A Parallelism between Human Body Temperature and Performance Independent of the Endogenous Circadian Pacemaker

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Abstract A battery of performance tests involving manual dexterity, serial search, and verbal reasoning was given about seven times per day to 2 healthy young male subjects (22 and 25 years of age) involved in separate forced desynchrony studies, each involving several months of temporal isolation. In these studies, the period lengths (denoted T) of the imposed day lengths (sleep / wake and light / dark cycles) were 25.8 and 26.0 h for the 2 subjects. For each subject, the endogenous circadian pacemaker (ECP) failed to entrain to a period of T and instead free ran at a period length denoted tau (24.2 and 24.5 h). By educing performance rhythms (and rectal temperature rhythms) separately at tau and at T (after three complete beating cycles for the first subject and two complete beating cycles for the second subject), the hypothesis could be tested as to whether performance and temperature were parallel, both when educed at tau (indicating ECP influence) and when educed at T (indicating sleep / wake cycle influences). The hypothesis was consistently confirmed at tau and mostly confirmed at T. For most variables, when educed at T, both performance speed and body temperature showed an inverted V-shaped function, with a peak about 9 to 12 h after waking.

Key words human circadian rhythm, performance, sleep, activity

INTRODUCTION

Almost 50 years ago, Kleitman and Jackson (1950) made the provocative assertion that thermometers could replace performance tests in human circadian studies because the circadian rhythm in performance could be inferred from the circadian rhythm in body temperature. Later investigators such as Colquhoun (1971) also held the view that performance and temperature rhythms were broadly parallel but noted that there were exceptions, such as tasks involving memory (e.g., Blake, 1967), and also were careful to discriminate between a parallel and a causal relationship between temperature and performance. Whereas Kleitman (1963) espoused a causal relationship, Colquhoun and coworkers (in today's terms) considered performance and body temperature rhythms to be "sister" rhythms, both driven by the endogenous circadian pacemaker (ECP). In a series of studies (summarized in Folkard and Monk, 1985; Folkard, 1983, 1989; Monk, 1986), the Colquhoun group demonstrated that there were intertask differences not only in baseline time of day effects but also in the rate of phase adjustment to a phase shift (Hughes and Fol-

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kard, 1976; Monk et al., 1978). This suggested that rhythmic processes other than the ECP were additionally involved in determining how performance might change over the 24 h. The obvious candidate was time since waking (a variable related to Process S, the Y oscillator or Group II oscillators, the term used depending on the model employed). Usually, time since waking and ECP phase are inextricably linked, but using a forced desynchrony protocol in which artificially long or short day lengths are imposed, one can pry the two rhythmic processes apart, with ECP processes running at a day length of tau and time since waking processes running at a period of T. By educing performance rhythms separately at tau and at T, after running the study for an integral number of "beating cycles," one can determine the relative contribution of the two rhythmic processes. Using just such a forced desynchrony protocol, Monk et al. (1983) showed that there were indeed intertask differences in the relative influence of these processes. In particular, whereas the ECP was shown to control both simple manual dexterity and complex verbal reasoning performance, only the complex verbal reasoning task had significant spectral power at T, indicating the influence of time since waking effects. The authors interpreted this as a possible reason for why circadian rhythms in complex cognitive tasks appeared to phase adjust more rapidly than those in simple repetitive tasks or in body temperature.

In the early 1990s, the Czeisler group (Johnson et al., 1992; Dijk et al., 1992) presented a careful series of unmasking and forced desynchrony studies that confirmed the importance of the ECP in driving performance rhythms and demonstrated a compelling parallelism between temperature and performance (even in memory tasks) when both were educed at tau. Thus, the phase of the ECP at which body temperature was lowest corresponded exactly to the phase at which performance was lowest, whatever the task given. This has very recently been confirmed using unmasking studies of dexterity, serial search, and verbal reasoning performance in our own laboratories (Monk et al., 1997). Noted in Johnson et al.'s (1992) and Dijk et al.'s (1992) studies, but comparatively underemphasized, was the fact that when educed at T, both temperature and performance still showed rhythms (or, more accurately, time of day effects given that performance was not assessed during sleep). This raises the natural question of what the relationship between temperature and performance might be when all ECP influences have been evened out by the forced desynchrony protocol. Would Kleitman's parallelism still hold? No previous study from either our own laboratory or that of Czeisler has specifically addressed that question. The present article comprises a reanalysis of two forced desynchrony experiments to determine whether performance and body temperature still are parallel when educed at T, the period length of the imposed sleep / wake (and light / dark [LD]) cycle.

