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Direct correlation between the circadian sleep-wakefulness rhythm and time estimation in humans under social and temporal isolation

M K CHANDRASHEKARAN*, G MARIMUTHU, R SUBBARAJ, P KUMARASAMY, M S RAMKUMAR and K SRIPATHI
Department of Animal Behaviour and Physiology, School of Biological Sciences, Madurai Kamaraj University, Madurai 625 021, India

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Abstract. Several bodily functions in humans vary on a 24 h pattern and most of these variations persist with a circadian period of *ca* 25 h when subjects are studied under conditions of social and temporal isolation. We report in this paper that the estimates of short time intervals (TE) of 2 h are strongly coupled to the circadian rhythm in sleep-wakefulness. There is a linear correlation between the number of hours humans stay awake (α) and their estimation of 2 h intervals. The coupling of TE to α appears to obtain only under conditions of physical well-being.

Keywords. Human circadian rhythms; sleep-wakefulness; temperature; freeruns; dissociation; biological oscillators and models.

1. Introduction

It is well established that almost all the bodily functions in the human organism show a 24 h (daily) variation and that these rhythms are in synchrony with sleep and wakefulness as well as with the alternation of day and night (Aschoff and Wever 1981). In subjects living in isolation without any time cues these rhythms persist, as they do in plants and in animals (Bunning 1973), with a circadian period of *ca* 25 h (Wever 1979). In the absence of entraining stimuli such as light/darkness and social cues, the rhythms freerun.

We have investigated the circadian rhythms in bodily functions of human subjects since November 1987 in a specially constructed and equipped 'human isolation facility' for periods of 15–35 days. So far experiments have been completed on 8 human subjects (6 men and 2 women) between the ages of 24 and 35 years. The social and temporal isolation of the subjects was total and rigorous. In two cases the subjects freeran impressively, their sleep-wakefulness cycles at times approximating circabidian periods of 48 h. We have reported in a recent paper (Chandrashekaran *et al* 1991) that a 24-year-old female subject experienced 22 subjective days while in isolation in the actual experimental duration of 35 calendar days. All experimental subjects stated on coming out of the isolation facility that they believed they had followed a 24 h schedule of sleep and wakefulness.

In spite of three decades of intense experimentation it is still not known how the passage of time is perceived by humans living in social isolation. We have investigated how human subjects in our isolation facility estimated 2 h intervals without the aid of watches or clocks. Aschoff (1985) first reported the correlation between estimation of duration of 1 h and the number of hours the subject stayed

*Corresponding author.

awake (α). Our studies reported here impressively confirm the correlation between TE (time estimates) of 2 h and hours of wakefulness (α). We conclude therefore that TE are coupled with the circadian rhythm underlying sleep-wakefulness.

2. Materials and methods

The subjects lived in 25' × 25' isolation quarters with fortified walls and no windows. Cool air was passed through a duct with sound muffles and the room was ventilated. A kitchenette, a bath room with toilet, refrigerator, bicycle ergometer, weighing scales, blood pressure (BP) monitor, books, writing materials, a video cassette player (with timer cut-off), beds, table, chairs and all facilities for cooking were available. The isolation facility was well lit by fluorescent tubes and the ambient lighting ranged from 1,300 to 1,800 l_x depending on the distance from the source of light. The subjects turned lights on and off at will and experienced darkness only during hours of sleep.

The subjects did not have access to clocks or any other cues to civil time but two of the subjects did have access to a stop-watch. All indications of measured activities were given by pressing the appropriate buttons on a panel which activated the writing stylets of an event recorder. Various channels of the event recorder (which was placed outside the isolation living quarters) were used for the different time series data on 2 h TE, breakfast, lunch, dinner, snacks, naps, toilet, to bed, wakeup, mental alertness tests, BP measurements etc. All our estimated TE readings were made by the subjects themselves, inevitably only during hours of wakefulness. The core (rectal) temperature and locomotor activity (wrist movements) were recorded continuously during sleep and wakefulness with a temperature probe and an ambulatory monitor connected to a Solicorder and Apple IIe set-up with an interface card which was replaced every 4–6 days. The data presented here on 2 h estimates (TE) represent 110 data points which were obtained from seven human subjects living in isolation for periods of 15–35 days. In practice, for TE of 2 h the human subjects pressed the appropriate button on the panel once every presumed 2h.

