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THE EFFECTS OF A SINGLE EXPOSURE TO EVENING BRIGHT-LIGHT vs PRE-EXPOSURE TO EVENING BRIGHT-LIGHT ON CORE TEMPERATURE AND SLEEP.

In Experiments 1 and 2 it was seen that exposure to evening bright-light on 2-3 consecutive nights produced reliable elevations in rectal temperature and enhanced SWS/SWA. However, neither the temperature nor SWS/SWA effects were found upon a single administration of evening bright-light (Night 1 Experiment 2). It is noteworthy that SWS/SWA enhancement following evening bright-light has only been previously reported in studies in which subjects received bright-light on more than one occasion (Bunnell et al., 1992). In this study subjects received a first exposure to BL approximately a week prior to a second exposure. As the nights were collapsed for analysis in this study, the data reported reflect the combined effects of two nights of bright-light exposure (though not two consecutive nights). Other studies of sleep immediately following evening bright-light have used a single exposure to bright-light and have found no enhancement to SWS/SWA. (Cajochen et al., 1992; Dijk et al., 1991).

Increased SOL following evening bright-light has also typically only been reported in studies utilising a single exposure to BL (Cajochen et al., 1992; Dijk et al., 1991). One exception to this is Drennen et al. (1989) who found increased SOL following 3 consecutive exposures evening bright-light. This study result is in contrast with Carrier et al. (1995) who found no such disturbance following 3 consecutive evening exposures to bright-light. It is possible that an initial exposure to BL results in sleep disturbance early in the night (Cajochen et al., 1992; Dijk et al., 1991) while subsequent exposures to BL do not disturb sleep, but enhance it via thermic effects (Bunnell et al., 1992).

It has recently been shown that melatonin suppression and temperature elevation occur similarly in consecutive all-night exposures to bright-light (Myers et al., 1995). Experiment 3 was designed to assess the possibility that temperature and sleep responses to evening bright-light administered until habitual bedtime vary according to whether or not bright-light is administered once or more than once. It was hypothesised that a single exposure to bright-light would elevate temperature and increase SOL but produce no enhancement of SWS/SWA across the night as a whole compared with dim-light, whereas exposure to bright-light on two occasions would produce reliable temperature and SWS/SWA elevations compared with dim-light exposure.

Method

Subjects. Subjects were 36 male University students randomly divided into three groups of 12. As in Experiments 1 and 2, female subjects were not used because of the confounding influence of gonadal hormones on core temperature. The subjects were aged between 18 and 25, were non-smokers and reported healthy, regular sleep free from respiratory or sleep pathology. The subjects were required to abstain from alcohol and caffeine during experimental periods and were paid for their participation. The project was approved by the University Ethics Committee.

Design. A between-groups design was employed in which subjects were run in three conditions: a Dim-Dim (DD) condition, a Dim-Bright (DB) condition and a Bright-Bright condition (BB). Each condition consisted of a 48hr period in which subjects spent both evenings at the sleep laboratory. In the DD condition the subjects arrived at the laboratory three hours prior to their habitual bedtime and watched TV/video under dim-light (DL) conditions (approx. 100lux) on both nights. The DB condition proceeded identically except that the subjects received bright-light (BL) on the second night. The same routine applied in the BB condition except that subjects received BL on both nights. The dependent variables were rectal temperature variables, sleep architecture variables and sleep EEG variables assessed by fast

fourier transform. Rectal temperature was measured continuously across the 48hr period and sleep was assessed on the second night of each condition.

Procedure. Subjects were given an adaptation night in the sleep laboratory within the week prior to commencing the experimental schedule (but not on the night before commencement of the schedule, as potentially poor sleep on this night might affect sleep in the experimental nights). Subjects arrived at the sleep laboratory on the morning of the first experimental day at which point they received instruction in the use and fitting of the Mini-logger and recording of ambulatory rectal temperature began. The subjects proceeded with normal daytime activities and returned to the sleep laboratory 3hrs prior to their habitual bedtime. At this point subjects received either DL or BL according to their experimental condition. Subjects retired to bed at their habitual times and rose in the morning at their habitual times. Following the second day the subjects again reported to the laboratory 3hrs prior to their habitual bedtime and received DL or BL. During this period electrodes were attached in readiness for sleep recordings. Immediately following light exposure subjects retired to bed and sleep recordings were started. Sleep recordings were stopped upon spontaneous awakening at habitual waking times. BL administration, temperature recordings, sleep recording and scoring all occurred according to the procedures adopted in Experiments 1 and 2.

Results

Temperature: Average rectal temperatures were calculated for the five hours following light administration in the same way as in Experiments 1 and 2. These means are shown in Table 10 and a graphed in the upper panel of Figure 10. It can be seen from the graph that temperatures early in the night were most noticeably elevated in the BB condition, though elevations were also evident in the DB condition compared with the DD condition. A 3 x 5 Groups (DD/DB/BB) x Hour (hours 1-5) ANOVA revealed no significant effect of Group [$F_{(2, 32)} = 1.85$, $p > .1$][1]

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[1] All ANOVA tables cited are contained in Appendix E.

but a significant effect of Hour [F(4, 128) = 179.41, p<.001] indicating declining

temperatures from hours 1-5, and a significant Groups x Hour interaction [F(8, 128)

= 2.73, p<.01). The interaction appeared to result form early increases in

temperature in the BB and DB Groups compared with the DD Group. Independent

groups t-tests used to explore the interaction confirmed that rectal temperature was

significantly higher in the BB (36.85°C) group than in the DD (36.56°C) group

during the first hour following light administration [t(20) = -2.31, p<.05) and a

similar trend existed during the second hour [t(20) = -1.92, p<.07]. Trends were also

evident for elevated rectal temperature during the first hour following light

administration in the DB group compared with the DD group [t(11) = -1.68, p=.1].

Examination of the standard deviations presented in Table 10 reveals

somewhat more variance in each Group of this experiment compared with any

conditions found in Experiments 1 or 2. The between-subjects design adopted in this

study might well account for this difference. It might also account for the

statistically modest increases in rectal temperature in the BB Group, and lack of

statistically significant increases in the DB Group.

Table 10. Experiment 3 mean rectal temperatures and standard deviations (degrees
Celsius) during each of the first six hours following bright-light administration.

MEAN RECTAL TEMPERATURES (°C)
(SDs in Parentheses)

HOUR	DIM-DIM	DIM-BRIGHT	BRIGHT-BRIGHT
HOUR 1	36.56 (.38)	36.75 (.22)	36.85 (.27)
HOUR 2	36.25 (.33)	36.39 (.19)	36.49 (.27)
HOUR 3	36.01 (.32)	36.24 (.22)	36.21 (.35)
HOUR 4	35.97 (.32)	36.11 (.23)	36.02 (.41)
HOUR 5	35.88 (.29)	36.01 (.27)	35.92 (.37)
HOUR 6	35.87 (.26)	35.97 (.28)	35.96 (.32)

Sleep. All sleep variables were assessed independently by one-way ANOVA. The means and standard deviations of these variables are presented in Table 11. Examination of this table shows that SWS was somewhat elevated in the BB group (137.1min) and the DB group (131.9min) compared with the DD group (122.3 min). SOL was somewhat increased in the BL groups compared with the DD group, especially so in the DB group (DD = 23.4min, DB = 36.7 min and BB = 33.3min). Wake was also somewhat elevated in the DB group (57.9min) compared with the DD group (38.3min). Nevertheless, no sleep stage variable was found to differ significantly between the Groups.

The finding that SWS was not increased over the night as a whole in either BL group was unexpected, as this effect was found in Experiments 1 and 2. In fact, increases in SWS of approximately 10min found in the present experiment to fall short of statistical significance were found to be significant in Experiment 1. The larger error variance associated with the present experiment may best explain this difference (standard deviations in SWS were approximately 20min in Experiment 1 but are as high as 35min in the present experiment).

Amounts of SWA occurring within each of the first four NREM periods was determined and calculated as in Experiment 2. The subsequent 3 x 4 Groups (DD/DB/BB) x NREMP (periods 1-4) ANOVA revealed declining amounts of SWA across NREM periods [$F(3,66) = 17.4$, $p<.001$] and a significant effect of Group in which more SWA was recorded in the DB and BB groups [$F(2,22) = 3.54$, $p<.05$]. In particular, independent groups post-hoc t-tests indicated significantly more SWA in the third NREM period in the BB group (46161µv/mm) compared with the DD group (32237 µv/mm) [$t(17) = -2.25$, $p<.05$]. This is shown graphically in the middle panel of Figure 8.

Other bandwidths of secondary interest were also analysed in separate 3 x 4 Group (DD/DB/BB) x NREM period (1, 2, 3, 4) ANOVAS. These analyses indicated no group differences for any bandwidth. However, significant Group x NREM period interactions occurred for the 3-8Hz, 8-12Hz and 12-30Hz bandwidths

[F(6, 66) = 3.0, p<.05; F(6, 66) = 2.2, p<.05; and F(6, 66) = 2.9, p<.05 respectively].