METHODS

Two healthy male subjects (22 and 25 years of age) were studied while the senior author was on the faculty of Cornell University Medical College. Each lived in complete temporal isolation for several months at a time. Complete details of the protocol were given in an earlier publication concerned with ratings of subjective alertness (Monk et al., 1989). Essentially, the protocol required a stretching of each subject's day length (i.e., rest / activity and LD cycle) coupled with a specific single phase shift to induce a desynchronization, whereby the ECP ran at a (free-running) period tau that was different from the imposed day length (T). Thus, throughout the study, each subject adhered to a strict regimen, being told when to get up, take meals, exercise, shower, do mood and performance tests, and go to bed, but otherwise had no temporal cues whatsoever. The imposed day lengths (T) were 25.8 h for Subject PB02 and 26.0 h for Subject PB03. Ambient light levels were about 300 to 500 lux during the "day" and 0 lux at "night." Precise details of the two protocols, including details of which portions were included in the present analysis, are given in the Appendix.

About seven times per day, at times scheduled by the experimenter, each subject was required to perform a mood and performance battery. These times corresponded to before each of the three meals, just before bedtime, before and after exercise, and after each use of the bathroom, although a mood and performance battery was excused if one had just been taken (within 1 h). On occasion, for various reasons, tests were given at times at variance with this schedule.

The mood assessment consisted of nine visual analog scales measuring mood and activation (Monk, 1989); it will not be discussed further. In the spirit of a heterogeneous model of circadian performance rhythms (Folkard and Monk, 1985), the performance battery sought to provide a broad sampling of various

aspects of performance. Thus, the level of cognitive complexity ranged from simple manual dexterity through serial search to a complex cognitive verbal reasoning task. All of these tests were fairly short, each component taking only 3 min or less. Because speed and accuracy scores can show different time of day effects (Folkard, 1975; Monk and Leng, 1982), both were considered. More complete details are given in Monk et al. (1985); a summary is given below. In order, the mood scales were followed by 32 trials of a serial search task (searching for the presence of a letter "E" in 30 random uppercase letters), 32 trials of a modified form of the Baddeley (1968) reasoning test (requiring the subject to determine whether sentences of the form "M is not followed by C — MC" were true or false), and dominant and nondominant hand versions of a dexterity task requiring the subject to fill 25 holes of a Purdue pegboard with metal pegs. Before the data to be reported here, Subject PB02 had experienced 82 versions of the battery and Subject PB03 had experienced 66 versions (in addition to prior training and practice booklets); thus, both subjects were well practiced at the tasks.

A Yellow Springs disposable thermistor was worn in the rectum to a depth of 10 cm and was removed only for defecation. The thermistor was connected (by a long "umbilical cord" allowing freedom of movement around the apartment) to a constant voltage generator and an ADC card in a microcomputer so that temperatures could be sampled every minute and recorded on magnetic disk and printed paper. Short losses of data due to probe slippage and defecation were replaced using linear interpolation. All scheduled sleep was recorded polygraphically, and sleep at other times of day was forbidden. Caffeine and alcohol were prohibited. Subjects were monitored both by closed circuit television and by technicians who worked irregular random shifts and thus could enter the apartment and chat with the subject without giving away time cues.

There were four stages to the data analysis. The first stage (reported in Monk et al., 1989) involved the determination of the value of tau—the period length of the ECP during the interval of forced desynchrony. This was accomplished, for each subject, by plotting a standard power frequency spectrum of the minute-by-minute temperature record. In the desynchronized condition, this spectrum should be bimodal, with one peak at tau and the other at T. For both subjects, this was indeed the case. Subject PB02, with an imposed T of 25.8 h, showed a tau of 24.2 h. Subject PB03, with an imposed T of 26.0 h, showed a tau of 24.5 h. The second stage was to select a portion of the experiment that represented an exactly integral number of "rounds" (or beating frequencies) of T and tau, that is, a length of time for which each T phase value was equally represented by each of the tau phase values and vice versa. This was vitally important for the present analysis in view of the known powerful influence of the ECP (running in this case at tau) on performance rhythms. Any inequality in ECP influence could result in spurious time of day functions when educed at T. Because it was desirable to maximize prior practice at the tasks, we went backward from the penultimate day of the study—three complete rounds ($3 \times 25.8 \times 24.2$ / [25.8 – 24.2] = 1171 h) for Subject PB02, two complete rounds ($2 \times 26.0 \times 24.5$ / [26.0 – 24.5] = 849 h) for Subject PB03. This was further checked by a computer program that noted the tau phases of each T sampling bin used to plot a time of day function, ensuring an average phase of 180º at tau (all observed means were between 165 and 189º).

To standardize performance scores with the minimum of data manipulation, each individual datum (i.e., total latency for 25 pegs or for 32 lines of the search or the reasoning task) was first transformed into a measure of pegs or lines per minute, after which it was expressed as a deviation from the subject's own mean rate for that measure over the time series in question. This had the additional advantage of rendering increasing scores as indicative of better performance.

