

SIMULATION OF THE ULTRA-SHORT SLEEP-WAKE PROTOCOL USING THE TWO PROCESS MODEL

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Abstract: An experimental sleep-wake protocol of 30-minute cycles with an allowed 10-minute sleep episode and an enforced 20-minute wake episode was carried out over 48 hours. The sleep and wake conditions of the experiment are simulated using the two process model. A fitness function measuring the occurrence of Non-REM sleep in the 10 minute episodes between experiment and model was defined. Parameter optimization with sub-harmonic frequency components resulted in an average prediction accuracy of 80 %.

Keywords: ultra-short sleep wake cycles, sleep latency, two-process model (TPM), simulation

Introduction

Sleep latency tests were introduced to investigate the rhythm of sleepiness and the effects of sleep fragmentation in man in the 1980s by Carskadon [1], thus revealing the circadian characteristics of sleepiness. Further experiments provided evidence for an increased sleep propensity after midday. Lavie introduced an ultra-short sleep wake cycle protocol with 7 min of allowed sleep and 13 min wakefulness to uncover ultradian cycles of sleepiness [2]. Regular sleep wake cycles can be modelled by the two-process model (TPM) [3]. As illustrated in figure 1, sleep pressure (dashed red line, $S_{regular}$) rises and falls between the upper and lower circadian thresholds (C_H and C_L , respectively). When S meets C_H , sleep starts and S declines. The TPM has been tested extensively against real sleep-wake episodes, and the agreement with the modelled sleep-wake data is impressive [4]. We simulate the ultra-short sleep-wake protocol with the TPM (see fig. 1). As extension of the original TPM model, phases and amplitudes of the harmonic components of C_H are varied to improve adaptation to experimental data.

Methods

We slightly modified the ultra-short sleep-wake protocol to blocks of 30 min, consisting of 10 min of sleep allowed (SA) and 20 min staying awake (SNA). Four subjects (21.8 years \pm 4.9 years) who completed the protocol were monitored by actigraphy and sleep log for 14 days prior and after the 48-hour protocol. The major aim of the study was the estimation of circadian and ultradian cycles and its correlation to physiological measures and performance tests. Here, we

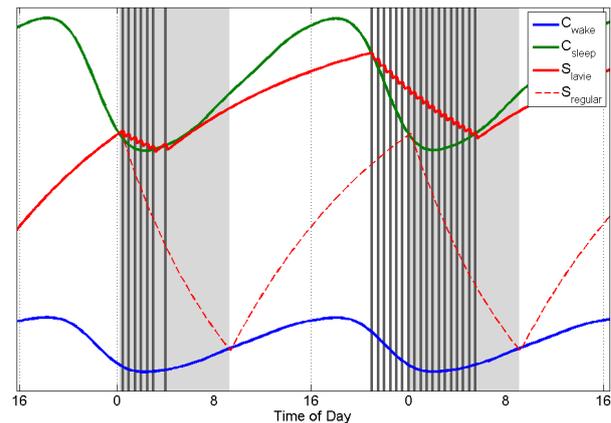


Figure 1: Simulation of the behaviour of regular sleep pressure ($S_{regular}$) compared to the sleep pressure during the 20/10 minute ultrashort sleep-wake cycle protocol (S_{lavie}) with the original circadian thresholds of the two-process model. Process S rises during wakefulness, and falls during sleep (grey). In contrast, sleep pressure S_{Lavie} during the protocol is barely reduced during SA episodes, and the rising slope of C_H during daytime does not allow sleep despite the high sleep pressure. A forbidden zone of sleep during daytime is clearly visible. In this case, the sleep prediction accuracy ACC for subject P08 is 73.85 %.

focus on simulating the sleep obtained during the intervals of SA.

Sleep states during all 48-hour sessions were determined with an EEG-based sleep stage classifier by Somnomedics GmbH, Kist, Germany. The real state of the subject during SA episodes was scored as "sleep" ($Z_{Exp}(SA_i) = 1$) if more than 4 min of non-REM sleep were registered. Otherwise, the state was scored as "awake" ($Z_{Exp}(SA_i) = 0$). During simulation of SA blocks, the TPM outputs sleep (black lines in figure 1) if process S is greater or equal the upper threshold ($Z_{Sim}(SA_i) = 1$). Otherwise, the output state is marked "awake" ($Z_{Sim}(SA_i) = 0$). All SNA episodes during the protocol were set as wake constraints during simulations. The sleep prediction accuracy ACC is defined as the difference between experimental Z_{Exp} and simulated states Z_{Sim} during 96 SA episodes:

