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Circadian Performance Rhythms: Some Practical and Theoretical Implications [and Discussion]

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Circadian performance rhythms: some practical and theoretical implications

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Safety and productivity are low at night and this would appear to be because we are a diurnal species. This is reflected not only in our habitual sleep time, but also in our endogenous body clocks that, together with exogenous influences, such as the patterning of meals and activity, result in predictable circadian (24 h) rhythms in our physiological processes. Our performance capabilities also vary over the course of our waking period, with task demands affecting both the precise trend over the day, and the rate at which it adjusts to the changes in sleep timing occasioned by shift work. Studies designed to examine the reasons for this have shown that memory loaded performance may have a quite separate endogenous component to that responsible for more simple performance, suggesting that these two types of performance cannot be causally related. Furthermore, it would appear that the exogenous component of circadian rhythms may also differ across measures, and our attempts to model these endogenous and exogenous components have led us to re-examine the evidence on adjustment to night work.

Our findings suggest that shiftworkers merely 'stay up late' on the night shift, rather than adjust to it, and that this is responsible for the reduced safety at night. It would seem that in situations where safety is paramount, the only solution to these problems is the creation of a nocturnal sub-society that not only always works at night but also remains on a nocturnal routine on rest days.

Introduction

Many of the major industrial accidents involving human error have occurred at night. The Three Mile Island incident occurred at 04h00, Chernobyl at 01h23, Bhopal just after midnight and the Rhine chemical spillage in the early hours of the morning. This may, of course, be a coincidence, but the few studies that have obtained relatively continuous productivity and safety measures over the 24-hour day agree in suggesting that our performance capabilities are reduced at night (Folkard & Monk 1979). Thus, for example, single-vehicle accidents have been found to be three times more likely to occur between 21h00 and 09h00 than between 09h00 and 21h00, despite a considerably reduced traffic density. If this latter factor is taken into account, the relative probability of a single vehicle accident is some twelve times higher at night, and shows a clear peak between 03h00 and 06h00 (van Ouwerkerk 1987).

This problem of impaired performance at night would appear to stem largely from the fact that we have evolved as a diurnal species. This is reflected not only in the obvious fact that we habitually sleep at night, but also in the phase of the circadian (24 h) rhythms that are now known to occur in virtually all our physiological processes (Minors & Waterhouse 1981). These circadian rhythms are thought to reflect an evolutionary internalization of the pronounced 24 h changes in the physical environment. They enable species to anticipate these changes and hence have presumably been strengthened by natural selection.

Our measured circadian rhythms reflect the combined influences of an endogenous 'body clock' and a range of exogenous or 'masking' influences such as the habitual timing of sleep, activity, and meals (Wever 1979). Whether or not some of these exogenous influences are themselves controlled by a second, relatively exogenous oscillator or body clock, as Wever (1979) argues, is immaterial to this paper. Under normal sleep–wake conditions, the phase relation between the endogenous and exogenous components is relatively constant from day to day, resulting in predictable circadian variations in our physiological state.

Time of day effects in performance

In view of this circadian variation in physiological state it is hardly surprising that performance ability on various tasks has also been found to vary over the course of our normal waking period. At one time it was thought that performance on all tasks showed a similar pattern over the day, a view that echoed an early view of physiological circadian rhythms (J. Aschoff, personal communication). Performance efficiency was argued to parallel variations either in body temperature (Kleitman 1939) or, somewhat later, in basal arousal which was itself thought to largely parallel temperature (Colquhoun 1971). It is now clear, however, that this view was oversimplistic and that the nature of the variation in performance over the day depends, among other factors, on task demands.

In the case of a small number of performance tasks, fairly consistent trends in performance over the day have been observed, in several different studies (see Folkard (1983) for details of these). By expressing the value for each time of day in each study as a percentage of the mean value over the whole day for that study and then interpolating two-hourly readings, 'normative' time of day effects can be derived. Three such 'normative' trends are shown in figure 1 together with the standard deviation across the studies they are based on. This figure also shows 'normative' trends in body temperature and rated alertness derived in a similar manner. A number of points emerge from inspection of this figure.

