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Individual differences in the phase and amplitude of the human circadian temperature rhythm: with an emphasis on morningness–eveningness

ERIN K. BAEHR[1,2], WILLIAM REVELLE[1] and CHARMANE I. EASTMAN[2]
[1]Department of Psychology, Northwestern University, Evanston, Illinois, USA, [2]Biological Rhythms Research Lab, Department of Psychology, Rush-Presbyterian-St. Luke's Medical Center, Chicago, Illinois, USA

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SUMMARY We studied the relationship between the phase and the amplitude of the circadian temperature rhythm using questionnaires that measure individual differences in personality variables, variables that relate to circadian rhythms, age and sex. The ambulatory core body temperature of 101 young men and 71 young women was recorded continuously over 6 days. The temperature minimum (T_{min}) and amplitude (T_{amp}) were derived by fitting a complex cosine curve to each day's data for each subject. Participants completed the Horne–Ostberg Morningness–Eveningness Questionnaire (MEQ), the Circadian Type Inventory (CTI) and the MMPI-2, scored for the Psychopathology-5 (PSY-5) personality variables. We found that the average T_{min} occurred at 03.50 h for morning-types (M-types), 05.02 h for the neither-types and 06.01 h for evening-types (E-types). Figures were presented that could provide an estimate of T_{min} given an individual's morningness–eveningness score or weekend wake time. The T_{min} occurred at approximately the middle of the 8-h sleep period, but it occurred closer to wake in subjects with later T_{min} values and increasing eveningness. In other words, E-types slept on an earlier part of their temperature cycle than M-types. This difference in the phase-relationship between temperature and sleep may explain why E-types are more alert at bedtime and sleepier after waking than M-types. The T_{min} occurred about a half-hour later for men than women. Another interesting finding included an association between circadian rhythm temperature phase and amplitude, in that subjects with more delayed phases had larger amplitudes. The greater amplitude was due to lower nocturnal temperature.

KEYWORDS body temperature, circadian rhythm, eveningness, human, morningness, sleep

INTRODUCTION

Knowing an individual's circadian phase is important for designing treatments for adaptation to jet-lag and shift work, and in the diagnosis and treatment of various circadian rhythm sleep disorders (e.g. delayed sleep-phase syndrome). Because measuring circadian rhythm phase using core body temperature or fluctuations in hormonal levels can be a fairly invasive and time-consuming process, questionnaires have been devised to produce an estimate.

The Horne–Ostberg Morningness–Eveningness Questionnaire (MEQ) is a 19-item questionnaire which assesses individual differences in the time of day a person prefers to carry-out various activities, and classifies people as morning-type (M-type), neither-type (N-type) or evening-type (E-type) individuals (Horne and Ostberg 1976). Several studies have shown that M-type subjects have an earlier sleep schedule (Horne and Ostberg 1976; Foret *et al.* 1982, 1985; Mecacci and Zani 1983; Kerkhof 1991; Kerkhof and Lancel 1991; Carrier *et al.* 1997) and an earlier circadian temperature phase as

Correspondence: Charmane Eastman, PhD, Biological Rhythms Research Laboratory, Rush-Presbyterian-St. Luke's Medical Center, 1653W. Congress Pkwy, Chicago, IL 60612, USA. Tel.: 1 312 942 4472; fax: 1 773 955 3958, e-mail: ceastman@rush.edu

measured by rectal temperature (Kerkhof 1991; Lack and Bailey 1994; Kerkhof and Van Dongen 1996; Duffy *et al.* 1999a) and oral temperature (Horne and Ostberg 1976, 1977; Vidacek *et al.* 1988; Kerkhof and Lancel 1991; Neubauer 1992; Gupta and Pati 1994). In accordance with oscillator theory (Wever 1965) and animal studies (e.g. Aschoff 1965, 1981; Pittendrigh and Daan 1976), it has been hypothesized that humans who have shorter free-running circadian periods would have an earlier circadian phase and more morning tendencies. One recent study revealed that, in fact, individuals with shorter intrinsic circadian periods rated themselves as more morning-like according to the MEQ (Duffy *et al.* 1999b).

Results from studies that have investigated sex differences in circadian phase are somewhat inconsistent, although it appears that women tend to have more morning characteristics than men (see Kerkhof 1985; Tankova *et al.* 1994 for reviews). With regard to the circadian rhythm of temperature, two studies found that elderly women had an earlier rectal temperature peak than elderly men (Campbell *et al.* 1989; Moe *et al.* 1991). In young subjects, two studies found that women had a slightly earlier temperature phase than men, but the differences were not statistically significant (Winget *et al.* 1977; Kattapong *et al.* 1995).

With increasing age, there is a greater tendency toward earlier circadian temperature phase (Weitzman *et al.* 1982; Nakazawa *et al.* 1991; Czeisler *et al.* 1992; Monk *et al.* 1995; Duffy *et al.* 1998), earlier sleep times (Costa *et al.* 1986; Czeisler *et al.* 1992; Carrier *et al.* 1997; Duffy *et al.* 1998) and morningness as assessed by the MEQ (Mecacci *et al.* 1986; Wilson 1990; Drennan *et al.* 1991; Monk *et al.* 1991; Adan 1992; Czeisler *et al.* 1992; Carrier *et al.* 1997).

