

# Forced splitting of human sleep in free-running rhythms

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**SUMMARY** The assumption of polyphasic sleep/wake regulation is based on the occurrence of nap-sleep at specific phase positions in the circadian cycle. Further support would be the split of the normal long major sleep episode into shorter components. Evidence for this hypothesis comes from the discovery of bimodal distribution in sleep duration. An experimental approach to test this hypothesis has been carried out by restricting sleep duration in free-running rhythms. The outcome was a biphasic distribution of sleep within a circadian cycle with sections of dissociation and synchronization of the two sleep blocks. The results show similarities with 'splitting', a phenomenon which has been found in animal studies. The relatively short duration of the different sections as well as the asymmetric distribution of the two sleep blocks in the circadian cycle leads to the assumption of a splitting of the major sleep episode and not of the circadian rhythm. Sleep split into two, relatively short sleep episodes of comparable duration contrasts with napping, which is characterized by an extra sleep episode in addition to the long major sleep.

**KEYWORDS** nap, polyphasic sleep, sleep duration, sleep/wake regulation, split-sleep

## INTRODUCTION

There is some evidence that the usual long major sleep episode can be split into shorter ones, from bedrest studies and from nap and split-sleep in free-run studies (Strogatz 1986; Zulley 1988). In studies using the constant bedrest design it has been shown that sleep duration shows a bimodal distribution, with sleep episodes either shorter than 4 h or longer than 5 h, while the occurrence of sleep durations between 4 and 5 h seems to be rare (Zulley 1988). In free-run studies, as well as in 24 h studies, additional short sleep episodes (naps) have been found to be an integral part of the overall sleep wake regulation (Campbell and Zulley 1985). Strogatz (1986 p. 120) differentiates between naps and split-sleep episodes whereby the latter: "... bracket the middle of the ordinary consolidated sleep and thus appear to be split versions of it."

This finding seems to be associated with the phenomenon of 'splitting'. This phenomenon has been observed in animal studies and has been described where two activity components free-run at temporarily different frequencies (Pittendrigh and Daan 1976; Daan and Berde 1978). The two components often resynchronize upon reaching a 180° phase relation and free-run with a common period. Splitting

can occur spontaneously or may be induced (Hoffmann 1971; Gwinner 1974). Thus splitting is characterized by two components per circadian cycle, a result which has also been found in nap and split-sleep. It remains unclear which characteristics differentiate napping, split-sleep and splitting.

An experiment was designed to try to uncover some of these differences by restricting sleep duration to short sleep episodes in a free-running rhythm.

## METHOD

Six subjects were kept singly in isolated conditions (like in the standard experiments for circadian research by Aschoff and Wever; see Wever 1979) for periods between 15 days and 28 days. The subjects had no information about the time of day and could go to sleep whenever they wanted to. They had to prepare their own meals, had no social contacts, and were instructed to turn the lights off when they decided to sleep. The only additional difference to the standard experiments was that subjects were woken by a tone after a specific time in bed (4 subjects were kept throughout the entire experimental episode at a 4-h sleep (Ss2–5), while the remaining 2 subjects (Ss1 and 6) had, in addition, a section where they could sleep *ad lib* (and hence had the standard free-run condition). One of these subjects (S6) also had an intervening section with sleep restricted to 5 h of sleep. The subjects were unaware of the enforced

duration. After the forced awakening, the subjects were asked to get up, and not to return to bed immediately: the instructions did not include a specific duration for staying awake to avoid artifacts. Activity was measured by electrical contacts in the floor of the isolation unit and under the bed. Body temperature was recorded continuously by a rectal probe. No temperature data were available for an extended period of time in S3 due to the malfunctioning of the temperature recordings. Subjects signalled the occurrence of several activities, including going to bed, getting up and meal times by pressing appropriately labelled buttons. The 'going to bed' signal started a clock, which activated an alarm after a fixed time interval (4 or 5 h). In the 'ad lib' condition, this alarm was deactivated. Thus, since sleep has not been measured polygraphically, only the 'time in bed' was registered; nevertheless, the term 'sleep' was used for the sake of argument. The circadian minima of rectal temperature were visually scored. Since this is a pilot study with only a small number of subjects, only a descriptive analysis was carried out. The Enright periodogram was used for the period analysis (Enright 1980) and average values are given as means with their standard deviations.