First, despite the notorious 'noisiness' of performance measures, the standard deviations across studies are relatively small, showing a fair degree of consistency in the mean trends obtained. Secondly, the three different types of performance show very different trends across the day. Performance on simple serial search tasks, a task similar to proof-reading, improves over the day to reach a maximum at 20h00, whereas the immediate retention of information presented in short texts or films decreases over the day to reach a minimum at 20h00. Performance on tasks involving 'working memory', such as verbal reasoning and mental arithmetic, shows an intermediate trend. These differences in the trend over the day suggest that the short term or 'working' memory load involved in the performance of a task may be important in determining the trend over the day, a suggestion borne out by the results of other studies (see, for example, Folkard *et al.* 1976). Finally, there is a marked parallelism between performance on the simple serial search task and changes in body temperature, but no such parallelism with rated alertness.

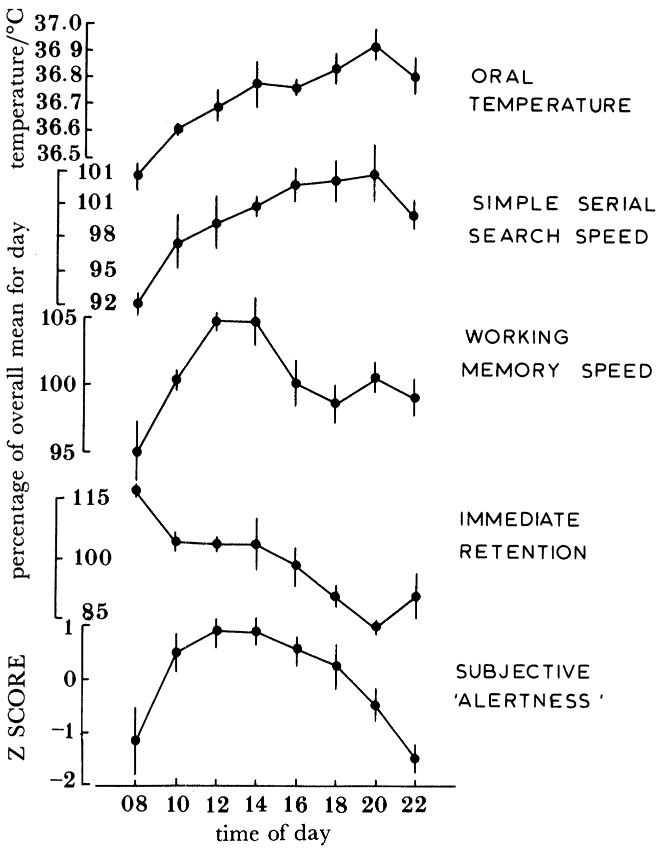

Figure 1. 'Normative' time of day effects in oral temperature, three different types of performance measure and rated alertness.

Adjustment to phase-shifts

These different trends in performance capability over the day could be interpreted as reflecting the combined effects of an underlying rhythm in basal arousal and task demand dependent differences in the 'optimal' level of arousal, that is, the Yerkes–Dodson law. However, such an explanation would predict that all performance rhythms should adjust at the same rate to one another to the change in sleep timing associated with shiftwork and rapid time-zone transitions. Although some support for this view has been claimed for a fairly restricted range of tasks (see Colquhoun 1971), there is evidence that the trend in 'working' memory performance may adjust to a change in sleep timing rather more quickly than that in either body temperature or performance on a serial search task (see, for example, Hughes & Folkard 1976). This has two important implications. First, it suggests that the optimal form of shift system may depend on the nature of the task being performed (Folkard & Monk 1979). Secondly, it clearly questions the validity of a simple arousal explanation, or any other single-factor explanation, of performance trends over the day.

The most parsimonious explanation of this task dependent difference in the rate of adjustment is that, like physiological rhythms, trends in performance over the waking period reflect both an endogenous body-clock component and the influence of various exogenous factors. These latter influences might include such factors as a build up of mental fatigue over time awake (Folkard & Akerstedt 1987) and the effects of food ingestion on performance (Craig & Richardson 1989). As the timing of both sleep and meals is changed almost immediately on the night shift and after time-zone transitions, performance trends that are largely dependent on exogenous factors might be expected to adjust more rapidly than those that are more dependent on the endogenous body clock.