The third stage of analysis was to confirm previous findings regarding the influence of the ECP. For this stage, each performance test was indexed by the phase value (circadian degrees), relative to tau, at which it occurred. Data were then cast into 20º bins, and educed rhythms were plotted for each performance measure. For comparison, the rectal temperature from the exact minute at which the performance test was started also was taken and subjected to the same analysis procedure as was applied to the performance data. For both temperature and performance eductions at tau, Phase 0 was defined as the time of the temperature nadir. A sinusoid also was fitted by a least squares technique (Monk and Fort, 1983) to each subject's time series (in both temperature and performance) to yield estimates of mesor (mean level of fitted curve), acrophase (time of fitted peak), amplitude (value of fitted peak minus mesor), and an *F* ratio statistic assessing goodness of fit. To remove residual

"learning curve" effects, each performance time series first had a linear trend removed, each datum being expressed as the deviation from that line.

The fourth stage of the analysis comprised the test of the study's major hypothesis. Each performance test (and related temperature sample) was indexed by the phase (time since waking) at the imposed day length T at which it occurred. Data were then cast into bins equivalent to the 20º bins used at tau (i.e., of size $T \times 20 / 360$ h), namely 86 min for Subject PB02 and 87 min for Subject PB03. Bins having fewer than seven samples were ignored and the remainder were plotted, with wake time defined as Phase 0. A within-subject one-way analysis of variance was then applied to each subject's data to determine the statistical reliability of time of day differences (at T), with orthogonal polynomials used to determine the significance of linear, quadratic, and cubic trends. As was done in the analysis at tau, a sinusoidal analysis also was applied to each complete time series (i.e., including all of the available data), yielding estimates of amplitude, acrophase, and significance of fit.

RESULTS

Accuracy scores from search and verbal reasoning tasks were uniformly high (mean accuracies all > 98%), showing too much of a "ceiling effect" for circadian variations to be apparent. The present analysis thus focuses on speed scores from search, reasoning, dominant hand dexterity, and nondominant hand dexterity performance scores. A total of 309 performance tests were available for Subject PB02 and 220 for Subject PB03, with up to three manual dexterity tests per subject lost to equipment malfunction. The educed functions at T used slightly fewer (294 and 210, respectively) because bins with fewer than seven items were not considered.

To confirm that spectral power was present at both tau (Subject PB02: 24.2 h; Subject PB03: 24.5 h) and T (Subject PB02: 25.8 h; Subject PB03: 26.0 h) for both temperature and (detrended) performance variables, single sinusoids were fitted iteratively to each complete time series (1171 h for Subject PB02; 849 h for Subject PB03) with period lengths ranging from 22 to 27 h in steps of 0.1 h. The square of the fitted amplitude at each period was then used as an approximation to "spectral power" so that the equivalent of a power frequency spectrum could be plotted for each variable (Figs. 1 and 2). As predicted, all plots showed spectral

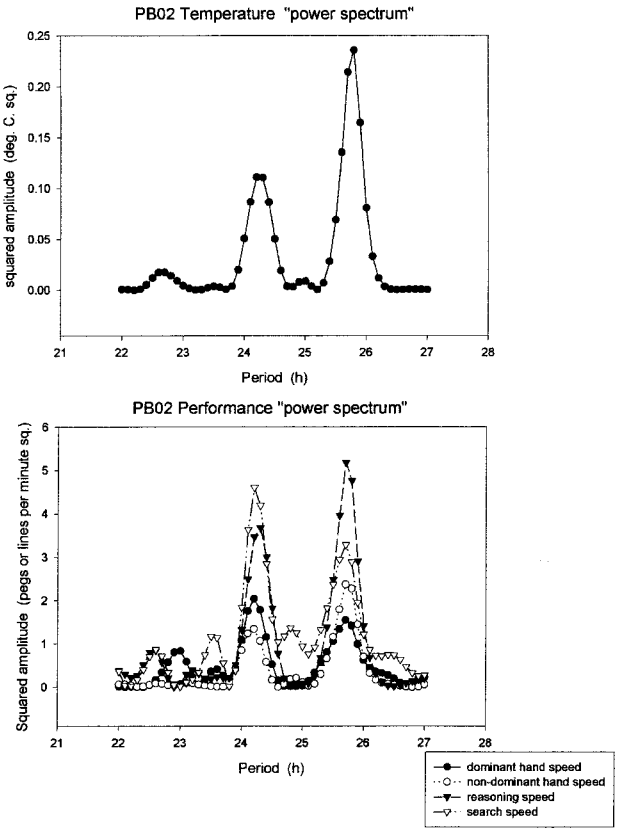

Figure 1. Subject PB02: Squared amplitude of best-fitting single sinusoid, plotted as a function of period length for rectal temperature at performance test (upper panel) and for performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel). These functions can be considered to approximate a power frequency spectrum.

peaks that were within 0.2 h (approximately 12 min) of the T and tau values for the given subject. In all cases, an *F* ratio statistic (Monk and Fort, 1983) confirmed the rhythms at both tau and T to be highly reliable for both subjects (Table 1).