Post-hoc analyses indicated no significant differences between Groups during any

NREM period, though examination of the means suggested increased activity in

these bandwidths during the first two NREM periods compared with the last two

NREM periods. A similar 3 x 4 Groups (DD/DB/BB) x NREMP (1, 2, 3 and 4)

ANOVA of the TP data indicated a significant decline in activity from NREM period

1 to 4 [F(3,66) = 12.88, p<.000] but only trends for a Group effect [F(2,22) = 3.14,

p<.07] or interaction [F(6,66) = 1.89, p<.09]. TP activity during each NREM period

is illustrated in the lower panel of Figure 8 for comparison with SWS and SWA.

For comparison with SWA, calculation of SWS amounts occurring during the

first four sleep cycles was also carried out according to the procedures used in

Experiments 1 and 2. Each sleep cycle was analysed separately by one-way

ANOVA. These analyses indicated no Group differences in cycles 1, 2 or 3.

However, a significant Group difference was found for SWS amounts in cycle 4

[F(2, 31) = 4.07, p<.05]. Significantly more SWS occurred during this sleep cycle

in the DB (14.6 min) and BB (10.9 min) Groups compared with the DD Group (3.6

min) [t(20) = -2.89 , p<.01 and t(22) = -2.35 , p<.05 respectively]. These effects are

graphed in the upper panel of Figure 8.

For further examination of the temporal distribution of SWS, amounts of

SWS occurring during each of the first 6 hrs of sleep were calculated and assessed in

a 3 x 6 Groups (DD/DB/BB) x Hour (hours 1-6) ANOVA. This analysis did not

indicate any Group differences or Group x Hour interaction.

The findings of increased SWS/SWA during the third and fourth sleep cycles/

NREM periods suggested that accumulation of SWS/SWA toward the end of the

subjective night might differ between groups. To provide an examination of

accumulation of SWS, SWA and TP, amounts of these variables were summed for

the first 6 hours of sleep. A 3 x 6 Groups (DD/DB/BB) x Hours (hours 1-6)

ANOVA of cumulative SWS indicated no effect of Group [F(2,26) = 1.47, p>.1] but

a significant effect of Time [F(5,130) = 332.89, p<.001] and a significant Groups x

Time interaction [$F(10,130) = 2.0$, p<.05]. As expected, this interaction appeared to result from elevated SWS during the latter part of the night, and exploration of the latter three hours indicated more SWS in the 5th hour of sleep in the BB Group (120.5min) than in the DD Group (105min) [$t(22) = -2.1$, p<.05]. These results are plotted in the upper panel of Figure 9.

Consistent with these results, the same analysis performed on the SWA data revealed no effect of Group [$F(2,26) = 1.47$, p>.1] but a significant effect of Time [$F(5,130) = 332.89$, p<.001] and Groups x Time interaction [$F(10,130) = 2.08$, p<.05]. Similar post-hoc exploration of the interaction indicated that the BB group had accumulated more SWA by the end of hours 4 (149433µv/mm), 5 (177857µv/mm) and 6 (198523µv/mm) than the DD Group (127030µv/mm, 145739µv/mm and 164015µv/mm respectively) [$t(18) = -2.17$, p<.05) $t(18) = -2.8$, p<.05 and $t(16) = -2.8$, p<.05]. These effects are shown graphically in the middle panel of Figure 9. The same analysis of TP resulted in significant effects for both Group [$F(2,26) = 3.7$, p<.05] and Time [$F(5,130) = 727.23$, p<.001] and a significant Group x Time interaction [$F(10,130) = 4.09$, p<.001]. Post-hoc analysis of the latter half of the night indicated more TP in the BB Group at hours 4 (373150µv/mm), 5 (449521µv/mm), and 6 (519950µv/mm) compared with the DD Group (303339µv/mm, 336186µv/mm and 406396µv/mm respectively) [$t(18) = -2.99$, p<.01, $t(18) = -3.13$, p<.01 and $t(16) = -3.3$, p<.01 respectively). In addition, there were trends in this direction for the DB Group during hours 4, and 5 (p<.07). The elevations in cumulative TP following BL are shown in the lower panel of Figure 9. Thus SWS/SWA and TP were enhanced following a single exposure to BL, though a second exposure was associated with even more pronounced increases in these sleep variables. These effects can be seen in Figure 10 which illustrates early elevation of rectal temperature followed later in the night by elevated SWA in the bright-light groups.

Table 11. Experiment 3 sleep stage means and standard deviations (minutes) for each experimental group.

SLEEP VARIABLES	MEAN TIMES (min) (SDs in Parentheses)					
	DIM-DIM		DIM-BRIGHT		BRIGHT-BRIGHT	
MT	2.3	(3.1)	1.4	(1.2)	2.9	(1.5)
WAKE	38.3	(34.7)	57.9	(48.4)	42.2	(27.4)
STAGE 1	33.1	(13.1)	26.9	(10.6)	23.8	(9.8)
STAGE 2	184.4	(35.1)	163.6	(36.1)	160.6	(37.8)
STAGE 3	34.3	(12.8)	41.5	(16.2)	46.3	(16.4)
STAGE 4	88.0	(18.3)	90.0	(25.2)	90.0	(26.4)
SWS	122.3	(23.0)	131.9	(35.9)	137.1	(31.5)
SWS CYCLE 1	54.7	(26.2)	57.7	(26.4)	52.4	(11.8)
SWS CYCLE 2	35.0	(17.3)	37.5	(23.1)	41.1	(16.6)
SWS CYCLE 3	22.2	(12.8)	22.2	(17.3)	26.7	(12.3)
SWS CYCLE 4	3.6	(4.4)	14.6	(12.4)	10.9	(10.0)*
REM	102.1	(27.3)	91.9	(35.9)	109.4	(30.8)
SOL	23.4	(10.0)	36.7	(28.8)	33.3	(17.4)

Asterisk indicates significant Main Effect ($p<.05$). Statistical analyses are described in the text.

Abbreviations: CYC = Sleep Cycle, SOL = Sleep Onset Latency

Note: SOL = Time from lights out to first minute of Stage 2 sleep.
REM LATENCY = Time from first Stage 2 to the first REM epoch.
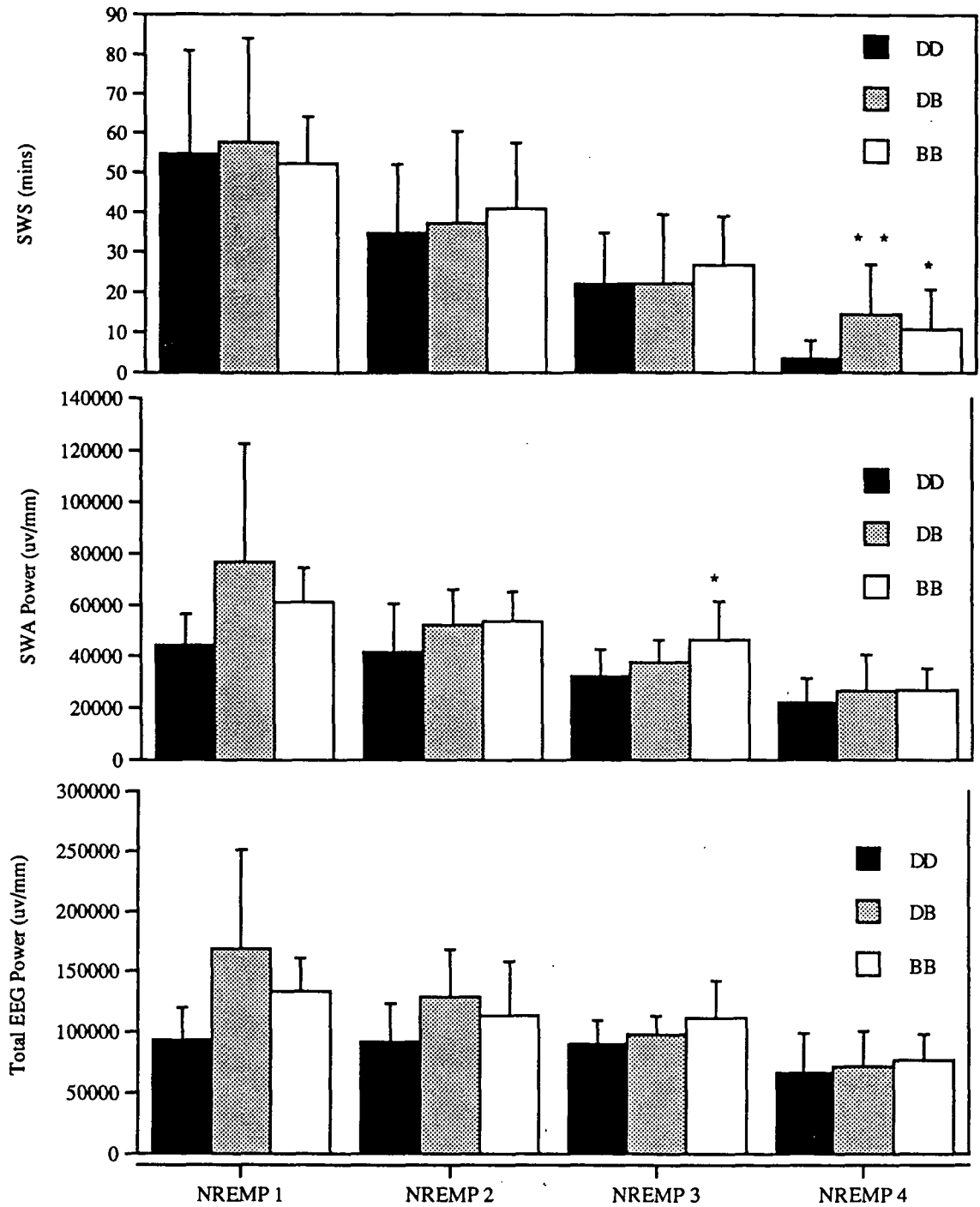
Figure 8: *Experiment 3 SWS, SWA and TP amounts and standard deviations recorded during each of the first four NREM periods.*