The Circadian Type Questionnaire (CTQ) was originally developed in an attempt to identify which individuals would adjust readily to shift work, and was based on the premise that variations observed in shift-work adjustment are due to underlying differences in circadian rhythm phase, amplitude and strength (Folkard *et al.* 1979). Since its initial development, it has been revised and renamed the Circadian Type Inventory (CTI; Barton *et al.* 1995). The CTI is an 18-item questionnaire with two independent factors. Individuals who score high on the first factor (Flexible/Rigid) are 'flexible' with the ability to stay awake at odd times of day or night. Those who score high on the second factor (Languid/Vigorous) are 'languid' and tend to report difficulty overcoming drowsiness, especially in the morning. One study found that eveningness on the MEQ corresponded to high scores on CTQ flexibility and low scores on CTQ languidity (Smith *et al.* 1989). However, there have been few published studies about circadian rhythm correlates with the current version of this questionnaire, the CTI. One recent study found a trend toward those with higher CTI flexibility scores having larger temperature rhythm phase shifts during simulated night shift-work (Martin and Eastman 1998).

The broad personality dimension of extraversion is associated with a later oral temperature rhythm rise and fall (Blake 1967; Colquhoun and Folkard 1978; Eysenck and Folkard 1980) and eveningness (Patkai 1971; Horne and Ostberg 1977; Larsen 1985; Mecacci *et al.* 1986; Adan and Almirall 1990; Wilson 1990; Neubauer 1992). However, the literature in this area is somewhat complicated due to the changing nature of the concept of extraversion (Rocklin and Revelle 1981). Some studies have suggested that impulsivity (which some consider a subcomponent of extraversion) produces the relationship to later circadian phase and evening tendencies (Eysenck and Folkard 1980; Neubauer 1992). Also, differences in performance in response to caffeine interact with impulsivity and time-of-day in a pattern suggesting that high impulsives have a later circadian phase (Revelle *et al.* 1980). Conversely, other studies have suggested that it is the sociability subcomponent of extraversion that is associated with eveningness (Larsen 1985; Wilson 1990).

Individual differences in temperature rhythm amplitude have also been investigated. According to oscillator theory, the strength of a circadian oscillator is reflected by its amplitude (Wever 1965; Aschoff and Pohl 1978). Thus, it may be easier to shift weaker oscillators (smaller amplitudes) with a shift of the zeitgeber (Aschoff and Pohl 1978). In other words, weaker oscillators may re-entrain faster and perhaps produce greater adjustment and tolerance to shift work. However, the research in this area is inconsistent. Some studies found that greater tolerance to shift work was associated with a smaller temperature rhythm amplitude, but others found the opposite (see Harma 1993 for a review). A major problem with many studies in this area is that the data tend to be masked by sleep and shift-work schedules. Other findings include that with older age, there is a decrease in the amplitude of the circadian temperature rhythm (Weitzman *et al.* 1982; Vitiello *et al.* 1986; Czeisler *et al.* 1992), although this relationship may be stronger for men than for women (Monk *et al.* 1995), and that the amplitude in women is dependent upon the phase of the menstrual cycle (Lee 1988; Kattapong *et al.* 1995).

The purpose of our study was to relate individual differences in circadian phase and amplitude to the questionnaires and variables described above in a large sample of subjects for whom multiple days of rectal temperature recordings were available.

METHODS

Subjects

We re-analysed baseline data from 101 men (aged 25.2 ± 5.3 y, range 18–41 y) and 71 women (aged 25.1 ± 5.4 y, range 18–43 y), who participated in various field studies of simulated night-shift work (Eastman *et al.* 1994, 1995a,b; Mitchell *et al.* 1997; Martin and Eastman 1998; Baehr *et al.* 1999).

Subjects had no evident sleep, medical or psychological disorders, as assessed by an interview and completion of a sleep questionnaire, a health questionnaire and the Minnesota Multiphasic Personality Inventory-2 (MMPI-2). None of the participants took prescription medications, except for oral contraceptives. Subjects signed informed consent forms and were paid for their participation.

Procedure

Sleep schedules (8 h in bed) were assigned to participants and were chosen to be close to the subject's habitual sleep times, as recorded on a sleep log for 1–2 weeks prior to beginning the study. The normal sleep patterns of these young subjects were usually rather erratic. Assigned sleep schedules were designed using subjects' later sleep times. The later times were chosen because they may be more natural sleep times (not as heavily influenced by societal demands such as morning classes), and we wanted to make sure we were scheduling wake time a few hours after the endogenous temperature minimum (T_{min}) to avoid masking of the T_{min} by waking activity. For example, if a subject slept from 02.00 to 10.00 h on Monday and Wednesday, 01.30 to 08.00 h on Tuesday and Thursday (to wake up for an early morning class), 03.00 to 12.00 h on Saturday (because he was out late with friends the night before), and 01.30 to 10.00 h on Sunday, he would have likely been assigned a sleep schedule from 02.00 to 10.00 h. Obviously, it was somewhat difficult to assign sleep times in a systematic manner due to irregular sleep schedules.

Subjects were required to remain in bed, in the dark during the designated 8 h periods, even if they could not sleep. Black plastic was installed over bedroom windows to ensure subjects were sleeping in a dark environment even after sunrise. To encourage compliance with the protocol, participants were required to call a time-stamp answering machine or voice mail just before bed, after waking and 30 min after waking. They also estimated sleep onset and wake times on daily sleep logs, which they completed immediately after waking. Overall, the reported sleep times were similar to the scheduled sleep times. Caffeine consumption was fixed to the amount that the participant usually drank and was limited to within the first 4 h after waking so as to not interfere with sleep. Alcohol and recreational drug use were prohibited.