When educed at tau, the period length of the ECP, all performance measures showed a clear circadian rhythm, with a low point broadly corresponding to the bathyphase of temperature (Figs. 3 and 4). When sinusoids were fitted to the entire time series at a period length of tau, all four performance variables showed an acrophase that was within 2.7 h of the temperature acrophase for Subject PB02 and within 1.3 h of the temperature acrophase for Subject PB03 (Table 1). Thus, previous results (using memory-based tasks), which had found a general parallelism between temperature and performance when sleep / wake cy-

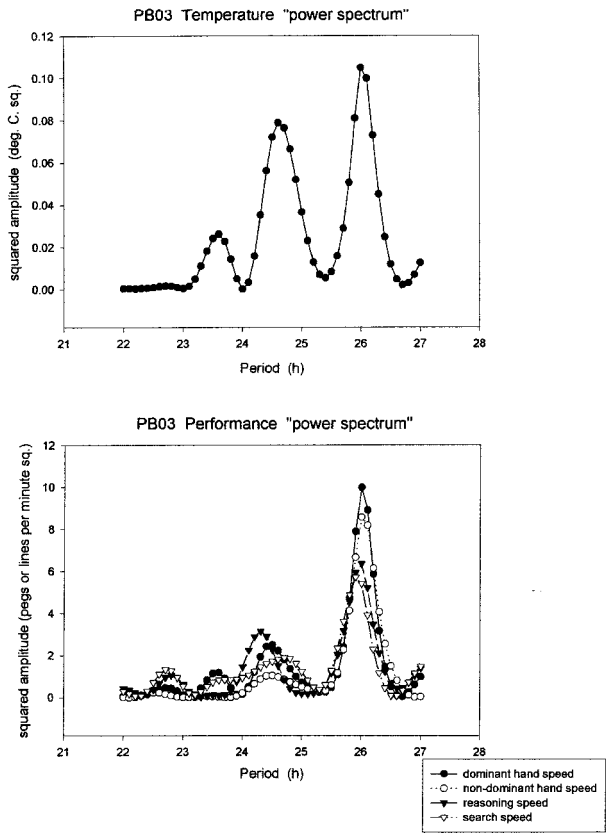

Figure 2. Subject PB03: Squared amplitude of best-fitting single sinusoid, plotted as a function of period length for rectal temperature at performance test (upper panel) and for performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel). These functions can be considered to approximate a power frequency spectrum.

cle or time since waking effects are evened out, were confirmed for a broader range of different performance tests.

When educed at T, the imposed sleep / wake cycle, there were, of course, no readings during sleep, but during the day both performance and temperature showed reliable time of day effects (Figs. 5 and 6). In particular, the fourth or fifth test of the day (about 9-12 h after waking) showed peak levels of body temperature with a fairly distinct inverted V-shaped function. Analysis of variance confirmed the statistical reliability of these time of day functions (main effect of time of day) in all cases (Table 2). In all cases, there was a reliable quadratic trend ($p < .002$), as one would infer from an inverted V-shaped function. There also was a reliable linear trend for search speed in Subject PB02, reliable cubic trends for all but verbal reasoning in Subject PB02, and all but the two dexterity tasks in Subject PB03 (Table 2). These trends suggest that intertask and intersubject differences also were present, superimposed on the inverted V function. Most notable of these were "post-lunch dips" in performance that appeared for the two dexterity tasks in Subject PB02 about 10 h after waking (bearing in mind that the day length was 25.8 h, not 24.0 h).

When sinusoidal fits at T were made to each subject's time series, the acrophases of temperature and performance were remarkably similar. Indeed, most performance acrophase values were closer to temperature acrophases when educed at T than when educed at tau (Table 1). The only major difference appeared to be that of reasoning speed for Subject PB03, which peaked 3.5 h before the temperature acrophase. Thus, for most measures, there was evidence to support Kleitman's parallelism, even when all ECP effects were evened out.