*Asterisks indicate statistically significant differences between Group indicated and DD Group. Statistical analyses are described in the text. * p<.05, ** p<.01.*
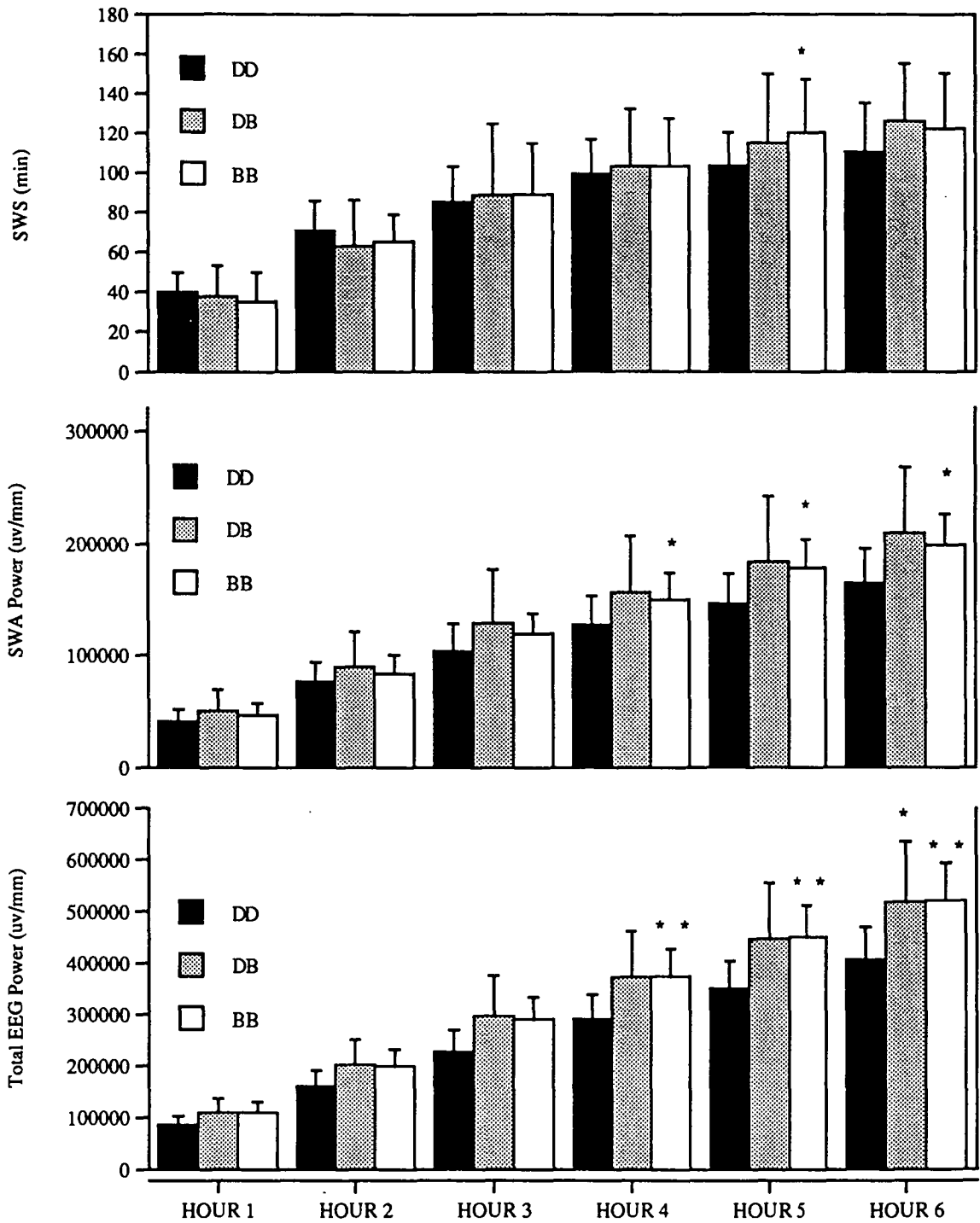
Figure 9: *Experiment 3 hour by hour accumulation of SWS, SWA and TP.*

Asterisks indicate significant differences between the group indicated and the DD Group. **p<.05,** ** **p<.01.**
Statistical analyses are described in the text.
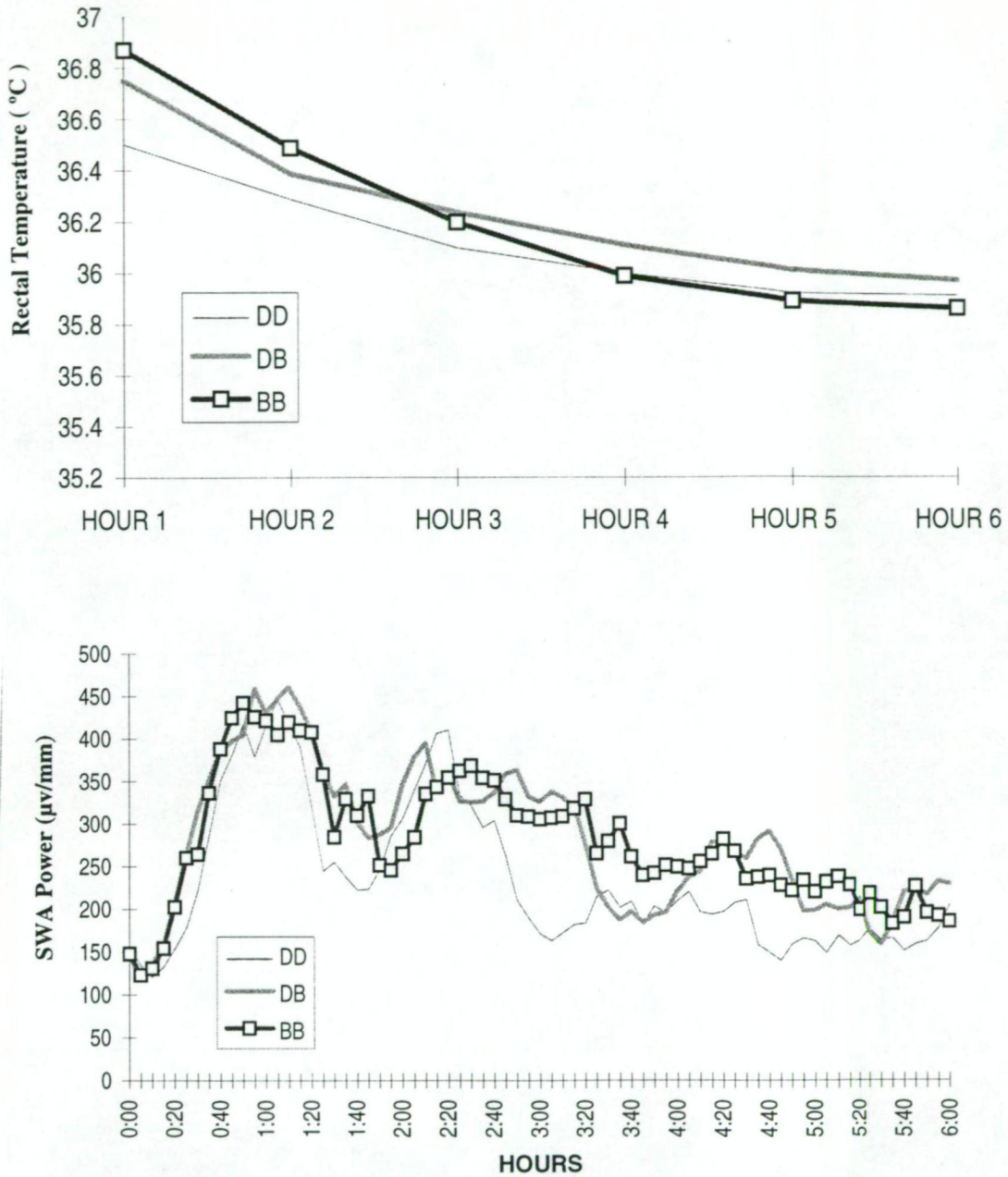
Figure 10: *Mean rectal temperature and SWA during the 6hrs following light-exposure. The temperature plot represents average temperature during each hour. The SWA plot represents SWA amounts averaged in 5min epochs. Note the early elevation in temperature in the bright-light Groups followed by increased SWA during the latter 3hrs.*