Temperature measurement and analyses

Core body temperature was measured at 1-min intervals using a flexible, disposable rectal thermistor, connected to either a Vitalog PMS-8 or a Consumer Sensory Products AMS-1000 portable monitor. The baseline portions of the studies were either 7 or 10 days. The first day was considered an adaptation day and days 2–7 were used in this analysis. Participant's data were included in this study if they had at least 4 days of complete temperature data (not more than 2 h of continuous missing data during sleep and not more than 8 h in a day).

Estimates of daily circadian temperature phase were made for each subject using a curve-fitting procedure. For each 24-h section (beginning at 12.00 h central standard time), temperature data were averaged into 15-min sections and missing data interpolated. A two-component Fourier series consisting of a 24-h fundamental cosine rhythm plus a 12-h cosine rhythm was fit to the data for each day. This is a procedure that has been used elsewhere for the analysis of temperature data (Barrett *et al.* 1993; Campbell 1995), and may more accurately fit the raw temperature data than a simple cosine because it allows for variations in the shape of the waveform which a simple cosine does not. The minimum of the composite fitted temperature curve was used as the circadian phase marker for each day. Mathematical demasking of the temperature curve was not necessary to estimate the endogenous T_{min} because subjects slept in-phase with their temperature rhythms; the later sleep schedules ensured that the T_{min} was not obscured by waking activity.

Circadian temperature rhythm amplitude (T_{amp}) was the difference between the peak and trough of the fitted curve. T_{amp} was calculated for each day for male participants only. Female subjects were excluded from this analysis since the amplitude of body temperature rhythm in women is dependent on menstrual cycle phase (Kattapong *et al.* 1995). The 4–6 T_{min} and T_{amp} values were averaged for each subject. All times are reported in local time (i.e. either central standard time or daylight saving time, depending on the time of year).

Reliability of temperature measurements

The T_{min} ($N = 172$) had an average between-day correlation of 0.78 and an alpha reliability for the 6 days of 0.96. The T_{amp} for male subjects ($N = 101$) had an average between-day correlation of 0.51 and an alpha reliability for the 6 days of 0.86. The strong day-to-day correlations for both T_{min} and T_{amp} suggest that the differences between subjects on any one day correlate highly with differences found on any other day. The high alpha reliability of these data indicate strong internal consistency of the measures, with the bulk of the total variation in T_{min} (96%) and T_{amp} (86%) associated with between subject variation, and little of the total variation in T_{min} (4%) and T_{amp} (14%) associated with within-subject variation.

Questionnaires

All subjects completed the MEQ, which was scored to determine if subjects were classified as M-type, N-type or E-type individuals (see Table 1 for raw score ranges).

A subset of participants completed the CTI questionnaire ($N = 75$), and the other subjects completed the older CTQ. Only data from the CTI were analysed and included in this study.

The MMPI-2 was used as a screening device in order to exclude individuals with possible psychopathology. For this report, responses were analysed according to the Harkness *et al.* (1995) method for obtaining the Personality Psychopathology Five (PSY-5) scales. The PSY-5 scales are based on personality disorder constructs and normal personality traits, and include aggressiveness, psychoticism, constraint, neuroticism and extraversion. Subjects had completed either the entire MMPI-2 or only the first 370 of 567 items (since these are the

Table 1 Summary statistics, mean ± SD, according to MEQ type

	E-type	*N-type*	*M-type*	*Total*
Morningness–eveningness score ranges	16–41	42–58	59–86	16–86
N [% of total]	46 [27%]	105 [61%]	21 [12%]	172
Morningness–eveningness score	34.9^{a} ± 4.6	49.9^{b} ± 4.6	63.1^{c} ± 3.5	47.5 ± 9.8
T_{min}	06.01^{a} h ± 01.14 h	05.02^{b} h ± 00.59 h	03.50^{c} h ± 00.40 h	05.09 h ± 01.13 h
Scheduled wake	09.33^{a} h ± 00.58 h	08.47^{b} h ± 00.54 h	08.00^{c} h ± 00.49 h	08.53 h ± 01.01 h
Interval between T_{min} and wake (h)	3.5^{a} ± 0.7	3.8^{ab} ± 0.7	4.2^{b} ± 0.7	3.8 ± 0.7

Means in the same row not sharing a similar superscript differ at $P < 0.05$ according to Tukey's HSD (total column not included in the ANOVA).

only items necessary for the clinical scales that were used for screening). For this analysis, missing items were replaced with the mean for that item that other subjects answered. Subjects completed the MEQ, the CTI and the MMPI-2 during or prior to baseline.

Summary statistics are presented as mean ± SD and *r* represents Pearson's correlation coefficient. One-way analysis of variance, followed by Tukey's HSD post hoc pairwise comparisons of means, was performed on the three MEQ categories for morningness–eveningness score, T_{min}, scheduled wake and the time from T_{min} to wake, and *t*-tests were performed on sex differences for these variables.

RESULTS

Circadian temperature rhythm phase (T_{min})

The morningness–eveningness scores for our sample ranged from 24 to 72 (Fig. 1). Table 1 shows summary statistics for the three categories (E-types, N-types and M-types) and for the entire sample. As expected, E-types had the latest and M-types had the earliest T_{min} and scheduled wake times. These relationships can also be seen in the scatter plots of scheduled wake vs. T_{min} (Fig. 2) and morningness–eveningness score vs. T_{min} (Fig. 3). As expected, a later T_{min} corresponded to a later wake time (Fig. 2) and to more eveningness on the MEQ (Fig. 3).