Comparisons also were made (within measure) of how rhythm amplitudes at tau compared with time of day amplitudes at T. As suggested from viewing the power frequency spectra (Figs. 1 and 2) and the educed time of day functions (Figs. 3-6), amplitudes educed at the period of T were, if anything, greater than those educed at tau. Indeed, of the eight sinusoidal fits made in analyzing the performance time series (2 subjects × 4 measures), only two showed an amplitude at T that was *smaller* than the corresponding amplitude at tau (Table 1). It is noteworthy that this finding even held for dominant hand dexterity speed, a variable for which a previous study of ours (Monk et al., 1983) had suggested minimal T influence.

DISCUSSION

Contemporary models of subjective alertness and performance efficiency view these variables as being determined both by a homeostatic process (duration of wakefulness) and by an input from the ECP (Monk et al., 1983, 1989; Folkard and Akerstedt, 1987, 1992). With regard to ECP influence, the present results confirm earlier studies (e.g., Johnson et al., 1992; Dijk et al., 1992; Monk et al., 1997) that have concluded that troughs in performance and temperature occur together when educed at a period length of tau or when studied in a protocol involving a suspension of the sleep / wake cycle. Indeed, they extend the generality of previous findings to a broader range of tasks than that previously studied under forced desynchrony.

Table 1. Results of sinusoidal analysis (see text) at tau (Subject PB02: 24.2 h; Subject PB03: 24.5 h) and at T (Subject PB02: 25.8 h; Subject PB03: 26.0 h). Performance time series had a linear trend removed first.

	Amplitude[a]		*Acrophase*[b]		F*(2, >200)*		p *Value*	
	PB02	*PB03*	*PB02*	*PB03*	*PB02*	*PB03*	*PB02*	*PB03*
Period = tau								
Temperature	0.33	0.27	10.7	13.7	58.9	38.7	**	**
Dominant dexterity	1.43	1.58	8.4	14.9	16.0	11.3	**	**
Nondominant dexterity	1.16	1.02	8.6	14.8	15.4	5.8	**	*
Reasoning	1.86	1.51	8.1	13.6	17.0	5.0	**	*
Search	2.15	1.31	8.0	14.1	15.5	7.4	**	**
Period = T								
Temperature	0.49	0.32	19.8	10.3	133.4	47.7	**	**
Dominant dexterity	1.19	3.16	19.9	9.9	9.7	45.6	**	**
Nondominant dexterity	1.51	2.93	19.8	10.3	24.4	53.3	**	**
Reasoning	2.18	2.52	18.5	6.7	22.1	13.4	**	**
Search	1.70	2.33	19.3	11.7	8.5	25.6	**	**

a. Units: degrees Celsius or pegs or lines per minute.
b. Circadian time, arbitrary base.
*$p < .01$, **$p < .001$.

Thus, whatever the task given, there appears to be a strong circadian influence from the ECP, with the time of poorest performance corresponding to the phase of the ECP at which the body temperature rhythm is lowest.

The present results also confirm that there is an equally strong influence from the sleep / wake cycle (time since waking) that is apparent in both body temperature and performance. The influence of the homeostatic process (Process S) usually is described as a linear decline of performance and / or subjective alertness with the amount of hours since waking. In the present study, most tasks did *not* show a linear decrease in performance efficiency over the waking hours but appeared to take the form of an inverted V with a peak of performance occurring about 9 to 12 h after waking, which was parallel to the changes in body temperature.

One feature of the present results was the broad similarity in circadian rhythms (at tau) and time of day functions (at T) that we observed among the various tasks. However, this uniformity might not have occurred had we used tasks with a greater memory load. It is useful to compare our results to the earlier forced desynchrony findings of Johnson et al. (1992) and Dijk et al. (1992), whose performance tasks were exclusively memory (or working memory) based. For these tasks, the time of day function, when educed at T was like an inverted check mark (tick), with a small increase at the beginning of the day akin to Process W in Folkard and Akerstedt's (1992) model of subjective alertness, followed by a subsequent linear decline over much of the waking day. This function deviated from that of body temperature, which showed an inverted V-shaped function very similar to our own. This difference between our own results and those of Johnson et al. (1992) and Dijk et al. (1992) suggests a possible mechanism by which intertask differences might appear under nycthemeral conditions. As has been confirmed in studies spanning seven decades (Laird, 1925; Folkard and Monk, 1980; Johnson et al., 1992), short-term memory tasks show a decline over the waking day under a normal nycthemeral routine. If sleep / wake cycle processes predominated over ECP processes for memory tasks under nycthemeral conditions, then such tasks would be expected to show a decline over much of the day, representing a deviation from temperature rhythm parallelism under those conditions. However, a return to parallelism would appear when the sleep / wake cycle was either suspended (under unmasking conditions) or balanced out by eduction at tau (under forced desynchrony conditions) whence only ECP influence would be apparent.