Discussion

A single 3hr exposure to bright-light produced trends for elevated temperature and enhanced SWS and SWA compared with a dim-light condition. However, following exposure to bright-light on two consecutive nights, rectal temperature was significantly elevated and SWS/SWA were enhanced to a more pronounced degree. Total EEG Power was significantly enhanced following only one bright-light exposure, but somewhat more so following two exposures. The failure to find significant elevations in rectal temperature following a single bright-light pulse is consistent with Experiment 2 but not with other studies (Cajochen et al., 1992; Dijk et al., 1989). However, trends for such an elevation were evident and as indicated previously, a between-subjects design was utilised which appears to have increased error variance. In addition, one other study (Carrier & Dumont, 1995) failed to find elevation of temperature immediately following three exposures to evening bright-light.

The finding that rectal temperature was significantly raised by approximately 0.3 °C following more than one exposure to evening bright-light is consistent with Experiments 1 and 2 and with Bunnell et al. (1992) who also administered bright-light twice to subjects. However, unlike Bunnell et al. (1992) or Experiments 1 and 2 the increase was only statistically significant during the first hour following light administration. Again, the higher variance recorded in this experiment (particularly in the DD group) may account for this finding.

Although no sleep-stage variable differed significantly between groups across the night as a whole, approximately 9 min more SWS resulted in the DB group and approximately 15 min more SWS resulted in the BB group compared with the DD group. Increased error variance associated with the between-subjects design appears to have prevented these differences from reaching significance, as similar mean differences with smaller standard deviations were found to be significant in Experiment which utilised a within-subjects design.

However, SWS and SWA distribution and accumulation were found to differ between groups. SWA amounts and accumulation were found to be significantly increased following both one and two nights of bright-light exposure, though these effects were somewhat more pronounced following two exposures. This result is consistent with Bunnell et al. (1992) who also reported enhanced low frequency EEG activity following evening bright-light administered on more than one occasion. Total EEG power accumulation was also enhanced in both the DB and BB group compared with the DD condition. Again, these differences were most pronounced in the BB group.

Increases in SWS were found in the fourth sleep cycle in both BL groups and an increase in SWA in the third NREM period was evident in the BB group compared with the DD group. These increases in SWS/SWA are consistent with Experiments 1 and 2 and with two other studies (Carrier et al., 1995; Cajochen et al., 1992). Consistent with the former study, and in contrast to the latter, these increases in SWS/SWA do not appear to be due to any sleep disturbance early in the night as no increases in SOL were found in either bright-light group, nor was there a reduction in SWS or SWA during the first NREM period. Increases in temperature during the early sleep period therefore appear to be a likely explanation for these effects, although SWS/SWA is usually enhanced during the early portions of sleep following pre-sleep elevations in temperature. Interpreted this way it appears that the thermic effects of bright-light on sleep evident in the early sleep period have been delayed until later sleep cycles. It is possible that immediate arousing or "energising" effects of bright-light associated with suppressed melatonin resulted in this delay, though such arousal was not reflected in the SOL or Wake data.

There are, however, other interpretations of the SWS/SWA facilitation effect. While the data do not support a role for melatonin inhibition disrupting sleep (as assessed by increased SOL and Wake), it is possible that melatonin inhibition before sleep may result in a melatonin rebound later in sleep and a subsequent facilitation of SWS/SWA at that time. Badia et al. (1991) reported that melatonin amounts rose to normal levels within approximately 40 min of cessation of bright-light during the

hours from 24:00hrs-8:00hrs. More recently, Tzischinsky and Lavie (1994) reported time-dependent hypnotic effects of exogenous melatonin administration, such that administrations of melatonin in the subjective night were followed by hypnotic effects relatively faster than daytime administrations. They reported that administration of melatonin at 21:00hrs produced increased sleepiness and elevations in SWA approximately an hour later. Thus, if melatonin levels reached normal amounts within an hour of cessation of bright-light and continued to increase, sleep might be expected to be noticeably enhanced within another hour or two. This possible delay of the hypnotic effects of melatonin might be consistent with the tendency for SWS/SWA to be more affected in later sleep cycles in the present experiment (and Experiments 1 and 2). However, the absence of melatonin measures in these studies makes this hypothesis difficult to evaluate, and Bunnell et al., (1992) reported enhanced low-frequency EEG activity during the first sleep cycle, rather than later cycles, following bright-light induced suppression of melatonin and elevation of temperature.

In conclusion, a single 3 hr exposure to bright-light produced trends for elevated temperature and enhanced SWS and SWA compared with a dim-light condition. Following exposure to bright-light on two consecutive nights, rectal temperature was significantly elevated and SWS/SWA were enhanced to a more pronounced degree. Total EEG Power was significantly enhanced following one bright-light exposure, and was even further enhanced following two such exposures. Thus pre-exposure to evening BL (the BB condition) produced more robust effects on core temperature and SWS/SWA than did a single exposure to BL (the DB condition). Evening BL was not associated with increased SOL, even when it was the first occasion of its administration.

CHAPTER EIGHT

GENERAL DISCUSSION

CHAPTER EIGHT

GENERAL DISCUSSION

8.1 Theoretical Issues Briefly Revisited

The studies reported in the present thesis were designed to assess the effects of evening bright-light on core temperature and sleep. The effects of evening bright-light on sleep are of theoretical and practical interest as evening bright-light both elevates core temperature and suppresses melatonin. These studies therefore speak to two streams of literature which predict diametrically opposite relationships between core temperature and SWS;

(1) first, the energy conservation theories and brain restorative/protective theories of sleep argue that SWS functions to reduce body and/or brain MR and temperature. Consistent with this notion have been many empirical findings in which increased SWS is found following pre-sleep temperature elevation. It can be argued that the greater temperature levels at sleep onset are, the greater will be the compensatory amounts of SWS needed to downregulate temperature. Thus SWS and temperature levels have been found to correlate positively with one another such that increased temperature prior to sleep promotes SWS.

(2) second, a growing literature suggests a positive relationship between melatonin (which *reduces* core temperature) and SWS. This literature suggests that enhanced SWS is associated with a reduction in core temperature mediated by melatonin. Thus melatonin suppression by evening bright-light (and subsequent elevation of temperature) might be followed by diminished SWS.

Thus, on one hand, elevation in temperature produced by evening bright-light (immediately, or by a potential phase delay of the CTR) might be expected to enhance SWS, but on the other hand suppression of melatonin by evening bright-light might be expected to disrupt sleep and diminish SWS.

8.2 Rationales and Methodologies Briefly Revisited

Three studies examining the effects of evening bright-light on sleep have been reported. Before going on to discuss the outcomes of these studies in detail, the rationales and methodologies of each study will be briefly reviewed.

8.2.1 Experiment One: The Direct Effects of Evening Bright-Light on Core Temperature and Sleep.

The first study was designed to investigate the effects of direct elevation of core temperature via evening bright-light on sleep. As reviewed, evening bright-light has been associated with a suppression of melatonin and subsequent increase in temperature lasting up to 4hrs into the sleep period (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1992; Strassman et al., 1991). Subjects were exposed to two consecutive evenings of bright-light and dim-light twice in a counterbalanced ABBA design. Ambulatory rectal temperature was continuously monitored across each experimental session. Light was administered during the two hours immediately prior to habitual bedtime and all-night polysomnographic recordings were made on the second night of each experimental session. It was hypothesised that an elevation in temperature around sleep onset following evening bright-light would result in enhanced SWS early in the night, consistent with exercise studies (e.g. Horne & Moore, 1985), passive heating studies (e.g. Jordan et al., 1990) and other experimental paradigms in which this relationship has been observed (e.g. Shapiro et al., 1989; Moriarty et al., 1988).