## RESULTS

The data analysis demonstrates, that with a restriction of sleep duration to 4 h the sleep/wake rhythm showed in all cases a biphasic pattern (S3 showed a triphasic pattern at times) within a circadian cycle. The change from the normal free-run to this biphasic pattern can be seen in subject 6, where a restriction of sleep to 5 h did not alter the sleep/wake pattern (Fig. 1). A biphasic pattern became obvious only with the restriction to 4 h.

A further characteristic is the change between states of dissociation and synchronization. While these two states are characterized by relatively constant periodicities, there are also sections where no periodicity can be observed [e.g. S2 (day 12–16) and S3 (day 10–22)]. The course of the experiments is characterized by an initial occurrence of dissociation (Fig. 1). Although in S1 dissociation and synchronization are easily distinguishable, in the other subjects the distinction is not so clear.

During dissociation, the two sleep blocks run with different periodicities. These relatively long periods show mean values of  $25.9 \pm 0.9$  h and  $27.6 \pm 0.8$  h, respectively. Furthermore, this state is not only characterized by a dissociation of the two sleep episodes, but also by a desynchronization from the temperature, which has a mean rhythm of  $24.7 \pm 0.6$  h. Table 1 shows the classification of sections of dissociation by visual scoring in each subject.

In contrast, during the synchronization, the two sleep episodes ran parallel with a similar period (mean  $24.4 \pm 0.6$  h). In addition, the sleep blocks are in synchrony with the circadian temperature rhythm ( $24.4 \pm 0.5$  h). The classification of the state of synchronization is shown in Table 1. During synchronization, the sleep episodes were