The question remains as to what underlying mechanisms might mediate the parallelism between performance and body temperature at T. This requires a more detailed analysis of activity and behavior patterns that was not available in the present data set. Also, there is a conceptual difficulty arising from recent findings on the influence of light on the circadian system. Boivin et al. (1996) showed that even with the relatively dim light levels used in the present study, the imposed light / dark cycle may exert a direct influence on the ECP. This could lead to relative coordina-

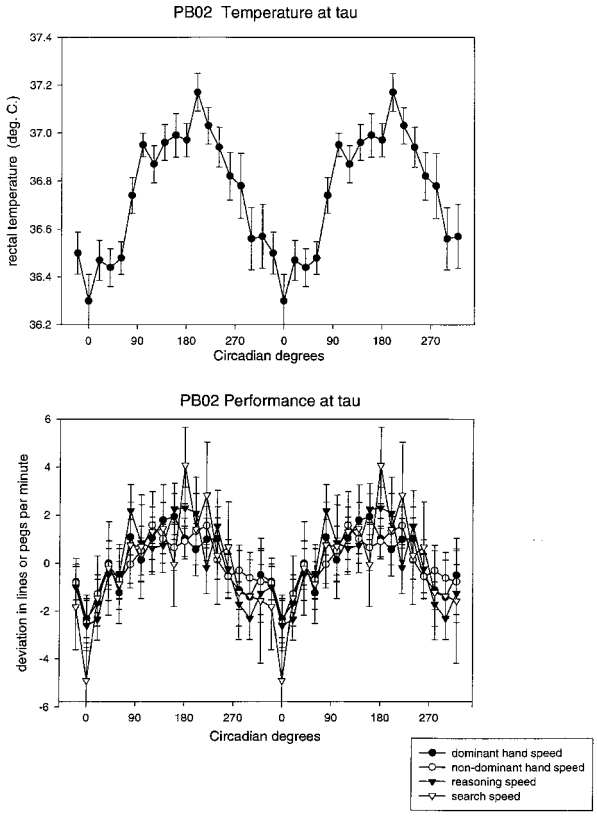

Figure 3. Subject PB02: Mean (± 1 *SEM*) rectal temperature at performance test (upper panel) and performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel) double plotted as a function of circadian degrees (20° bins) when educed at tau, the period length at which the endogenous circadian pacemaker was running (24.2 h). Each bin contained between 13 and 20 samples. Performance speeds are expressed as deviation from overall mean level in pegs or lines per minute.

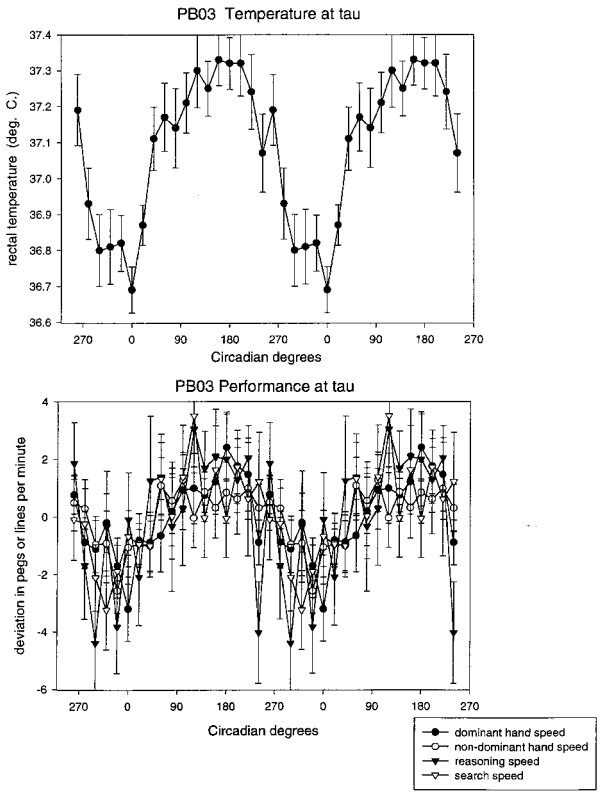

Figure 4. Subject PB03: Mean (± 1 *SEM*) rectal temperature at performance test (upper panel) and performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel) double plotted as a function of circadian degrees (20° bins) when educed at tau, the period length at which the endogenous circadian pacemaker was running (24.5 h). Each bin contained between 10 and 15 samples. Performance speeds are expressed as deviation from overall mean level in pegs or lines per minute.

tion between the two rhythmic processes, resulting in a loss of stationarity in the tau rhythm and thus a loss in a true balancing of tau with respect to T (Klerman et al., 1996). It is not possible to determine whether relative coordination occurred in the present experiments. To completely avoid such relative coordination, the experiments would need to be rerun in much dimmer (< 10 lux) "daytime" illumination. However, it should be noted that in the series of experiments reported by Dijk et al. (1992) and Johnson et al. (1992), extremely low levels of illumination (mostly < 15 lux) were used, and body temperature still showed an inverted V-shaped function with time since waking that was very similar to our own. Another complication arises from Jewett et al.'s (1996) recent finding that the effects of the ECP and the sleep / wake cycle might not be simply additive. Although this would not negate the present findings, it undoubtedly would add to the noise and would complicate any model of circadian performance rhythms.