8.2.2 Experiment Two: The Direct vs Phase-Delaying Effects of Evening Bright-Light on Sleep.

The rationale for the second study derives from findings which suggest the possibility that SWS propensity, usually thought to vary with duration of prior wakefulness, may also vary according to a circadian influence. It was seen that in some studies of extended sleep SWS reappears after approximately 12hrs (e.g. Webb, 1986), suggesting a circadian/ultradian rhythm in SWS propensity. Further evidence for

such an influence comes from studies using the ultra-short sleep-wake schedule (Lavie, 1991). Perhaps most convincingly, it has also been shown that when the effects of prior wakefullness are partialled out of analysis, naps taken by subjects under free-running conditions show most SWS if initiated high on the CTR, near the acrophase (Campbell & Zulley, 1989). As well as producing immediate physiological changes, bright-light shifts the human CTR according to a phase response curve such that administration of bright-light in the hours preceding the CTR nadir delays the CTR relative to clock time. Evening bright-light administered before habitual bedtime has previously been shown to produce such a delay in the CTR (Dawson et al., 1993). Sleep onset would occur relatively higher on the CTR following such a delay if it were held constant relative to clock time. These conditions might therefore be expected to enhance SWS if indeed SWS propensity varies according to a circadian influence as described. The second study was designed to investigate the possible contribution of CTR phase-delaying effects of evening bright-light on sleep separately from the effects of immediate elevation in core temperature. Subjects were run in a counterbalanced fully repeated measures design in which sleep and ambulatory rectal temperature were assessed during a four day period containing no exposure to evening bright-light and a four day period in which bright-light was administered on the first three evenings and dim-light was administered on the fourth. Sleep was assessed on Nights 1, 3 and 4. It was hoped that the immediate effects of evening bight-light on core temperature and sleep could be assessed on Nights 1 and 3, while the effects on sleep of a phase-delay of the CTR could be assessed independently of bright-light itself on Night 4.

8.2.3 Experiment Three: The Effects of Pre-exposure vs No Pre-exposure to Bright-Light on Core Temperature and Sleep.

The results of Experiments 1 and 2 suggested the possibility that a single exposure to evening bright-light might produce a different constellation of temperature and sleep effects than following more than one exposure to evening bright-light. This observation appeared consistent with the literature in which increased sleep onset latency and wake have followed a single exposure to evening bright-light (Cajochen et al., 1992; Dijk et al ., 1992) and enhanced sleep during the first two sleep cycles has

been found to follow administration of evening bright-light on more than one occasion (though not on consecutive nights) (Bunnell et al., 1992). It was hypothesised that compared with a dim-light condition, exposure to a single pulse of bright-light would produce moderate elevations in temperature and a disturbance to the early sleep period, whereas exposure to a second evening of bright-light would result in more robust elevations in temperature and enhanced SWS/SWA. A between-subjects design was utilised in which subjects were run in three groups: the dim-dim group were exposed to dim-light on two consecutive nights, the dim-bright group received dim-light on Night 1 and bright-light on Night 2 and the bright-bright group received bright-light on both Nights 1 and 2. Sleep was assessed on the second night of each experimental session. Thus the effects of pre-exposure and non pre-exposure to evening bright-light could be compared separately with a dim-light exposure by comparing the bright-bright and dim-bright groups to the dim-dim group respectively.

The effects of evening bright-light on core temperature and sleep architecture investigated in these experiments will be discussed separately, followed by a discussion of possible relationships between these effects.

8.3 The Effect of Evening Bright-Light on Rectal Temperature

8.3.1 Immediate Elevation

Rectal temperature was found to be elevated following exposure to evening bright-light in all three Experiments. This effect was seen most clearly in Experiment 1, on Night 3 of Experiment 2, and in the Bright-Bright Group of Experiment 3. On these occasions 2 or 3hrs of exposure to 3200lux of full-spectrum light prior to habitual bedtime was associated with elevations in rectal temperature of 0.2 - 0.3°C. These statistically significant elevations were evident by sleep onset and persisted for approximately two hours following termination of light exposure. The magnitude of temperature elevation found is consistent with other reports (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991) and the duration of the elevation is consistent

with one report (Bunnell et al., 1992) though others have reported even longer durations of temperature elevations (Cajochen et al., 1992; Dijk et al., 1992).

However, increases in rectal temperature following evening bright-light fell short of statistical significance on Night 1 of Experiment 2 and in the Dim-Bright Group of Experiment 3. Thus exposure to evening bright-light on a single or first occasion was associated with only modest elevations in rectal temperature compared with second or third exposures. This result is not consistent with Cajochen et al. (1992) or Dijk et al. (1991) in which rectal temperature was found to be significantly elevated following a single exposure to bright-light from 21:00hrs to 24:00hrs. Increased SOL was also reported in these studies and was not found in the present experiments. It appears that a single exposure to evening bright-light was not associated with as great an "energising" effect as reported elsewhere. This maybe because of a difference in methodology; in the present experiment light administration was until habitual bedtime whereas in the latter two studies it was till 24:00hrs. It is possible that some or all subjects in the latter studies had habitual bedtimes earlier than 24:00hrs. Exposure to bright-light would have occurred relatively closer to the CTR nadir in these subjects relative to the present experiments, and thus might have produced greater temperature effects than found in the present studies.

8.3.2 CTR Delay

In Experiment 2, no evidence for a phase-delay of the CTR was found following exposure to evening bright-light until habitual bedtime on three consecutive nights. This is in contrast to Dawson et al. (1993) who found a phase-shift of the CTR following a single exposure until habitual bedtime, Carrier and Dumont (1995) and Drennen et al. (1989) who found a delay of the CTR following three consecutive evening exposures.

Dawson and Campbell (1990) noted the importance of subject gaze in bright-light manipulations, pointing out that having the lights turned on is no guarantee of correct subject exposure to light. Thus it is possible that inconsistent subject gaze

resulted in the lack of CTR shift, though this possibility is considered unlikely for a number of reasons. First, subjects were monitored during the exposure and were not free simply to disregard experimental requirements. Second, subjects were not permitted to read or engage in any activity but viewing of the TV or video. This ensured constancy in gaze, and as illustrated in Experiment 1, the TV/Video monitor was surrounded by white reflective backing board. It is therefore considered unlikely that poor subject compliance or wandering gaze could account for lack of exposure to bright-light. Third, the elevations in rectal temperature described in the previous section strongly indicates that subjects were correctly exposed to the bright-light.

In addition, some studies suggest evening bright-light may not always phase-delay the CTR. Daurat et al. (1993) reported no change in either mean body temperature or CTR phase during a constant-routine protocol in which bright-light was continuously administered (although in this case the counter opposing effects of administration of bright-light both before and after the CTR nadir may have prevented any net phase-shift). In another study Rosenthal et al. (1990) found only four of ten subjects had delayed CTRs following 9 consecutive nights of BL exposure until 21:00hrs. Horne et al. (1991) reported no change in the oral temperature rhythm during a protocol in which 10min pulses of bright-light were administered hourly from 00:00hrs-6:00hrs. None of the three studies reporting the effects of a single exposure of evening bright-light on formally measured CTR phase, but examination of the data suggests no shift took place (Bunnell et al., 1992; Cajochen et al., 1992; Dijk et al., 1991). Thus some studies suggest that evening bright-light exposure may not be associated with a phase-delay. In addition, the studies finding a phase-delay of the CTR following bright-light prior to the sleep period have sometimes used light intensities greater than used in the present study (Carrier & Dumont, 1995; Drennen et al., 1989). It is possible that the presleep period is sufficiently far from the CTR minimum that CTR phase-shifts will not result from bright-light administration at this time unless very intense bright-light and/or large samples are used.

Lastly, it is possible that the downregulating effects of sleep itself on temperature masked a shift of the underlying circadian oscillator. It is well known that

sleep reduces temperature at all phases of the CTR and especially on the falling phase of the CTR. Accordingly, the purest measures of CTR phase control for the downregulating effect of sleep using a protocol such as the constant routine (e.g. Barrett, Morris, & Lack, 1993; Carrier & Dumont, 1995) in which this variable, and other potentially confounding variables, are controlled. It is therefore recognised that a phase-delay of the CTR might have been apparent in Experiment 2 had a constant routine procedure been used. However, the finding that no delay in REM latency occurred is a further indication that no delay of underlying circadian pacemaker in fact took place. The finding that no delay of REM sleep occurred following evening bright-light is in contrast with Bunnell et al. (1992) in which no evidence of a CTR delay was present, but in which a delay of REM sleep was found. In this case the delay of REM sleep was interpreted as indicating the possibility that a delay of the underlying pacemaker may have occurred, despite the apparent lack of delay of the CTR. The finding of no such increase in REM latency in the present experiments suggests, with the CTR results, that no delay of the underlying circadian pacemaker occurred.

It therefore appears in the present experiments that evening bright-light sufficient to produce elevated rectal temperature may not necessarily also produce shifts of the CTR; that the immediate effects of evening bright-light may occur independently from the phase-delaying effects.