The relative dependence of different overt circadian rhythms on endogenous and exogenous factors can be examined by using the 'fractional desynchronization' technique (Wever 1983). This involves isolating individuals from normal time cues, or 'zeitgebers', in a temporal isolation unit (Wever 1979) and subjecting them to progressively shortening or lengthening artificial zeitgebers. The sleep–wake cycle, meal timing, and other exogenous influences such as activity level have been found to follow this changing 'day' length with considerable accuracy to day lengths as short as 19 h or as long as 35 h (Wever 1979, 1983). In contrast, the circadian rhythm in body temperature, and hence presumably the endogenous body clock, will normally only follow the changing day length down to a period of about 22.5h or up to about 27.0h. After these 'limits of entrainment' the body temperature rhythm 'breaks out' from the artificial zeitgebers and free-runs with an endogenous period of 25 h.

Rhythms with a small exogenous component will follow the artificial zeitgebers to a lesser extent than those with a larger exogenous component. Thus, for example, body temperature typically breaks out somewhat earlier than urinary potassium, which in turn breaks out earlier than urinary sodium (Wever 1983; Folkard *et al.* 1984). This implies less exogenous control, and hence more endogenous control, of the circadian rhythm in temperature than of that in urinary sodium, a finding that agrees favourably with the results of other studies (see, for example, Wever 1979; Minors & Waterhouse 1981).

The use of this fractional desynchronization technique to examine the components of performance rhythms has produced some rather unexpected findings. In one series of studies (Folkard *et al.* 1983) individually isolated subjects were given performance tasks at the 'local time' equivalents of 06h30, 09h30, 12h30, 15h30, 18h30, 21h30 and 02h00. Subjects performed a simple serial search task and a verbal reasoning (working memory) task (Baddeley 1968) at each of these times, or different versions of a serial search and memory (SAM) task in which the memory load could be systematically varied from one (SAM-1) to five (SAM-5) items, for the 28 days duration of the study.

The circadian rhythm in performance on the simple serial search and SAM-1 tasks consistently followed that in body temperature in both shortening and lengthening studies. They had similar limits of entrainment and subsequently free-ran with indistinguishable periods. This contrasts sharply with the somewhat different limits found for the body temperature and urinary potassium rhythms (Folkard *et al.* 1984), despite both having a strong endogenous component (Minors & Waterhouse 1981), and implies that the rhythms in body temperature and serial search performance reflect a very similar mix of endogenous and exogenous influences.

About half the subjects run in this series of studies showed a roughly similar pattern of results in their verbal reasoning rhythm. In contrast, the remaining subjects showed a rapid phase advance of this rhythm, relative to both that in body temperature rhythm and their sleep–wake cycle, at some stage of the study. More detailed analyses of these sections of the total time series showed that their verbal reasoning rhythm was running independently with a 21 h period.

Further, all the subjects given the SAM-5 task either showed a 21 h period in their performance of it at some stage of the study or, in the case of (unpublished) shortening studies, their rhythms remained entrained to a period, of 21 h or less. In contrast their performance rhythm on an intermediate memory load version (SAM-3) showed an inconsistent pattern of results. This suggests that a 21 h period in performance may only occur if the subject's short-term or 'working' memory capacity is taxed by the task demands, and that individuals differ in the degree to which this capacity is taxed by tasks such as SAM-3 and verbal reasoning.

This finding of a 21 h period in memory-loaded performance is totally inexplicable in terms of the current view of the circadian system outlined above. It is, however, consistent with the more detailed analysis of the results of some earlier phase shift studies of performance rhythms (Folkard & Monk 1982). It implies the existence of a second, previously unidentified, endogenous body clock that has a free running period of 21 h.