One obvious candidate to explain the parallelism between body temperature and performance at T is activity and / or arousal level, which might be expected to both raise body temperature and improve performance. Indeed, Hockey and Colquhoun's (1972) "arousal model" of circadian performance rhythms has been extremely successful in explaining

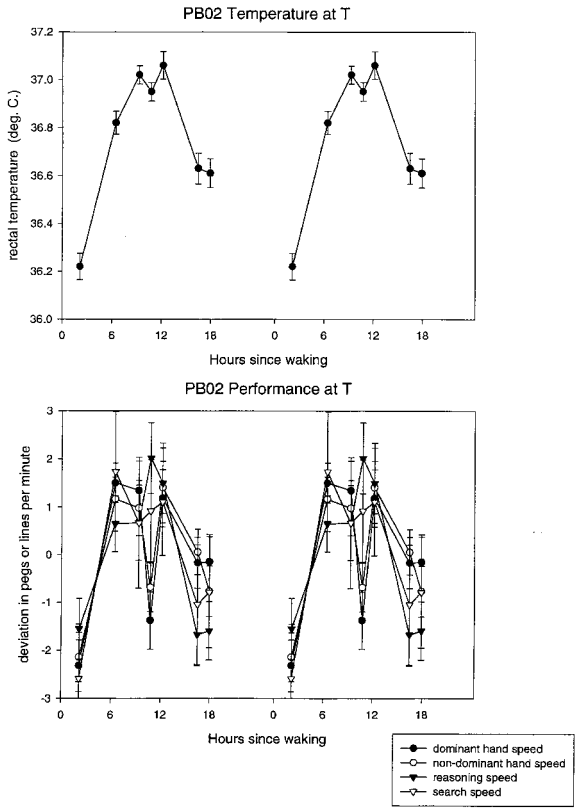

Figure 5. Subject PB02: Mean (± 1 *SEM*) rectal temperature at performance test (upper panel) and performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel) double plotted as a function of time from waking (in 86-min bins) when educed at T, the period length of the imposed sleep/wake (and light/dark) cycle (25.8 h). The gap in the graph denotes the sleep (and dark) episode, during which performance was not sampled. Zero on the abscissa represents wake time. Bins with fewer than seven data points are not plotted. Plotted sample sizes ranged from 40 to 44. Performance speeds are expressed as deviation from overall mean level in pegs or lines per minute.

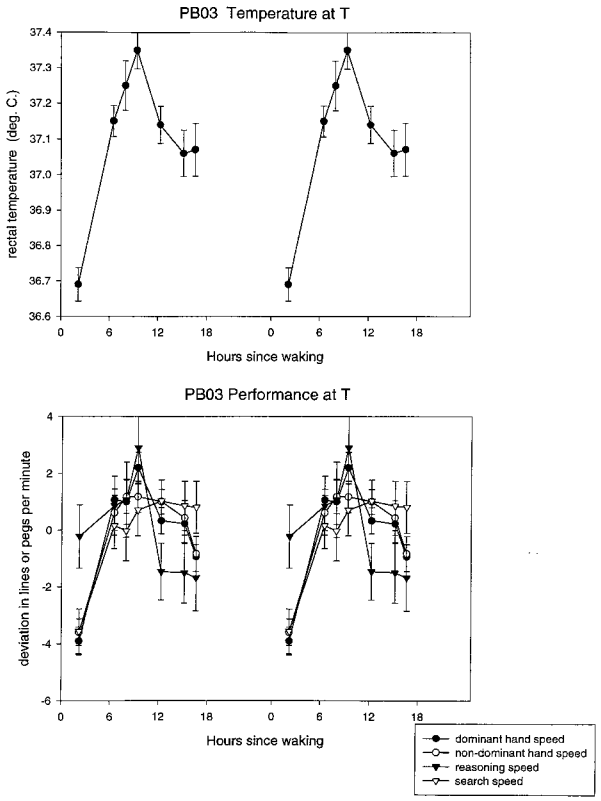

Figure 6. Subject PB03: Mean (± 1 *SEM*) rectal temperature at performance test (upper panel) and performance speed at dominant hand dexterity, nondominant hand dexterity, verbal reasoning, and serial search tasks (lower panel) double plotted as a function of time from waking (in 87-min bins) when educed at T, the period length of the imposed sleep/wake (and light/dark) cycle (26.0 h). The gap in the graph denotes the sleep (and dark) episode, during which performance was not sampled. Zero on the abscissa represents wake time. Bins with fewer than seven data points are not plotted. Plotted sample sizes ranged from 18 to 33. Performance speeds are expressed as deviation from overall mean level in pegs or lines per minute.