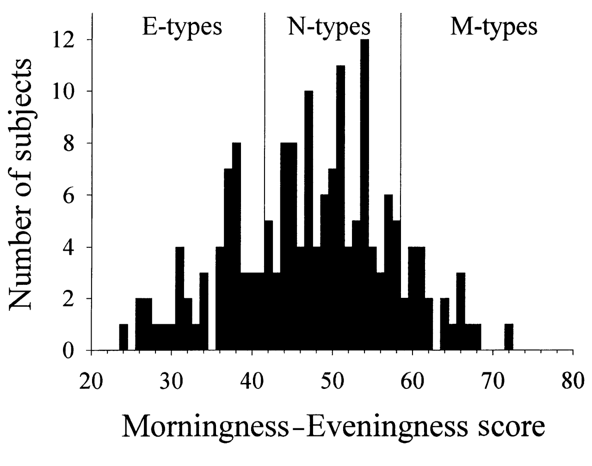

Figure 1. Distribution of morningness–eveningness scores for the 172 subjects. Vertical lines separate the E-type, N-type and M-type subjects.

Interestingly, the time between the T_{min} and scheduled wake was related to circadian phase, with the T_{min} occurring closer to wake time with later T_{min} and increasing eveningness (Table 1, last row). This relationship can also be seen in Fig. 2, which shows that wake increased at a slower rate than T_{min}; as T_{min} got later and later, subjects woke up closer to their T_{min}. For example, according to the regression line, a T_{min} at 03.00 h corresponds to a wake time at 07.26 h, with a distance between T_{min} and wake of 4 h 26 min. However, a T_{min} at 08.00 h corresponds to a wake time at 10.49 h with an interval between T_{min} and wake of only 2 h 49 min. To further illustrate these findings, we averaged the data from the subjects with the most extreme (earliest and latest) T_{min} (Fig. 4). We planned to used the 10 earliest and 10 latest T_{min} from males and from females, but because of ties, we included 11 in the two groups of early subjects. This figure shows that the subjects with the latest T_{min} reached their lowest temperature later in the night and closer to wake. The figure also shows that these subjects went to bed when their temperature was much higher than its lowest level, whereas the subjects with the earliest T_{min} went to bed when their temperature was close to its lowest level. Furthermore, when the subjects with late T_{min} were scheduled to wake, their temperature was lower than when they went to bed. For subjects with early T_{min}, the temperature level at wake time was similar to the temperature at bed time.

The T_{min} occurred about half an hour later in the men and occurred slightly closer to wake for men than women (Table 2). However, there were no statistically significant differences between men and women in sleep schedules or in morningness–eveningness scores.

Table 3 shows the correlation matrix between the variables in this study. Older subjects had earlier T_{min}, earlier sleep schedules and scored more towards morningness on the MEQ.

Individuals with high scores on CTI Flexibility had later T_{min}, later sleep schedules and scored more toward eveningness on the MEQ (Table 3). Those who had high scores on CTI Languidity also had later T_{min} and scored more toward eveningness on the MEQ.

More constrained subjects (higher scores on PSY-5 Constraint) had earlier T_{min} and scored more towards morningness on the MEQ (Table 3). None of the other four PSY-5 scales had significant correlations with circadian parameters.

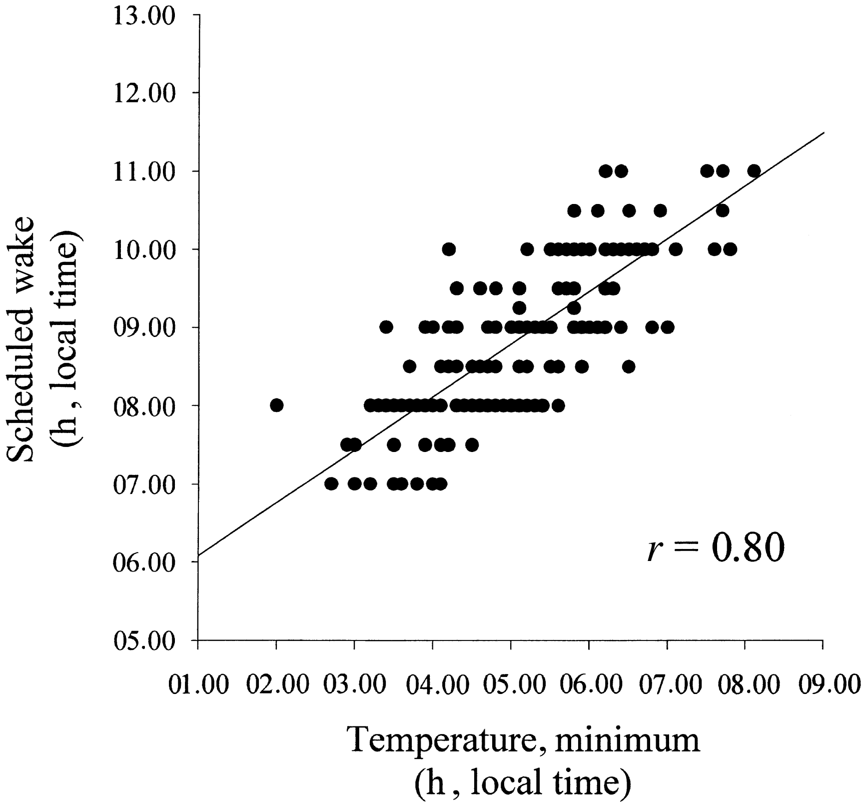

Figure 2. Scatter plot of scheduled wake time vs. temperature minimum (T_{min}) for the 172 subjects. The equation of the regression line is: Wake = (.67)(T_{min}) + 5.4.