THE RELATIONS BETWEEN PSYCHOLOGICAL AND PHYSIOLOGICAL MEASURES

The separation of the endogenous component of the rhythm in memory loaded performance from that in both simple serial search performance and body temperature also implies that there can be no causal relation between these functions. Indeed, Wever (1983) argued that any temporary separation of two overt rhythms must imply that there is no direct causal relation between the processes in which they occur, although, unlike a separation of the endogenous components, it clearly does not rule out their common control by different proportions of the same two underlying processes. As it is now clear that a single factor arousal theory is oversimplistic (Broadbent 1971) and that there must be a number of different arousal states (see, for example, Hockey & Hamilton 1983), there is a considerable interest in determining the relations between different physiological and performance measures.

The above results suggest that the circadian rhythmicity in different measures could be used to determine their functional relation or 'causal nexus'. Unfortunately, the number of measures included in these studies was limited by the high cost of assaying the large number of urine samples produced. There are, however, published studies that have obtained a greater range of measures and that can be re-analysed to explore this possibility. The first of these is a study in which subjects were sleep deprived and temporally isolated for 75 h (Froberg 1977). During this time exogenous influences were minimized by keeping activity level constant and giving identical three-hourly snacks. A range of performance and physiological measures were obtained at three hourly intervals, and the circadian rhythm in these would be expected to phase delay, or free-run, under these conditions (Aschoff *et al.* 1975). Our re-analysis involved estimating the best fitting period (that is, direction and extent of phase shift) for each variable and for each subject, and then examining the relation between these estimates (Folkard *et al.* 1986).

In view of the design of this study, no reliable rhythm could be detected for many of the subjects in the two measures with a strong exogenous component, namely, pulse rate and urinary noradrenalin. Our analysis was thus limited to measures with a relatively large endogenous component to their circadian rhythms. In most of the measures the endogenous circadian rhythm showed the expected tendency to phase delay. However, digit span, a classic measure of short-term memory capacity, had a mean best fitting period of 21.7 h, that is, it phase-advanced. This estimate was reliably shorter than that of any of the other measures taken ($p < 0.01$ in all cases) and concurs well with the results reported above. Further, and again consistent with our earlier findings, approximately half the subjects showed a mean best-fitting period of 21.4 h in their performance of a verbal reasoning task, while the remainder showed a phase delay.

To explore the relation between these estimates, principal components analyses with varimax rotation and hierarchical cluster analyses were performed. The results of these are shown in figure 2, together with the results of parallel analyses based on the mean level for each individual for each variable. This allows the present approach to be contrasted with that of Fleishman (see, for example, Fleishman & Quiantance 1984). The analyses based on best fitting period, that is, on the response of the endogenous circadian rhythm, showed a number of interesting results. First, it suggested that temperature, adrenalin and vigilance performance are probably related to one another, in agreement with the results of earlier studies (O'Hanlon 1965; Colquhoun 1971). Secondly, it suggested that this group of measures may also be related to a second group of related measures comprising ratings of alertness and fatigue and performance on a complex coding task. Finally, it confirmed that digit span performance showed no relation to temperature, but may have been related to performance on a more simple version of the coding task that could have been performed by using a high working memory load strategy. This pattern of findings contrasts sharply with that obtained by using Fleishman's approach that yielded two groups of performance measures, but no relation between these and either physiological measures or subjective ratings of affective state.