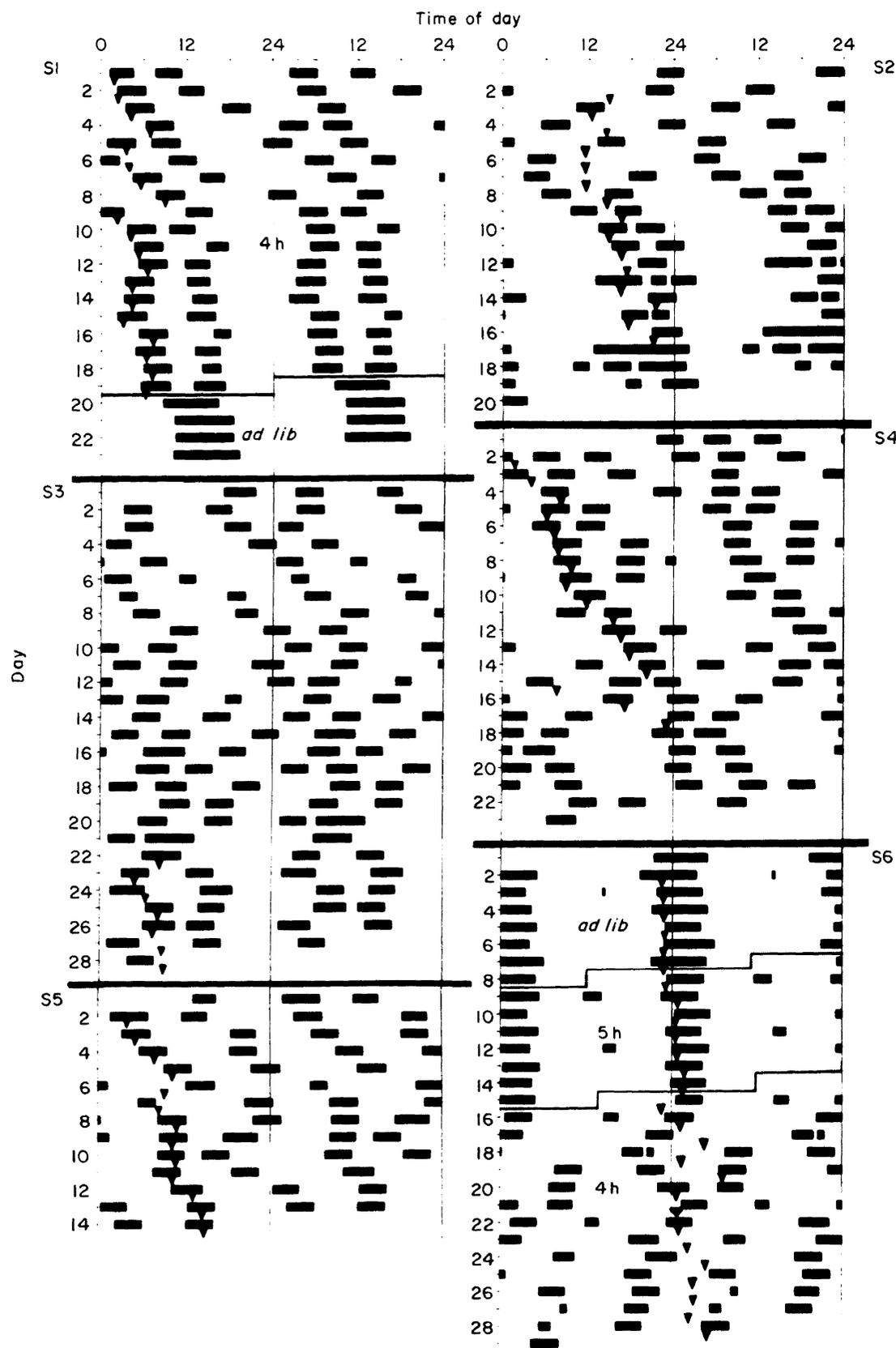
characteristically distributed asymmetrically in the circadian cycle (Fig. 2): one sleep block at the temperature minimum (onset of sleep  $1.7 \pm 0.24$  h before the minimum) and the other sleep block  $7.1 \pm 1.2$  h after the minimum. This resulted in a relatively short wake episode ( $5.2 \pm 1.5$  h) after the sleep episode at the temperature minimum (the 'first' sleep block) compared to the wake duration ( $11.9 \pm 3.4$  h) after the 'second' sleep block.

This second sleep block ( $3.78 \pm 0.44$  h) was slightly shorter than the first one ( $4.05 \pm 0.41$  h). That this difference is of practical significance can be seen in the result, that in the first sleep block 19% of the subjects woke up before the alarm, while in the second sleep block 60% of the subjects woke up prematurely. Nevertheless, in one subject (S6) a symmetric distribution of the two sleep blocks was found with  $9.9 \pm 2.5$  h for the first wake duration and  $8.7 \pm 3.1$  h for the second wake duration. He was also the only subject, who showed no differences between the two sleep block durations ( $3.92 \pm 0.51$  h;  $3.94 \pm 0.30$  h).

## DISCUSSION

Restriction of sleep duration to 4 h in an otherwise free-running rhythm leads to the occurrence of two sleep blocks within a circadian cycle and to the occurrence of two distinct states with regard to the respective course of these two blocks during the experiment. This course is expressed by an initial dissociation, which leads to synchronization. Dissociation is characterized by two sleep blocks which have two different circadian frequencies, that differ from the temperature rhythm. This state changes into synchronization when the 'first' sleep block synchronizes with the temperature rhythm (occurs at the temperature minimum). The 'second' sleep block keeps a stable phase relationship relative to the 'first' sleep block; this could be interpreted by the finding of Minors and Waterhouse (1984), that "the rhythms undergoing irregular routines free-run but that, in the presence of an anchor sleep, the rhythms are stabilized with a period indistinguishable from 24 hours". In the present experiment, the sleep block at the temperature minimum acts in this sense as the 'anchor' sleep, which synchronizes the 'second' sleep block and seems to shorten the period of the temperature rhythm.