8.4 Sleep Architecture Following Evening Bright-Light

8.4.1 SOL and Wake

No increases in SOL or Wake were noted following exposure to evening bright-light until habitual bedtime. These results are consistent with Bunnell et al. (1992) but not with Cajochen et al. (1992) or Dijk et al. (1991). As indicated previously, this difference maybe due to differences in methodologies; in the present experiment, and in Bunnell et al. (1992), light exposure was until habitual bedtime, whereas in Cajochen et

al. (1992) and Dijk et al. (1991) exposure was until 24:00hrs. As discussed, if some or all subjects were accustomed to retiring earlier than 24:00hrs then exposure to bright-light at this time in the latter two studies might well have been more disruptive to sleep than exposure in the hours prior to habitual bedtime. In addition, as suggested in Chapter 4, the excessively low light levels used in the dim-light condition by Cajochen et al., (1992) and Dijk et al., (1991) may have resulted in artificially short SOL times in this condition.

8.4.2 REM Sleep

No differences in amounts of REM or REM latency were found to occur on any night of the present experiments. These results are consistent with most published studies (e.g. Cajochen et al., 1992; Carrier & Dumont, 1995; Dijk et al., 1991; Drennen et al., 1989; Sack et al., 1986) though not with Bunnell et al. (1992) who reported increased REM latency following evening bright-light. In this case it is possible, as discussed, that the longer REM latency reflected a delay of the underlying circadian pacemaker. Another possibility is that the enhanced sleep found in the first two sleep cycles in this study (and not found in any of the studies cited immediately above) resulted in a delay of REM sleep.

8.4.3 Slow Wave Sleep and Slow Wave Activity

Consistent increases in SWS/SWA were noted in all three experiments following evening bright-light. Most notable were the increases in SWS/SWA across the night observed in Experiment 1, Night 3 Experiment 2 and in the Bright-Bright Group of Experiment 3.

These increases are consistent with Bunnell et al. (1992) who reported enhanced SWA in the first two sleep cycles, but are inconsistent with Cajochen et al . (1992) , Dijk et al. (1991) and Carrier et al. (1995) who reported no overall elevations in SWS or SWA following evening bright-light.

The elevations in SWS/SWA found in the present experiments appeared to be most pronounced in the third and fourth sleep cycles. This is consistent with Cajochen et al. (1992) and Carrier et al. (1995) who reported a similar enhancement to SWA in the late sleep period following evening bright-light. This delay did not appear to be due to a sleep or SWS/SWA debt incurred early in the night (this will be discussed further presently).

8.5 Possible Relationships Between Temperature Effects and Sleep Architecture

In the previous sections the effects of evening bright-light on rectal temperature and sleep found in the present experiments have been briefly described and compared with existing literature. It is the purpose of this section to consider how the effects of bright-light on sleep might have been mediated by temperature effects and other means.

8.5.1 Increased SOL, Wake and Early Disruption to SWS/SWA

Before commencing discussion of temperature effects, brief consideration of the influence of SOL, Wake and early disturbance to SWS/SWA will be given. It is notable that unlike Cajochen et al., (1992) and Dijk et al., (1991), no increases in SOL, Wake or disturbance to early SWS/SWA were evident in the present experiments. However, the lack of disruption to sleep early in the night is consistent with Bunnell et al., (1992) who found no disruption to sleep onset or early SWS even after evening bright-light suppression of melatonin and temperature elevation. These results suggest that while the presence of melatonin may enhance sleep, its absence or suppression by bright-light to habitual bedtime may not necessarily diminish sleep. The possibility that thermic effects countered the effects of suppressed melatonin during early sleep will be considered shortly.

Cajochen et al., (1992) accounted for the increase in SWA during the fourth NREM period as a rebound in SWA following early suppression and increased SOL following bright-light. As no such disruption to sleep was found in the present studies

(or in Carrier et al., 1995 who reported a similar increase of SWS late in the night) the increases in SWS/SWA found in the present experiments do not appear to be due to increased sleep pressure following bright-light.

8.5.2 Immediate Temperature Elevation

The first alternative possibility is that the increases noted in SWS/SWA were due to elevations in rectal temperature found early in the subjective night. Elevations in temperature at this time have been empirically associated with increased SWS/SWA in studies of exercise and sleep (e.g. Horne & Moore, 1985), increased ambient temperature prior to sleep (Shapiro et al., 1989) and passive heating of the body (e.g. Jordan et al., 1990) and head (Moriaty et al., 1988) (see Chapter 2).

However, it is noteworthy that most of these conditions result in temperature elevations of greater than 0.2-0.3°C as found following evening bright-light. For instance, warm baths used in passive heating studies typically result in elevations in rectal temperature of 1.4°C immediately after heating, which fall to just above control values by sleep onset. No such large increases occur following evening bright-light as temperature is merely maintained, or prevented from coming under the downregulating influence of melatonin. It is therefore of some interest that SWS/SWA enhancements were found to follow the relatively modest increases in temperature associated with evening bright-light.

Interpreted this way the present results are consistent with Berger and Phillips (1988) in suggesting that SWS is an energy conserving mechanism and that SWS/SWA amounts are positively related to temperature at sleep onset. The present results suggest that this relationship holds for even modest differences in temperature (0.2-0.3°C) which do not occur following a large increase in temperature, so much as a maintenance of it within a normal range against a downregulating influence.

The increase in SWS/SWA following relative elevation of rectal temperature may also be interpreted as consistent with the suggestion that the primary function of

SWS is to downregulate cerebral metabolic rate for restoration (Horne, 1988) or protection against overheating (Szymusiak & McGinty, 1990). For this interpretation to succeed it would need to be assumed that evening bright-light elevated cerebral temperature and metabolism in addition to core or rectal temperature. This assumption should not be made automatically, as although many studies have reported elevated tympanic temperature during all-night exposure to bright-light (e.g. Badia et al., 1991; Myers et al., 1995), Bunnell et al. (1992) found elevated rectal temperature, but not tympanic temperature, following bright-light until habitual bedtime. It is possible that exposure only until habitual bedtime does not produce elevations in tympanic temperature during the subsequent sleep period. It was also suggested by Bunnell et al. (1992) that more sensitive thermoregulation of brain than body temperature might account for the differences observed between rectal and tympanic temperature.

A final consideration is that most SWS/SWA enhancements found to follow temperature elevations occur within the first two sleep cycles. In contrast, no significant increase in SWS/SWA was found in either of these cycles. Instead there was a trend for increases in the third and fourth sleep cycles. It is possible that the thermic effects on SWS/SWA usually evident in the first two sleep cycles were delayed to the last two sleep cycles by possible arousing effects of bright-light on sleep. This possibility was suggested by Cajochen et al., (1992) who found evidence of disturbance to sleep early in the night. Although no significant disturbance was found in the present studies it is possible that undetected arousing effects of bright-light operative early in the sleep period delayed the thermic effects on SWS/SWA until later cycles.

8.5.3 Phase-Delay of the CTR

As described in the rationale for Experiment 2, a small literature exists suggesting that SWS propensity has a circadian influence such that initiation of sleep near the acrophase of the CTR (as would occur following phase-delay of the CTR) results in relatively greater amounts of SWS. However, the increases in SWS/SWA found in the present experiments cannot be due to such a factor, as no evidence of CTR delay was found.

8.5.4 Melatonin Suppression and Rebound

Although melatonin assays were not possible in the present experiments, speculation about the possible influences of melatonin appears warranted given the increases in temperature following evening bright-light and in SWS/SWA during subsequent sleep. As indicated in the discussion section of Experiment 3, it is possible that the increases in SWS/SWA found in later sleep cycles were associated with a rebound in melatonin following early suppression by bright-light.

Increases in temperature following bright-light suggest that melatonin levels were also significantly suppressed. Badia et al. (1991) reported that melatonin levels rose to normal within approximately an hour of termination of bright-light during the hours of 24:00-08:00hrs. Thus normal levels of melatonin might have been found following approximately an hour of sleep in the present experiments. Tzischinsky and Lavie (1994) have reported time-dependent hypnotic effects of melatonin such that melatonin administrations in the subjective night are associated with shorter SOLs than daytime administrations. They found that melatonin administered at 21:00hrs produced measurable hypnotic effects within an hour. Thus normal or increased levels of melatonin present during the second hour of sleep might be expected to produce measurable enhancement to SWS in the third or fourth hours. This interpretation is consistent with the present findings and those of Cajochen et al. (1992) and Carrier et al. (1995) that SWS/SWA is most noticeably enhanced in the latter parts of the sleep period.

8.5.5 Thermic and Melatonin Rebound Effects

SWS/SWA amounts were generally found to be equivalent in the first sleep cycle and increased in the last two sleep cycles following bright-light. This suggests the possibility that both thermic and melatonin rebound effects may have combined to produce the results on SWS/SWA observed. In the first two sleep cycles it is possible that the counter-opposing effects of elevated temperature and suppressed melatonin on SWS cancelled each other out, resulting in approximately equivalent amounts of

SWS/SWA in these periods under bright-light and dim-light conditions. More noticeable increases in SWS/SWA found in latter cycles may have been caused by the melatonin rebound speculated upon in the last section.