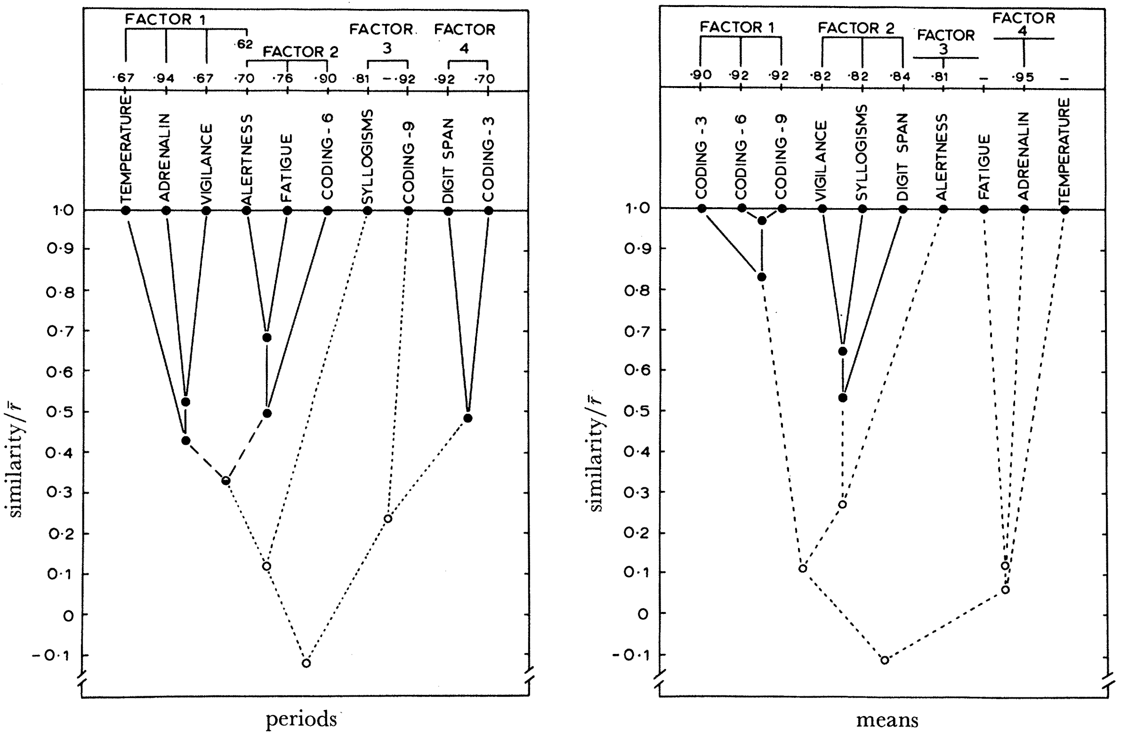

FIGURE 2. The relation between the measures as assessed by principal components (top panels) and hierarchical clustering (bottom panels) analyses based on the best fitting periods (*a*) and mean levels (*b*). Both figures show probable (solid lines), possible (dashed lines) and improbable (dotted lines) relations between the variables.

This pattern of results clearly confirms the potential usefulness of circadian rhythmicity in exploring the relation between variables. However, our attempts to extend this approach to studies of the phase shift imposed by eastward rapid time-zone transitions met with only limited success (Folkard *et al.* 1982). Our estimates of phase shift proved to be very noisy, presumably due to 'masking' by the exogenous factors that typically adjust almost immediately to such time-zone transitions.

Separating the endogenous and exogenous components

Our most recent efforts have thus been directed at trying to separate the endogenous and exogenous components of rhythms without the cumbersome and costly use of temporal isolation facilities. The reasons for this are twofold. First, it is clear that we can only examine the relation between endogenous circadian rhythms in, for example, rapid time-zone transition or shiftwork studies if we can somehow remove the exogenous component. Secondly, it would seem that the amplitude of circadian performance rhythms is insufficient in itself to account for the increased risk of accidents at night alluded to above. Rather, it would appear that there must be other factors associated with night work that contribute to impaired safety and productivity. The most obvious candidates are our natural inclination to sleep at night, and the reduced duration of sleeps taken between successive night shifts. Both these factors are influenced by our endogenous body clock.

Our first attempt to separate the endogenous and exogenous components of circadian rhythms was based on the results of a second series of fractional desynchronization studies (Folkard *et al.* 1984). The major finding from these studies was that the circadian rhythm in rated alertness not only broke out from the artificial zeitgebers, but did so before that in body temperature (Folkard *et al.* 1985). After this break out it free-ran through approximately 360° relative to the sleep–wake cycle and other exogenous influences. Thus the 'local time of day effect' after this break out could be argued to reflect the exogenous influences averaged over different phases of the endogenous component. Our more detailed analysis of this exogenous component showed that it could be described very accurately by two mathematical functions (Folkard & Akerstedt 1987). The more important, process 'S', is an exponential decrease in alertness (or increase in tiredness) over time awake, and is very similar to the hypothetical build up in sleep need postulated by Borbely (1982). The second, short lived, exponential function (process 'W') reflects a reduction from the extrapolated values of process 'S' on awakening, takes three hours to dissipate and is assumed to reflect the process of 'waking up'.