Circadian temperature rhythm amplitude (T_{amp})

We calculated T_{amp} for men only and found that a larger T_{amp} was associated with a later T_{min}, greater eveningness on the MEQ, younger age and higher scores on CTI Flexibility (Table 3). E-types had a larger T_{amp} than M-types (1.3 ± 0.3 vs. 1.1 ± 0.2°C), due to reaching a lower temperature during sleep (Fig. 5), and this difference in amplitude was on the borderline of statistical significance by *t*-test ($P = 0.07$). The same relationship between amplitude and phase can be seen in the top two panels of Fig. 4. The men with the latest T_{min} had larger amplitudes than those with the earliest T_{min}. The bottom panels of Fig. 4 show that this relationship may also be true for women, however, we did not control for phase of the menstrual cycle, which is known to affect the amplitude of the temperature rhythm.

DISCUSSION

Circadian temperature rhythm phase (T_{min})

As expected, a later circadian temperature rhythm phase (T_{min}) was associated with a later sleep schedule and greater eveningness on the MEQ. Figures 2 and 3 demonstrate these relationships and can be useful for estimating T_{min} from an individual's morningness–eveningness score or weekend wake time.

The relationship that we found between morningness–eveningness score and temperature rhythm phase is consistent with studies that used the MEQ and measured temperature phase during a constant routine (Lack and Bailey 1994; Kerkhof and Van Dongen 1996; Duffy *et al.* 1999a). The clock times reported for the T_{min} were similar among the constant routine studies, and ranged from about 04.34 to 05.15 h for M-types and from about 06.45 to 07.30 h for E-types, with a difference between the T_{min} of the M- and E-type groups of ≈ 2 h. The T_{min} in our study were slightly earlier and occurred at 03.50 h for M-types and 06.01 h for E-types, with a similar difference between the T_{min} of ≈ 2 h. Kerkhof and Van Dongen (1996) measured both ambulatory and constant routine body temperature data in their study and found that the constant routine T_{min} occurred ≈ 1 h later than the ambulatory T_{min}, which is similar to how our data compare with the constant routine data. It is possible that the constant routine is distorting the phase estimate, yielding a later phase due to the free run associated with sleep deprivation in dim light (Van Dongen *et al.* 1998). Alternatively, our slightly earlier clock times for the T_{min} could be due to actual differences between our sample and the samples used in the constant routine studies, to methodological differences in curve-fitting techniques, and to whether the data for the constant routine studies were reported in local or standard time. The fact that our results were so similar to those of constant routine studies suggests that it is not always necessary to use the expensive and arduous constant routine method to determine temperature rhythm phase. However, in situations in which subjects are sleeping at the wrong phase of their

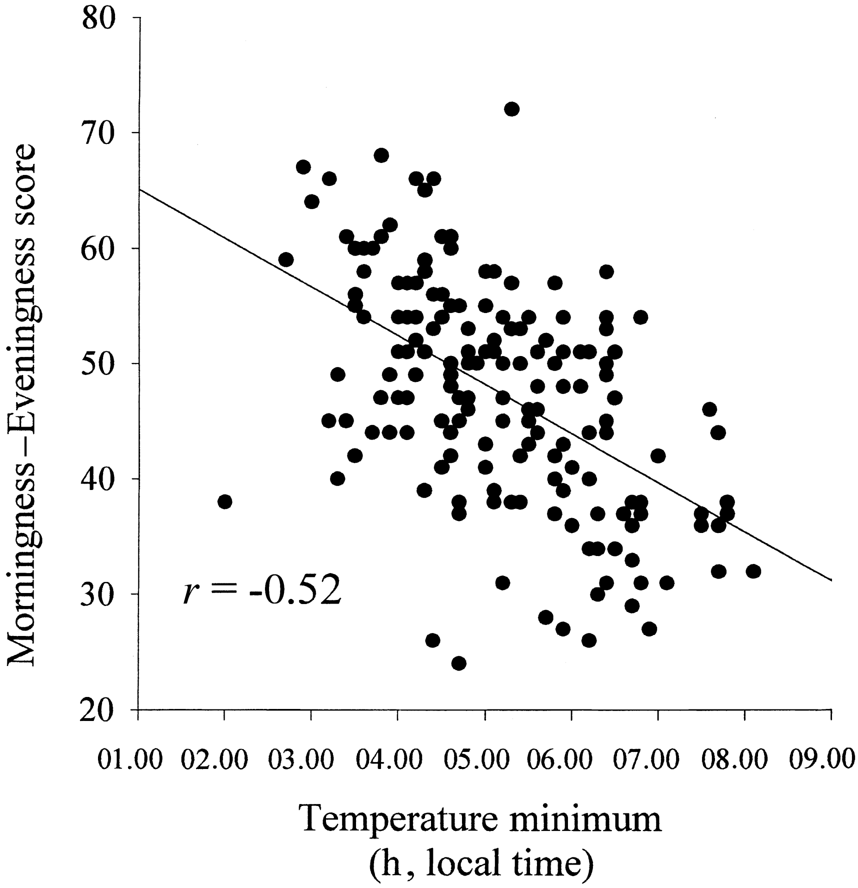

Figure 3. Scatter plot of morningness–eveningness scores vs. T_{min} for the 172 subjects. Higher scores represent more morningness. The equation of the regression line is: morningness–eveningness score $= (-4.25)(T_{min}) + 69.4$.