$$ACC = \left(1 - \frac{\sum |Z_{Exp} - Z_{Sim}|}{96}\right) \cdot 100$$

Parameter optimization was first executed for four subjects

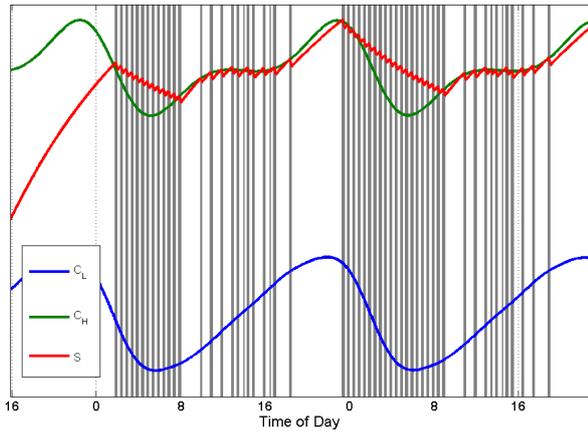


Figure 2: Sleep pressure S bounces between circadian sleep gate C_H with fitted ultradian components during the 48-hour ultrashort sleep-wake protocol of P08. Sleep pressure is often, but not always big enough to allow sleep (grey bars) during the 10-minute sleep bins.

with the original fixed ultradian components of C_H , according to [4]. The free model variables were optimized using evolutionary algorithms [5] to maximize ACC . To improve adaptation, we set phases and amplitudes of the harmonic components of C_H as free variables and optimized all parameters again.

Results

Optimization of the TPM parameters with fixed ultradian components of C_H led to an accuracy ACC of 73.85% for subject P08. Fig. 1 illustrates the respective model behaviour. Further improvement was achieved with free parameters for the ultradian components. Fig. 3 illustrates the close match of simulated sleep compared to the experimental data of subject P08 with $ACC = 83.75$. The altered ultradian model behaviour is shown in Fig. 2. With variable ultradian components, an average agreement $ACC = 79.4\%$ was achieved, compared to the average $ACC = 74.4\%$ achieved with fixed ultradian components. Table 1 contains the best results for each subject.

Table 1: Sleep prediction accuracy

	Standard Model	Ultradian
P04	76.70%	76.50%
P06	76.35%	81.25%
P08	73.85%	83.75%
P12	70.70%	76.20%
Mean	74.40%	79.43%

Discussion

The ultradian cycles of the human biological clock unveiled by the ultra-short sleep-wake protocol were successfully simulated with an extension of the well-established TPM.

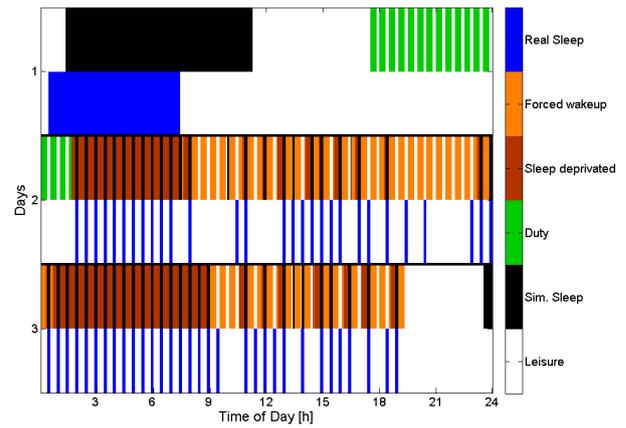


Figure 3: Real sleep during the 48-hour protocol for subject P08 (blue lines), compared to simulated sleep with variable ultradian components for C_H (black lines). Green areas indicate wakefulness without sleep deprivation, orange areas are forced wake times with sleep deprivation, and brown areas indicate premature waking. Sleep was predicted with an accuracy ACC of 83.75%. Real sleep outside the experiment was not taken into account.

The adaptation of the higher harmonics to the experimental data displayed the impressive generality and flexibility of the TPM. This is further supported by the possibility to combine the TPM with the phase shifting effects of light. The here presented results show clearly that the upper threshold of the TPM is influenced not only by circadian components, but by ultradian oscillations as well and underline the importance of ultradian processes for the understanding of the timing of sleep and wake in man.

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