By subtracting this trend due to exogenous influences from the 'time of local day effect' before the break out, that is, when both exogenous and endogenous influences were present, we were also able to estimate the endogenous component. This was described very accurately by a 24 h cosine curve with an acrophase (peak) at 17h00. Thus the normal trend in alertness over the day could be accurately represented as the sum of three mathematical processes. By extrapolating these and summing their products it has also proved possible to account for the results of both prolonged sleep deprivation and phase shift studies with considerable accuracy (Folkard & Akerstedt 1989). Further, although based on alertness, this mathematical model has successfully been generalized to vigilance performance, and would appear to be capable of being generalized to other, non-memory loaded, performance measures (Spencer 1987). More recent and preliminary results suggest that we may also be able to extend this model to account for the recuperation of process 'S' during sleep, and the point at which individuals will spontaneously wake up. This would allow us to predict the level of sleep deprivation associated with any given shift system.

In parallel to this, we have estimated the endogenous and exogenous components of the body temperature rhythm based on published 'normative' trends obtained under different conditions (Folkard 1988, 1989). The advantages of using the temperature rhythm are: (i) that most published field studies of the adjustment of circadian rhythms to phase shifts have included body temperature measures; (ii) that laboratory studies of the circadian control of sleep have used the circadian temperature rhythm as a 'marker' for the endogenous body clock. Like that in alertness, our estimated endogenous component of the temperature rhythm approximated very well to a cosine curve with an acrophase of 17h00. However, the shape of the exogenous component was such that it could not easily be described in terms of simple mathematical functions, and hence could not be extrapolated. Nevertheless, these two components could be phase-shifted relative to one another, and then summed to simulate the trend for various shiftwork and rapid time-zone transition studies.

These estimates have been used to 'predict' the overt body temperature rhythm on the sixth successive night shift of the studies of Colquhoun *et al.* (Colquhoun 1971). This is the normal maximum number of night shifts before a change to a different shift or rest days (Kogi 1985), when any partial adjustment is likely to be lost. These night shift studies involved either an eight- or twelve-hour change in sleep timing, and the estimated exogenous component was thus phase delayed by these amounts and then summed with an unshifted endogenous component. In both cases, the resultant simulated temperature curves matched the actual curves very well, and considerably better than a partial adjustment of the whole curve. We (in collaboration with Drs Minors and Waterhouse) are currently extending this model to other phase-shift studies and are finding that an extension of this basic technique produces estimates of endogenous phase shift that are indistinguishable from those obtained by using costly and cumbersome 'constant routines' (Minors & Waterhouse 1981).

The conclusion to be drawn from this is that we may have grossly overestimated the adjustment of shiftworkers' endogenous body clocks to night work. Rather, over the course of a normal span of night shifts, shiftworkers would appear to simply 'stay up late' relative to their normally phased, endogenous clocks. As both the probability of falling asleep, and the subsequent sleep duration, are dependent on the phase of this body clock (for example, Zulley *et al.* 1981), this has two important implications for safety on the night shift. First, the individuals concerned will be trying to work when their ability to resist sleep is at its lowest ebb (Lavie 1986). Secondly, the duration of sleeps taken between successive night shifts is likely to be curtailed. Indeed, when translated onto 24-hour time, the body clock control of sleep duration in temporally isolated subjects cross-correlates highly ($r = 0.903$) with the time of day effect in shiftworkers' sleep duration (Folkard 1988). Consequently, a cumulative sleep debt may accrue over successive night shifts, which will probably exacerbate the night worker's natural tendency to fall asleep.

DISCUSSION

At a theoretical level, these findings clearly suggest that the time of day effect in the performance of any given task will reflect a mix of endogenous and exogenous influences. Further, the endogenous component would itself appear to differ with task demands. In the case of simple serial search and vigilance performance it would seem to be the same as that responsible for urinary adrenalin, body temperature and probably rated alertness. The temporary separation of these latter two rhythms observed by Folkard *et al.* (1985) can now be attributed to their rather different exogenous components rather than to a more fundamental difference. In contrast, the endogenous component of performance on highly memory loaded tasks would appear to be totally independent to that contributing to these other rhythms. As yet, no physiological circadian rhythm has been identified that is controlled by this second endogenous (21 h) oscillator, but this may simply reflect on the very limited range of measures that have been taken.