circadian cycle, it is necessary to either use the constant routine method or to mathematically demask the temperature recording (e.g. Folkard 1989; Carrier and Monk 1997; Martin and Eastman 1998). It was not necessary to demask the data in our study in order to estimate endogenous phase because we assigned sleep times that were late enough for the sleep schedule to be in sync with the temperature rhythm (i.e. subjects did not wake before their T_{min} occurred). It appears that, at least in conditions in which subjects are sleeping at normal (weekend) times, ambulatory measurements produce similar results as the constant routine method.

The T_{min} occurred closer to wake with later circadian phase, consistent with a recent study that used the constant routine to estimate T_{min} (Duffy *et al.* 1999a). Another way to state this finding is that subjects with later phases went to bed and woke up on an earlier part of their temperature cycle, and those with earlier phases went to bed and woke up on a later part of their temperature cycle (Fig. 4). Thus, the difference in temperature phase between M-types and E-types is not just a result of the difference in sleep schedules; it is made even more extreme by the different phase relationships between temperature and sleep. It may be that societal demands force evening people to go to bed earlier and wake earlier than their circadian clocks would have them do naturally and/or force M-types to go to bed later than their circadian clocks would naturally put them to sleep. In other words, we suggest that it is possible that societal demands may have a large impact on when people sleep in relation to the circadian clock. Figure 4 shows that the subjects with extremely late T_{min} went to bed when their temperature was still relatively high and got up before their temperature had risen very much, whereas the subjects with extremely early T_{min} went to bed when their temperature was closer to its lowest level and woke after their temperature had more time to rise. Since the temperature trough is the time of least alertness (Akerstedt and Gillberg 1982; Johnson *et al.* 1992), this explains why E-types are less alert in the morning and why it is difficult for them to wake in the morning, and why M-types are more alert in the morning.

It has long been assumed, and recently confirmed (Duffy *et al.* 1999b) that E-types have longer free-running periods (taus) than M-types. Thus, E-types need to advance more each day to entrain to the 24-h day. The phase-relationships in Fig. 4 show that individuals with late T_{min} wake closer to their T_{min} and thus get light (upon opening their eyes) on a more sensitive portion of the light-phase response curve (PRC), which will produce a larger phase advance than if they woke later. (For a schematic human light PRC that will help explain this, see Fig. 6 in Eastman and Martin 1999.) Thus, the phase relationships in Fig. 4 may be necessary in order for the subjects to remain entrained to the 24-h day. Oscillator theory also explains these relationships; a longer tau results in a later phase when entrained to a zeitgeber (Wever 1965; Aschoff