This course shows similarities to the phenomenon of 'splitting', since a single function is distinguished by two components per cycle, temporarily having two different frequencies and then phase locking to each other at a stable phase-angle difference. The dissimilarity to the phenomenon of 'splitting' is the result, that this phase-difference is not  $180^\circ$ . In addition, the sections with dissociation are too short to assume a constant periodicity. During synchronization, the two sleep blocks are different in their duration as well in the duration of the intervening wakefulness and in subjective estimations (anecdotal reports). In the 'first' sleep block (at the temperature minimum) the subjects had to be woken, found it hard to get up, and had the feeling of not



**Figure 1.** Consecutive sleep episodes (black bars: bedrest) double plotted for all subjects (S1–S6). Visually scored temperature minima are indicated by triangles. Some temperature minima are missing. S1 had a section of free-run condition (*ad lib*) after the 4-h sleep limitation. S6 initially had a section with free-run (*ad lib*), followed by a section with a 5 h sleep restriction (5 h), which was followed by a 4-h sleep restriction (4 h). All other subjects had a 4-h sleep restriction throughout the entire experiment.

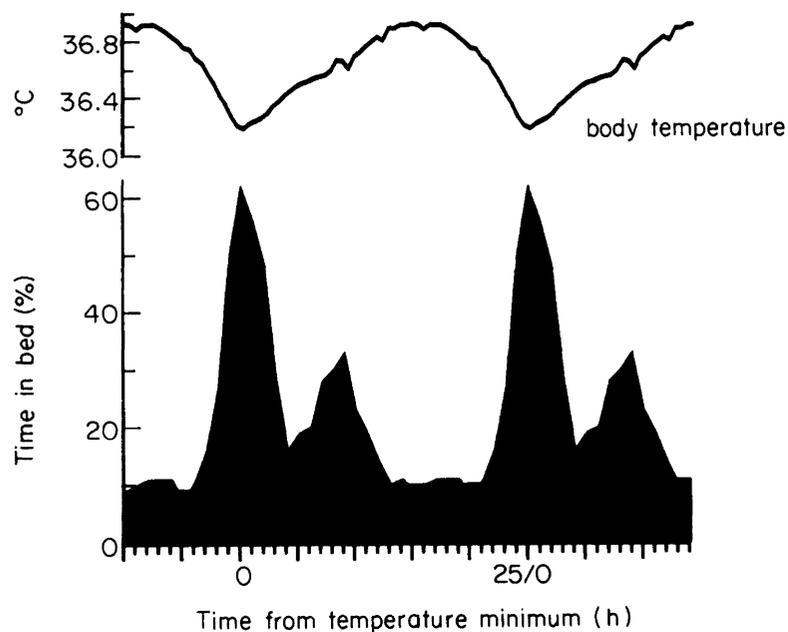
having had enough sleep. The succeeding wake episode was short and the subjects left drowsy throughout the period. In the 'second' sleep block, the majority of the subjects woke up before the alarm, and felt alert throughout the longer succeeding wake episode. This finding is in accordance with the results of Wehr (1991), who found a split-sleep pattern with a comparable asymmetric distribution of sleep in

subjects under a photoperiod of 10 h light and 14 h darkness.

This finding can be interpreted if the 'first' sleep block (the 'anchor' sleep at the temperature minimum) represents the major sleep, while the 'second' sleep block compensates the restricted sleep duration of the first sleep block, which was too short. Therefore, the 'second' sleep block is shorter

**Table 1** Classification of the states of dissociation and synchronization

	S1	S2	S3	S4	S5	S6
Dissociation	Day 1–11	Day 1–8	Day 1–9	Day 1–4	Day 1–6	Day 16–22
Synchronization	Day 12–19	Day 9–11	Day 22–27	Day 7–9, 17–21	Day 7–13	Day 25–28



**Figure 2.** Distribution (double plotted) of the relative frequency of sleep (time in bed) relative to the sleep/wake cycle. Reference point is the circadian minimum of rectal temperature ('0' or '25/0' on the time scale). Averaged course of rectal temperature (above). Values are from all 4-h sections of the six subjects.

and more labile in phase position. The asymmetric distribution of sleeping and waking with the short wake duration after the 'first' sleep block may reflect the need for sleep after this short sleep episode. This distribution allows sleep to remain within the preferred phase position for sleep, which has been found in free-run studies (Zulley *et al.* 1981); the two sleep blocks are placed at the beginning and at the end of the ascending slope of the temperature rhythm (see Fig. 2). These results favour the interpretation that the major sleep episode and not the circadian rhythm is 'split' into two components.