8.6 Future Research

The interpretations of the SWS/SWA facilitation effects offered above suggest the need for direct testing of melatonin levels concurrent with all night polysomnography following evening bright-light. Such an experiment would allow the testing of the melatonin rebound hypothesis. The possibility that thermic effects allow SOL and early SWS to remain intact following evening bright-light might be tested by lowering body temperature during this period with aspirin. If SOL and early SWS were disturbed under these conditions it would strongly suggest that elevated temperature may counter the "energising" effects also associated with suppressed melatonin.

8.7 Implications for Applications

The "energising" and phase-shifting effects of bright-light are being investigated for their application in both clinical and industrial settings. In sleep medicine the phase-shifting properties of bright-light are being used to treat delayed/advanced sleep phase insomnia, major depression and seasonal depression. Both the immediate "energising"effects and phase-shifting effects are being investigated for application in industry to improve nighttime performance and circadian adaptation to shift work. The present findings are relevant to these applications on at least two counts. Firstly, the present findings suggest that exposure to bright-light until habitual bedtime does not necessarily increase sleep onset latency or disrupt early SWS. Thus, the "energising" effects of bright-light administered until habitual bedtime might be exploited, even on multiple consecutive nights, without necessarily disrupting subsequent sleep.

Secondly, the results suggest that the "energising" effects of such bright-light until habitual bedtime may not necessarily be associated with a delay to the CTR. This is of benefit if no shift of the CTR is desired, but suggests that if a CTR shift is desired, bright-light should be exposed somewhat beyond habitual bedtime.

8.8 Summary and Conclusions

The present experiments have indicated that evening bright-light administered until habitual bedtime elevates rectal temperature and increases SWS/SWA during the subsequent habitual sleep period. This pattern of results has been found to occur most reliably following more than one exposure to bright-light. No increase in SOL or early amounts of SWS/SWA have been found, suggesting that suppression of melatonin by bright-light until habitual bedtime may not necessarily disturb sleep. It has been suggested that this lack of disturbance may be due to the thermic effects also present during this period. In later sleep cycles SWS/SWA were more noticeably enhanced following bright-light. It is possible these elevations in SWS/SWA were a consequence of the thermic effects present early in the sleep period. Interpreted this way the present results are consistent with the notion that SWS/SWA amounts are positively correlated with body temperature at sleep onset (Berger & Phillips, 1988) and that the function of SWS may be to downregulate body temperature for energy conservation. The results are also generally consistent with the notion that that SWS serves primarily to downregulate cerebral temperature for CNS protection (Szymusiak & McGinty, 1990) and/or restoration (Horne, 1988), though tympanic temperature was not assessed in the present experiments and it is recognised that it may not necessarily be elevated following evening bright-light (Bunnell et al., 1992).

Alternatively it is possible that melatonin, suppressed early in the sleep period, rebounded during the later sleep period and enhanced SWS/SWA. Interpreted this way the results add to a growing literature suggesting that melatonin influences both body temperature and SWS. Further study is needed to test this hypothesis. However, the SWS/SWA effects do not appear to be due to a phase-delay of the CTR by evening

bright-light as no such delay was evident in the present data. The present results thus suggest that exposure to evening bright-light may elevate temperature without necessarily delaying the CTR.

The present studies suggest that thermic and melatonin effects following evening bright-light may combine to produce a net increase in SWS/SWA in the subsequent sleep period. This hypothesis is consistent with literature arguing for both (a) a positive relationship between body temperature at sleep onset and SWS, and (b) the role of melatonin as a somnogenic agent, but requires empirical testing in further research.

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APPENDIX A

PRESENTATION OF DATA AT CONFERENCES

APPENDIX A

PRESENTATION OF DATA AT CONFERENCES

Australasian Psychophysiological Society Conference, Dec 3-5, 1993 Sydney, Australia.

Australian Sleep Association Annual Conference, March 30-31, 1995, Hobart, Australia.

APPENDIX B

TABLE OF ABBREVIATIONS

APPENDIX B

TABLE OF ABBREVIATIONS

VARIABLE	ABBREVIATION
Movement Time	MT
Slow Wave Sleep	SWS
Slow Wave Activity	SWA
Total EEG Power	TP
Sleep Cycle	Cyc
Rapid Eye Movement sleep	REM sleep
Latency to REM sleep	REMLAT
Sleep Onset Latency	SOL
Non-REM sleep	NREM sleep
Core Temperature Rhythm	CTR
Phase Response Curve	PRC
Minutes	mins
Hours	hrs
Dim-light	DL
Bright-light	BL
Fast Fourier Transform	FFT

APPENDIX C

EXPERIMENT 1 ANOVA TABLES

APPENDIX C

EXPERIMENT ONE ANOVA TABLES

Average Hourly Rectal Temperature 6 x 2 Time (BL period + each of the following 5 hrs) x Condition (BL/DL) ANOVA
Summary of all effects; design:
1-Time, 2-Condition

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	5	2.79	45	0.01	157.96	.000
2	1	0.14	9	0.06	2.34	.16
12	5	0.10	45	0.007	13.74	.000

SWS per Sleep Cycle 4 x 2 Cycle (1 to 4) x Condition (BL/DL) ANOVA
Summary of all effects; design:
1- Cycle, 2 - Condition

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	3	25805.94	30	1262.67	20.43	.000
2	1	1053.64	10	117.39	8.97	.01
12	3	82.48	30	283.22	0.29	.83

SWS per Hour 2 x 7 Condition (BL/DL) x Hour (1-7) ANOVA
Summary of all effects; design:
1- Condition, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	662.86	10	123.30	5.37	.042
2	6	10130.25	60	292.61	34.62	.000
12	6	39	60	166.72	.23	.963

**Cumulative SWS per Hour 2 x 7 Condition (BL/DL) x Hour (1-7) ANOVA
Summary of all effect; design:
1- Condition, 2 - Hour**

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	3177.27	10	500.62	6.34	.030
2	6	7998.09	60	108.78	73.52	.000
12	6	226.73	60	35.69	6.35	.000

APPENDIX D

EXPERIMENT 2 ANOVA TABLES

APPENDIX D

EXPERIMENT TWO ANOVA TABLES

Average Rectal Temperature per hour during first 2 hrs following Bright-light 2 x 3 x 2 Hour (1 and 2) x Night (1,3,4) x Condition (BL/DL) ANOVA Summary of all effects; design:
1- hr, 2 - Night, 3 - Condition

Effect	df Effect	MS Effect	df Error	MS Error	F	p-value
1	1	0.03	8	0.10	0.29	.602
2	2	0.05	16	0.11	0.51	.607
3	1	1.74	8	0.02	59.60	.000
12	2	0.31	16	0.07	4.30	.031
13	1	0.00	8	0.00	1.07	.329
23	2	0.00	16	0.00	0.83	.453
123	2	0.00	16	0.00	0.45	.640

Average Rectal Temperature per hour during the 3rd, 4th and 5th hrs following Bright-light 3 x 3 x 2 Hour (3, 4, 5) x Night (1,3,4) x Condition (BL/DL) ANOVA
Summary of all effects; design:
1- Condition, 2 - Night, 3 -hr

Effect	df Effect	MS Effect	df Error	MS Error	F	p-value
1	1	0.12	8	0.04	3.05	.11
2	2	0.11	16	0.12	0.92	.41
3	2	0.16	16	0.01	8.21	.003
12	2	0.14	16	0.06	2.28	.13
13	2	0.04	16	0.02	2.16	.14
23	4	0.00	32	0.01	0.91	.46
123	4	0.02	32	0.01	2.05	.11

Rectal Temperature at Sleep Onset
2 x 3 Condition (BL/DL) x Night (1,3,4)
Summary of all effect; design:
1- Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	0.01	8	0.03	0.36	.563
2	2	0.03	16	0.03	0.91	.422
12	2	0.26	16	0.05	5.20	.018

Time of Circadian Minimum of Rectal Temperature
2 x 3 Condition (BL/DL) x Night (1,3,4) ANOVA
Summary of all effects; design:
1 - Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	1.69	7	6747.83	0.00	.987
2	2	3507.56	14	6708.72	0.52	.603
12	2	3175.73	14	8841.60	0.35	.704

Stage 2 Sleep 2 x 3 Condition (BL/DL) x Night (1,3,4) ANOVA
Summary of all effects; design:
1 - Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	954.23	8	144.61	6.59	.033
2	2	18.34	16	1090.65	0.01	.983
12	2	152.08	16	603.96	0.25	.780

Stage 3 Sleep 2 x 3 Condition (BL/DL) x Night (1,3,4) ANOVA
Summary of all effects; design:
1 - Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	342.51	8	63.83	5.36	.049
2	2	267.14	16	150.71	1.77	.201
12	2	200.56	16	73.66	2.72	.096