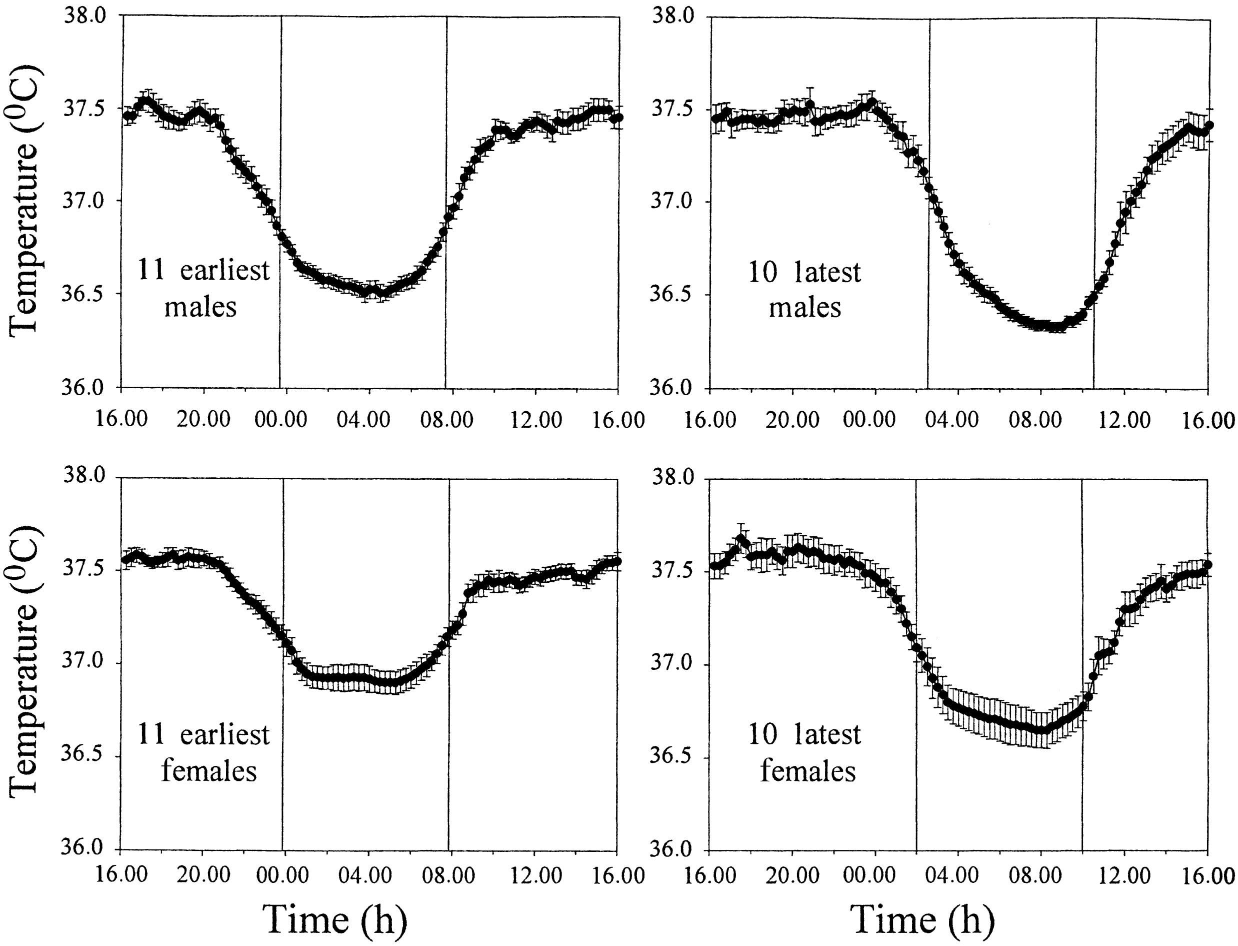

Figure 4. Raw temperature curves from male and female subjects with the 11 earliest and the 10 latest T_{min}. Round symbols show 15-min averages with standard error bars. Vertical lines represent average bed and wake times (which were scheduled 8 h apart).

Table 2 Summary statistics, mean ± SD, according to sex

	Men	*Women*
N	101	71
Morningness–eveningness score	48.2 ± 9.6	46.6 ± 10.0
% E-types	27	27
% M-types	12	13
T_{min}	05.23 h ± 01.15 h	04.49* h ± 01.05 h
Scheduled wake	08.58 h ± 01.02 h	08.47 h ± 01.01 h
Interval between T_{min} and wake (h)	3.6 ± 0.7	4.0* ± 0.7

* $P < 0.05$ for men vs. women by *t*-test.

1981). It is of interest to note that in patients with delayed sleep phase syndrome (DSPS), a population with extreme evening tendencies, the interval between the T_{min} and wake does not appear to be reduced (Ozaki *et al.* 1996; Okawa *et al.* 1998) as it was in our E-types. It is possible that patients with DSPS find it very difficult to get up at an early part of the circadian cycle (close to the T_{min}). Perhaps these patients have a larger amplitude (like our E-types) and therefore a stronger circadian oscillator, which they find difficult to override. In any case, if they do not get enough morning advancing light, they could easily slip to later and later sleep times and progress to a free-running circadian sleep disorder.

We found that women had a T_{min} about half an hour earlier than men. Other studies have found that in entrained conditions, young women have a slightly earlier phase than young men, although these differences were not statistically significant (Winget *et al.* 1977; Kattapong *et al.* 1995). It could be that the difference between the phase of men and women is so slight that it is necessary to increase statistical power in order to detect this effect. The sex difference in entrained phase found in our study (women earlier) is consistent with the difference in the period length of free-running temperature rhythms in temporal isolation (shorter tau for women; Wever 1984a,b). In addition, our finding that the T_{min} was closer to wake for men than women is consistent with the finding that when the T_{min} is later, it is also closer to wake.

Older age was associated with an earlier temperature rhythm phase and more morningness on the MEQ. These findings are consistent with the majority of studies that have investigated individual differences in age and circadian phase or morningness–eveningness tendencies (see Kerkhof 1985; Tankova *et al.* 1994 for reviews). It is remarkable that we found these

Table 3 Pearson correlation table with number of subjects in parentheses

	T_{min}	T_{amp} (men only)	*Scheduled wake time*	*MEQ score*	*Age*	*CTI Flexible/Rigid*	*CTI Languid/Vigorous*
T_{amp} (men only)	0.28* (101)	–					
Scheduled wake time	0.80* (172)	0.15 (101)	–				
MEQ score	−0.52* (172)	−0.29* (101)	−0.48* (172)	–			
Age	−0.26* (172)	−0.30* (101)	−0.23* (172)	0.33* (172)	–		
CTI Flexible/Rigid	0.41* (75)	0.33* (47)	0.31* (75)	−0.45* (75)	−0.11 (75)	–	
CTI Languid/Vigorous	0.33* (75)	0.27 (47)	0.21 (75)	−0.46* (75)	−0.22 (75)	−0.06 (75)	–
PSY-5 Constraint	−0.20* (161)	−0.09 (90)	−0.15 (161)	0.21* (161)	0.17 (161)	−0.12 (75)	0.03 (75)

* $P < 0.05$.

relationships with age to be significant given the restricted age range of our participants (18–43 y).

Greater flexibility and languidity on the CTI were associated with a later T_{min} and eveningness on the MEQ. This relationship is in contrast to a previous study that found laguidity was associated with morningness (Smith *et al.* 1989). However, this is likely to be due to the changes that have occurred over time in the structure of the CTI. The ability for E-types to stay awake at unusual times of day or night (flexibility) and drowsiness especially in the morning (languidity) may be involved in their tendency to tolerate night work better. Specifically, a tendency for drowsiness in the morning may make it easier to fall asleep in the morning after working the night shift.