In contrast to napping, which is an *additional* relatively short sleep episode (to the long major sleep), placed halfway between the major sleep episodes (Campbell and Zulley 1985), split-sleep is the *breaking down* of the long major sleep episode into two components of approximately similar short duration. This is in accordance with the description by Strogatz (1986; p. 120) "But the essential distinction is that the relative durations of the nap/sleep pair are more asymmetrical for nappers than for split sleepers". The present results, as well as the results in the literature (Strogatz 1986) have the disadvantage of having stable intervals of dissociation and synchronization which are too short to assume a splitting of the rhythm as a relatively stable state as has been found in animals.

There is growing evidence that the regulation of human sleeping and waking is, in addition to the strong circadian regulation, influenced by ultradian periodicities (Dinges and Broughton 1989). The occurrence of napping is the empirical basis for the assumption of polyphasic sleep/wake regulation with short sleep episodes during the day. A further hint is that the splitting of the normally long major sleep episode leads to shorter components placed at specific phase positions. This result suggests, together with the finding from the nap studies, the participation of shorter components in the dominating circadian process.

## REFERENCES

- Campbell, S. and Zulley, J. Ultradian components of human sleep/wake patterns during disentrainment. In: H. Schulz and P. Lavie (Eds) *Ultradian Rhythms in Physiology and Behavior*. Springer Verlag, Berlin, 1985: 234–254.
- Daan, S. and Berde, C. Two coupled oscillators: Simulations of the circadian pacemaker in mammalian activity rhythms. *J. Theor. Biol.*, 1978, 70: 297–313.
- Dinges, D. F. and Broughton R. J. *Sleep and Alertness*. Raven Press, New York, 1989.
- Enright, J. T. *The Timing of Sleep and Wakefulness*. Springer-Verlag, Berlin, 1980.
- Gwinner, E. Testosterone induces 'splitting' of circadian locomotor activity rhythms in birds. *Science*, 1974, 185: 72–74.
- Hoffmann, K. Splitting of the circadian rhythm as a function of light intensity. In: M. Menaker (Ed.) *Biocronometry*. National Academy of Sciences, Washington, DC, 1971: 134–151.
- Minors, D. S. and Waterhouse, J. M. Anchor sleep as a synchronizer of rhythms on abnormal routines. In: L. C. Johnson, P. I. Tepas, W. P. Colquhan, M. P. Colligar (Eds) *Biological Rhythms, Sleep and Shift Work*. Spectrum Press, New York, 1984: 399–414.
- Pittendrigh, C. S. and Daan, S. A functional analysis of circadian pacemakers in nocturnal rodents: The stability and lability of spontaneous frequency. *J. Comp. Physiol.*, 1976, 106: 223–252.
- Strogatz, S. H. *The Mathematical Structure of the Human Sleep-Wake Cycle*. Springer-Verlag, Berlin, 1986.
- Wehr, T. The durations of human melatonin secretion and sleep respond to changes in daylength (photoperiod). *J. Clin. Endocrinol. Metab.*, 1991, 73: 1276–1280.
- Wever, R. *The Circadian System of Man*. Springer-Verlag, New York, 1979.
- Zulley, J., Wever, R. and Aschoff, J. The dependence of onset and duration of sleep on the circadian rhythm of rectal temperature. *Pflügers Arch*, 1981, 391: 314–318.
- Zulley, J. and Campbell, S. S. Napping behavior during "spontaneous internal desynchronization": Sleep remains in synchrony with body temperature. *Human Neurobiol.*, 1985, 4: 123–126.
- Zulley, J. The four hour sleep wake cycle. *Sleep Res.*, 1988, 17: 403.