3. Results

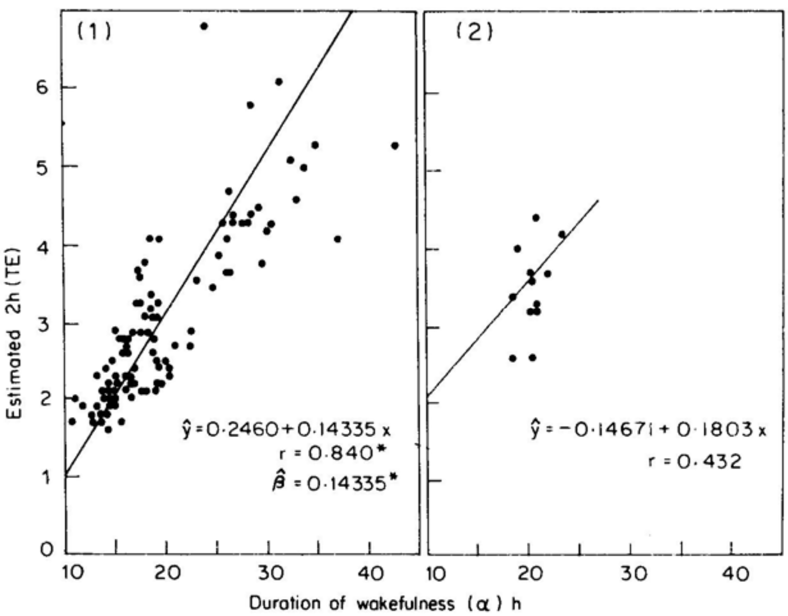
Humans almost always underestimate the passage of time when they live in isolation without external or societal time cues. In keeping with this tendency the sleep-wakefulness cycles also lengthen their period (τ). The TE of 2 h of six of our seven subjects 'contracted' and 'dilated' as a function of correspondingly shorter and longer spells of α in the same subject. The correlation between TE and α extended also to individual subjects as shown in table 1. Figure 1 illustrates how the 2 h TE are directly correlated with a. In the course of our experiments we could even predict how long the subject was likely to stay up that day on the basis of the first two or three TE readings at the beginning of that subjective day.

Figure 2 contains the TE data, which are random and independent of α, of a deviant subject, a 29-year-old male. It might be of general interest to note that this individual slept only for very short periods of 1·5–4·0 h in a sleep-wake cycle (as against the range of hours of sleep (ρ) values of 6·0–18 h of other subjects). Further, he contracted fever on day 4 of the experiment which was unfortunately detected

Table 1. Correlation of 2 h TE and α.

Subject code	$n-2$	r value	P
1	13	0·548	0·10
2	27	0·377	0·10
3	15**	0·902	<0·01
4	10	0·432	NS
5	15*	0·541	0·05
6	19**	0·613	<0·01
7	09	0·606	0·01

NS, Not significant.



Figures 1 and 2. 1. The direct correlation between 2h TE and α representing 110 data points made on seven human subjects living in social isolation for periods of 15–35 days. Each point represents the mean estimates of 5-7 readings made during one 'day' *Significant at $P < 0{\cdot}01$. **2.** The lack of correlation between 2 h TE and α in the human subject who showed curtailed sleep of 1·5–4·0 h per cycle and lived in isolation for 15 days

only on day 15 from the printout data of our Solicorder when the experiment was prematurely terminated and the subject came out of isolation quarters.

4. Discussion

In reporting the dependence of 1 h time estimates on α Aschoff (1985) remarked ".....it must be admitted that a reconfirmation of the results reported here by other methods …would be worthwhile". This is accomplished in the present report. It is worth pointing out that the first three participants were not aware of the dependence of TE on α nor of Aschoffs paper. No human subject studied so far

(Wever 1975; Aschoff and Wever 1976; Minors and Waterhouse 1981; Arendt *et al* 1989, present study) has been able to "will" his α, *ρ* or TE. In a recent paper Aschoff (1990) has made another interesting observation, namely that locomotor activity and α are negatively correlated in humans during isolation. It will be of considerable interest to further investigate if artificial shortening or lengthening of α will result in contracting and dilating TE and if locomotory activity will also show homeostatic adjustments in accordance with variations in α.

Aschoff (1985) found that short time estimates of 10, 20, 30 and 120 s are independent of the duration of α and claimed that "…somewhere between 120 s and 1 h the perception of time seems to change from being independent to being dependent on α". In contrast, we find a correlation of TE of 1 and 2 min with α values longer than 20 h (unpublished). It would appear from our findings on TE that it is difficult to precisely measure the interval at which TE switches from independence to dependence on α. The values of α seem to be more critical in the equation between TE and α. TE of 2 h of all our subjects show a strong correlation with α. We are unable to explain our finding that TE is a function of α in humans in isolation, a finding which suggests that the human mind 'knows' already at the time. of waking how long the day will last. The coupling of TE with the α of the circadian rhythm we are reporting, is reminiscent of the coupling of ultradian courtship song cycles of *ca* 1 min in *Drosophila melanogaster* with τ of the circadian rhythm in their locomotory activity (Konopka and Benzer 1971; Kyriacou and Hall 1980; Yu *et al* 1987).

All subjects adjusted meal timings in consonance with α so that the midday lunch was roughly midway through α, as was reported by Aschoff (1985). Although TE could be made only during α, the correlation between the two suggests that α and TE are coupled with the basic circadian rhythm underlying sleep and wakefulness. The circadian sleep-wakefulness rhythm and the circadian rhythm modulating core temperature dissociated only in one case in our studies. Data obtained by Aschoff (1985) and our own data from desynchronized rhythms clearly demonstrate that TE are not related to the circadian clock that controls the rhythms of autonomic functions such as body temperature. As we report in a recent communication (Chandrashekaran *et al* 1991) the menstrual cycle in a human female in isolation, contrary to TE, was not correlated with the circadian rhythm in sleep-wakefulness. These findings lend credence to models (Aschoff and Wever 1976) which postulate that the sleep-wakefulness rhythm and the body temperature rhythm are driven by two separate clocks. Since data of the kind obtained on our deviant subject and illustrated in figure 2 cannot be easily replicated, we speculate on the basis of existing data (which is not statistically significant) that the coupling of TE with α may be obtained only under conditions of physiological and physical harmony, and that under stressful conditions leading to discomfort and fever the coupling between the two might break down.

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