Stage 4 Sleep 2 x 3 Condition (BL/DL) x Night (1,3,4) ANOVA
Summary of all effects; design:
1 - Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	1256.66	8	163.10	7.70	.021
2	2	51.68	16	174.69	0.29	.747
12	2	338.31	16	214.29	1.57	.236

SWS 2 x 3 Condition (BL/DL) x Night (1,3,4) ANOVA
Summary of all effects; design:
1 - Condition, 2 - Night

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	2940.78	8	362.21	8.11	.021
2	2	448.85	16	231.59	1.93	.176
12	2	919.64	16	261.44	3.51	.054

SWS per sleep cycle 3 x 3 x 4 Condition (DL/BL) x Night (1,3,4) x Cycle (1-4)
ANOVA. Summary od all effects; design:
1 - Condition, 2 - Night, 3 - Cycle

Effect	df Effect	MS Effect	df Error	MS Error	F	p-value
1	1	605.01	8	115.99	5.22	.052
2	2	355.22	16	212.15	1.67	.219
3	3	31676.54	24	693.25	45.69	.000
12	2	444.34	16	80.46	5.52	.015
13	3	436.15	24	491.24	0.89	.462
23	6	146.18	48	424.06	0.45	.841
123	6	443.06	48	192.16	2.31	.049

SWA per NREM period Night 3 2 X 4 Condition (BL/DL) x NREM Period
(1-4) ANOVA. Summary of all effects; design:
1 - Condition, 2 - NREM Period

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	776433E3	5	45499E3	1.70	.248
2	3	205247E4	15	172861E3	11.87	.000
12	3	116948E3	15	31767E3	3.68	.036

Total EEG Power per NREM Period Night 3 2 X 4 Condition (BL/DL) x
NREM Period (1-4) ANOVA. Summary of all effects; design:
1 - Condition, 2 - NREM Period

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	20028E5	5	290177E4	0.69	.443
2	3	544746E4	15	745473E3	7.30	.003
12	3	821393E3	15	206886E3	3.97	.028

SWS per hour Night 3 2 x 6 Condition (BL/DL) x Hour (1 to 6) ANOVA
Summary of all effects; design:
1- Condition, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	1933.78	8	288.05	6.71	.032
2	5	8989.12	40	689.47	13.03	.000
12	5	413.84	40	264.07	1.56	.191

Cumulative SWS per hour Night 3 2 x 6 Condition (BL/DL) x Hour (1 to 6) ANOVA
Summary of all effects; design:
1- Condition, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	4200.83	9	740.04	5.67	.041
2	5	17668.63	45	169.88	104.00	.000
12	5	201.15	45	48.81	4.12	.003

Cumulative SWA per hour Night 3 2 x 6 Condition (BL/DL) x Hour (1 to 6) ANOVA
Summary of all effects; design:
1- Condition, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	1	251966E4	6	238848E4	1.05	.343
2	5	468488E5	30	230797E3	202.98	.000
12	5	182358E3	30	631956E2	2.88	.030

APPENDIX E

<u>EXPERIMENT 3 ANOVA TABLES</u>

APPENDIX E

EXPERIMENT THREE ANOVA TABLES

Average rectal temperature 3 x 5 Groups (DD/DB/BB) x Hour (1-5) ANOVA
Summary of all effects; design:
1- Group, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	0.45	32	0.39	1.19	.319
2	4	3.32	128	0.02	179.42	.000
12	8	0.05	128	0.02	2.73	.008

SWA per NREM Period 3 x 4 Groups ((DD/DB/BB) x NREM Period (1-4)
ANOVA
Summary of all effects; design:
1- Group, 2 - NREM Period

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	144290E4	22	40758E4	3.54	.046
2	3	546082E4	66	313783E3	17.40	.000
12	6	413070E3	66	313783E3	1.32	.262

3Hz-8Hz per NREM Period 3 x 4 Groups ((DD/DB/BB) x NREM Period (1-4) ANOVA. Summary of all effects; design:
1- Group, 2 - NREM Period

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	35089E4	22	126503E3	2.77	.084
2	3	626942E3	66	785324E2	7.98	.000
12	6	235768E3	66	785324E2	3.00	.012

**8Hz-12Hz per NREM Period 3 x 4 Groups ((DD/DB/BB) x NREM Period
(1-4) ANOVA. Summary of all effects; design:
1- Group, 2 - NREM Period**

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	88873E3	22	317176E2	2.80	.082
2	3	704599E2	66	8188097.	8.61	.000
12	6	186829E2	66	8188097.	2.28	.046

**12Hz-30Hz per NREM Period 3 x 4 Groups ((DD/DB/BB) x NREM Period
(1-4) ANOVA. Summary of all effects; design:
1- Group, 2 - NREM Period**

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	167427E3	22	686556E2	2.44	.111
2	3	10131E4	66	239049E2	4.24	.008
12	6	704263E2	66	239049E2	2.95	.013

**Total EEG Power per NREM Period 3 x 4 Groups ((DD/DB/BB) x NREM
Period (1-4) ANOVA. Summary of all effects; design:
1- Group, 2 - NREM Period**

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	732452E4	22	233108E4	3.14	.063
2	3	151214E5	66	117329E4	12.89	.000
12	6	22212E5	66	117329E4	1.89	.095

SWS Cumulative per hour 3 x 6 Groups (DD/DB/BB) x Hour (1-6) ANOVA
Summary of all effects; design:
1 - Group, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	1625.29	33	2325.93	0.70	.504
2	5	33305.92	165	128.60	259	.000
12	10	261.57	165	128.60	2.03	.033

SWA Cumulative per hour 3 x 6 Groups (DD/DB/BB) x Hour (1-6) ANOVA
Summary of all effects; design:
1 - Group, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	879266E4	26	597342E4	1.47	.248
2	5	800540E5	130	24048E4	332.89	.000
12	10	500411E3	130	24048E4	2.08	.030

Total EEG Power per hour 3 x 6 Groups (DD/DB/BB) x Hour (1-6) ANOVA
Summary of all effects; design:
1 - Group, 2 - Hour

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	785978E5	26	212300E5	3.70	.038
2	5	560140E6	130	770233E3	727.23	.000
12	10	315256E4	130	770233E3	4.09	.000

SWS during the 4th sleep cycle in DD, DB and BB Groups
1-Group

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
1	2	1418.41	31	348.23	4.07	.02

APPENDIX F

SUBJECTS' HABITUAL BEDTIMES AND WAKETIMES

APPENDIX F

SUBJECTS' HABITUAL BEDTIMES AND WAKETIMES

Bedtimes and Waketimes are given in clock hours
Standard Deviations are given in minutes

EXPERIMENT ONE

Subject	Habitual Bedtime	Habitual Waketime
MP	01:00	09:30
SC	23:30	07:00
PJ	00:10	08:00
DA	00:00	09:00
MK	00:20	08:00
LE	00:00	09:30
SP	23:30	08:30
CG	23:00	07:00
CW	00:00	08:00
TB	23:30	07:00
BP	00:00	08:30
Mean	23:55	08:10
SD	31.7	55.7

EXPERIMENT TWO

Subject	Habitual Bedtime	Habitual Waketime
DA	01:00	10:00
PJ	00:30	07:00
CG	00:10	09:20
JP	00:00	08:30
MK	00:00	08:30
MP	23:00	07:30
MW	00:10	07:20
SC	23:00	07:40
SB	01:30	09:30
SK	23:50	09:10
ST	22:30	06:30
Mean	23:58	08:13
SD	53.1	68.8

EXPERIMENT THREE

Dim-Dim			Dim-Bright			Bright-Bright		
Subject	Bed	Wake	Subject	Bed	Wake	Subject	Bed	Wake
MK	23:50	08:00	PJ	00:20	08:30	LH	00:10	09:00
SC	23:30	08:00	MP	00:30	07:30	LE	00:10	08:30
RW	23:50	07:50	JP	23:40	08:00	JK	00:10	09:00
MJ	23:45	08:50	BP	00:00	08:30	AM	00:30	07:30
DK	23:40	08:00	CM	00:30	07:40	FA	00:10	08:45
SS	23:30	07:30	CK	00:00	08:00	DD	00:20	07:40
AM	23:40	07:30	TF	00:00	08:30	SP	00:20	07:40
RS	23:30	06:30	MU	00:20	08:30	PS	00:30	08:30
MD	23:00	07:00	MM	00:20	07:30	MS	00:30	11:00
JR	00:10	08:30	TK	23:40	08:00	AE	00:00	06:30
MT	00:00	08:00	SC	23:10	07:30	JM	23:30	08:00
PB	23:10	08:20	RB	00:00	08:30	SF	23:20	08:00
Mean	23:47	07:50		00:02	08:03		00:08	08:22
SD	20.0	38.4		23.8	26.0		22.5	65.9