Of the questionnaire variables that had statistically significant correlations with circadian phase, constraint had the weakest relationship. However, the MEQ and CTI are designed to assess circadian phase, whereas constraint is not. PSY-5 Constraint was associated with an earlier T_{min} and morningness on the MEQ, whereas sociability (assessed by PSY-5 Extraversion) did not relate to circadian phase or morning or evening tendencies. Given the impulsive content of many of the PSY-5 Constraint items, these results are consistent with previous findings of the association of impulsivity with eveningness (Eysenck and Folkard 1980; Neubauer 1992). The correlation of constraint with T_{min} and MEQ gives strength to the argument that the relationship found in the past between extraversion and evening tendencies (Blake 1967; Patkai 1971; Horne and Ostberg 1977; Colquhoun and Folkard 1978; Eysenck and Folkard 1980; Mecacci *et al.* 1986; Adan and Almirall 1990; Neubauer 1992) has more to do with the impulsivity subcomponent of extraversion rather than the sociability subcomponent.

Circadian temperature rhythm amplitude (T_{amp})

Considering only the data from the men (because we could not control for menstrual cycle phase in women), we found that older age was associated with a smaller T_{amp}. This supports previous findings that the temperature rhythm tends to flatten

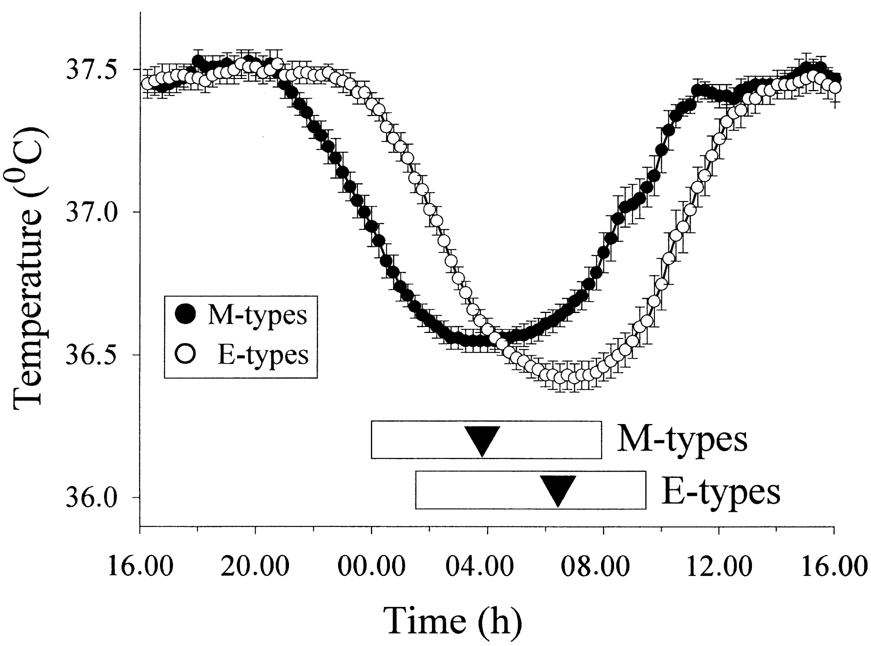

Figure 5. Raw temperature curves from the male M-type ($n = 12$) and E-type ($n = 27$) subjects. Round symbols show 15-min averages with standard error bars. Rectangles represent scheduled sleep times and triangles represent T_{min} averages.

with increasing age (Weitzman *et al.* 1982; Vitiello *et al.* 1986; Czeisler *et al.* 1992; Monk *et al.* 1995). We found this result despite the fact that our sample was fairly young, with a relatively restricted age range (18–41 y). We also found that a larger T_{amp} was significantly correlated with a later T_{min} and eveningness on the MEQ. Although we could not carry out similar statistical analyses on the women's data, the graphs of extreme early and late females (Fig. 4 bottom) show the same phenomena, with a lower nocturnal temperature and a larger amplitude in the group with later phases. An early study using oral temperature found a similar result, although both men and women were studied and, again the results may have been influenced by the menstrual cycle phase of the female participants (Ostberg and Nicholl 1973). We found two figures in more recent papers which compared M- and E-types during a constant routine (Fig. 1 in Kerkhof and Van Dongen 1996 and Fig. 4 in Duffy *et al.* 1999a), that show that E-types have a larger amplitude due to lower temperature during the night. The authors did not comment on this difference. These graphs from constant routine studies suggest that the lower temperature level at night in our E-type subjects is not related to the temperature-lowering effects of sleep. One of these figures was of men only (Duffy *et al.* 1999a) so the result was not confounded by menstrual phase in women. Further studies are needed to determine whether our finding on the relationship between entrained phase and amplitude in men is also found in women, while controlling for the phase of the menstrual cycle.

The reason for the relationship between larger circadian amplitude and later circadian phase (e.g. Figs 4 and 5) is not obvious. However, classic oscillator theory does predict this relationship. Given a weaker zeitgeber (or a stronger circadian rhythm, i.e. larger amplitude), the rhythm lags the zeitgeber and is more phase delayed (Fig. 7 in Wever 1965). Therefore, the larger amplitude of the rhythm in E-types could be the cause of the delayed phase relationship relative to the zeitgebers.

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