time of day effects in performance (Monk, 1982) and their relation to body temperature. Because the present study never determined whether the observed rhythms at T were indeed *endogenous*—capable of continuing, even when activity, meals, light, and so on were homogenized at all phases of T—we do not know whether the process underlying them can truly be referred to as a biological oscillator. Previous models of the circadian system did indeed regard human sleep / wake processes as having a separate circadian oscillator (Wever et al., 1975; Kronauer et al., 1982). These models posited two mutually interactive oscillators (or groups of oscillators) to underlie the human circadian system. The strong oscillator(s), denoted "Group I" or "X," was indicated by the body temperature rhythm and was less labile than the weak oscillator(s), denoted "Group II" or "Y," which was held to control the sleep / wake cycle. In terms of these models, one would argue that the weak oscillator, like its stronger partner, also generates a circadian rhythm in both body temperature and performance, with the two rhythms showing a parallelism. Although this might be difficult to explain from a physiological perspective, it would make sense from a behavioral viewpoint because if the weak oscillator is to control the

Table 2. Results of analysis of variance on time of day effects when the time series were educed at T and data were cast into 20° bins (see text).

	Main Effect		*Orthogonal Polynomials (p)*		
	F[a]	p	*Linear*	*Quadratic*	*Cubic*
Subject PB02					
Temperature	31.74	.0001	.06	.0001	.0001
Dominant dexterity	11.97	.0001	n.s.	.001	.001
Nondominant dexterity	13.66	.0001	.06	.0001	.02
Reasoning	8.65	.0001	n.s.	.0001	n.s.
Search	7.48	.0001	n.s.	.0001	.02
Subject PB03					
Temperature	7.74	.0001	n.s.	.0001	.001
Dominant dexterity	7.11	.0001	n.s.	.0001	.06
Nondominant dexterity	8.81	.0001	n.s.	.0001	.08
Reasoning	3.74	.0021	n.s.	.001	.005
Search	6.43	.0001	.05	.002	.005

NOTE: Bins with fewer than seven items were discarded. Significance levels (*p* values) are given for the main effect of time of day and for linear, quadratic, and cubic fits using orthogonal polynomials; n.s. = $p > .10$.
a. $F(6, 234)$ for Subject PB02; $F(6, 102)$ for Subject PB03.

sleep / wake cycle, then it would need some sanction, such as poor performance, to persuade the individual of the need to find somewhere to sleep for the night (Monk, 1991). Thus, it would be useful to have both oscillators involved in circadian alertness and performance rhythms—the more labile weak oscillator(s) to be responsive to unanticipated changes in routine and the strong oscillator(s) to provide an underlying stability to the system. Moreover, one could go further and explain some of the intertask differences that have been observed previously in phase shift reentrainment rates (Klein et al., 1972; Folkard and Monk, 1982). Because of the increased lability of the weak oscillator, the greater the influence of the weak oscillator on a given performance rhythm, the faster should be its apparent rate of entrainment to an imposed phase shift.

CONCLUSIONS

When measured in forced desynchrony protocols, circadian performance rhythms usually appear to be broadly parallel to circadian temperature rhythms, whether educed at tau (the period of the ECP) or at T (the period of the imposed sleep / wake cycle). Moreover, the influence of the sleep / wake cycle on time of day effects in performance is at least as strong as the influence of the ECP.

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APPENDIX
Experimental Details

Subject PB02: 11 Jan 83 to 14 Mar 83, age 22 years
SP 1-8 (entrained 24 h) LM 15482-27660
SP 9 (shift of 5 h) LM 27661-28176
SP 10-58 (entrained 25.8-h day) LM 28177-104446
LM used in present analysis: 33737-104000 (1171 h)

Subject PB03: 22 Feb 83 to 1 Jun 83, age 25 years
SP 1-7 (entrained 24-h day) LM 75908-86760
SP 8 (shift of 6 h) LM 86761-87312
SP 9-44 (entrained 26-h day) LM 87313-143458
SP 45-68 (entrained 25.3-h day) LM 143459-180870
SP 69 (transitional) LM 180871-181298
SP 70-87 (free running) LM 181299-217905
LM used in present analysis: 90383-141333 (849 h)

NOTE: SP = sleep period; LM = log minute (a clock counting minutes that starts at midnight on January 1 of each year).

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