One, admittedly speculative, interpretation of these results is that they reflect separate oscillatory control of the two hemispheres. Such separate control is suggested by Reinberg *et al.* (1988) who found the rhythms in right- and left-hand grip strength to desynchronize. In the present context, it seems possible that the memory loaded tasks may have placed greater reliance on left hemisphere activity, and indeed there is some evidence that it may be the verbal component of these tasks, rather than working memory load *per se*, which is important in determining the trend over the day. However, it should be noted that Reinberg *et al.* (1988) also found the period of the rhythm in right, but not left, hand grip strength to be correlated with that of body temperature, a finding that appears to contradict any simple interpretation of these results.

Unfortunately, it also seems probable that the exogenous component of a performance rhythm will vary across tasks, both in terms of its relative size and its shape. We already know that the exogenous components of the temperature and alertness rhythms differ, and it seems unlikely that those of different performance will not do so. We are thus faced with the possibility that similarities or differences between the trends in performance over the day may tell us little, if anything, about their underlying control (cf. Broadbent *et al.* 1989). Nor need differences in the rate of phase shift of overt rhythms help much in this respect as they could simply reflect differences in their exogenous components. It is only if one component can be removed, either experimentally or by modelling (see above), can inferences concerning causality be made based on the behaviour of the other component.

At a more practical level, the implications seem rather more straightforward. Reduced productivity and safety at night would appear to be due to the shiftworkers' relatively normally phased body temperature clocks. As a consequence, they will be trying to work when many of their performance capabilities are at a low ebb, when they are relatively unable to resist sleep, and when they may have accrued a cumulative sleep debt. This latter problem can be minimized by the use of rapidly rotating shift systems that involve a maximum of two or three successive night shifts, and which are generally socially acceptable. Such systems may also be beneficial for more memory-loaded jobs (Folkard & Monk 1979).

However, in situations where safety is paramount, such as in the control room of a nuclear power plant, more extreme measures may be required. The best solution here would appear to be to create a nocturnal sub-society that not only always works at night, but also remains on a nocturnal routine on rest days. It seems that only under these extreme conditions will the shiftworkers' body clocks totally adjust, and remain adjusted, to night work and hence safety be raised to daytime levels.

I thank my colleagues and collaborators for their contribution to the studies discussed in this paper, and without whom this paper would not have been possible. In particular W. Peter Colquhoun and Timothy H. Monk (Sussex); Torbjorn Akerstedt and Jan E. Froberg (Stockholm); Hans M. Wegmann (Cologne); Rutger A. Wever (Munich); David S. Minors and Jim M. Waterhouse (Manchester), and Mick Spencer (Farnborough).

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Discussion

S. D. Rosen (*Charing Cross Hospital, London, U.K.*). Dr Folkard has very convincingly shown the impairment of performance that occurs in shift workers, and the role of the body's clocks and exogenous cues in maintaining the stability of cycling internal systems. I feel that it must again be stated that besides the effect upon industry of impairment of performance of workers, shift work is frequently very injurious to their health because of the cumulative sleep deprivation. Long-term follow-up of the adverse effects on many aspects of health of chronic sleep deprivation have been demonstrated in very large numbers of individuals followed by the U.S. Cancer Registry. Also, our own (smaller) experience has noted an excess of cardiovascular morbidity in shift workers.

Secondly, it would be of great interest to assess a possible connection between perturbations of the temperature–adrenaline–vigilance cycle and the known circadian rhythms of angina, platelet aggregation and myocardial infarction all of which have been related to cyclical catecholamine excesses.

The above, coupled with Dr Folkard's suggestion of separate biological clocks in the two cerebral hemispheres, is of particular interest to us in the light of collaborative research between our own department, and the Charing Cross Neuropsychophysiology Laboratory, showing hemispheric asymmetry and disturbed left hemispheric function in patients with cardiovascular disorders.