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AGARDograph No. 247

SIGNIFICANCE OF CIRCADIAN RHYTHMS IN AEROSPACE OPERATIONS

by

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SUMMARY

Reviewing our own experimental research and results from the pertinent literature, the significance of circadian rhythms in aerospace operations is discussed under the following aspects:

- Characteristics and interrelationship o. environmental and biological circadian systems
- Circadian rhythms of mental and physical performance, as well as of susceptibility and resistance
- Modification of circadian cycling through external and internal factors
- Disturbance of circadian rhythmicity and sleep-wake cycling in air and space operations and shiftwork ;
- Consequences for performance efficiency and health
- Formulas, models and rest duty regulations
- Recommendations for the passenger, crew and management

Finally, the "Biorhythm Theory" is critically reviewed.

GLOSSARY[*]

Acrophase. Phase angle of the maximum in a sinusoidal function or in a function used to approximate a rhythm; given in units of time, angular degrees or radians.

Amplitude. Difference between maximum and mean value, or between minimum and mean value.

Circadian. With a period of approximately 24 h (strictly 20-28 h); c i r c a (about, approximately) and d i e s (day, 24 h).

Desynchronization. State in which different rhythms previously synchronized run with different periods.

Dissociation, Internal. Transitory state in which different rhythms within one organism temporarily loose their mutual phase relationship (e.g. adjustment to a change in external Zeitgeber with a different speed).

Endogenous Rhythm. Self-sustained biological rhythm, maintained from within the organism independently of external periodicities.

Entrainment. Steady state in which a self-sustained rhythm runs synchronously with a Zeitgeber.

Free-Running. Running autonomously under constant conditions, i.e. after removal of Zeitgeber.

Lighting Regimen. Schedule of light and/or darkness exposition.
L = light; D = dark; LL = continuous light; DD = continuous dark.
Figures in brackets after L and D indicate duration or span of clock hours in local time (e.g. L (16) : D (8) = 24-h cycle of 16 h of light and 8 h of darkness).

Oscillator. Mechanism generating a rhythm.

Period. Time after which a phase of an oscillation recurs; duration of a complete cycle.

Phase. Instantaneous state of a rhythm within a period; in a looser sense also used for phase angle.

Phase Angle. Value of the time scale (abscissa) corresponding to a phase of a rhythm; given in fractions of the period (units of time, angular degrees or radians).

Phase shift. Abrupt or gradual displacement of a rhythm along the time scale.

Range of Oscillation. Difference between maximum and minimum value of a rhythm within a period.

Re-entrainment. Transient state of an endogenous rhythm after a phase shift of its Zeitgeber with the tendency to achieve the previous constant phase relationship again.

Resynchronization. Transient state of a rhythm after a phase shift of the synchronizing rhythm, lasting until the previous constant phase relationship between the two rhythms is achieved again.

Rhythm. Changes of a biologic variable recurring systematically with detectable periods; normally superimposed with random noise.

Synchronization. Steady state in which rhythms run with equal periods and constant phase relationships.

Synchronizer. See Zeitgeber.

Wave. Pattern of periodic variations.

Zeitgeber. External periodicity driving an endogenous biological rhythm to achieve a certain phase or period; also called time-giver, synchronizer, entraining agent, cue or clue.

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[*]When possible, the terminology follows that recommended by Halberg and Lee (1974) and Wever (1979)

INTRODUCTION

For over a century it has been recognized, that the functional state of the human body is subject to periodic daytime-dependent oscillations which - because of the period length of a b o u t 24 hours - were called "circadian" rhythms. It was later established that not only sleep and wakefulness alternate in parallel with the environmental light-dark cycle but the oscillatory nature was quantified for most physiological, psychological, and behavioral functions. Certain hours of the 24-hour cycle were identified as those where tonic physiologic levels are set for sleep and "readiness for efficiency" is reduced. Though the underlying mechanisms for biological circadian periodicity are as yet unknown, the interrelationships of biological periodicity with the environment and with controlling endogenous and exogenous factors have become increasingly clear.

There are basically two different ways of interference of biological periodicity with operational requirements: Man is required to work at unusual times of the day, i.e. the work-rest schedule is shifted in relation to the environmental timing system, or the temporal characteristics of the environment change in relation to man's living routine. Both occur in air and space operations.

Prime operational factors involved are start time, duration and regularity of work and, consequently, sleep periods within a circadian cycle; prime rhythm-related variables are external synchronization (entrainment) between body and environment, internal synchronization between several circadian systems within one organism, and frequency and duration of rhythm disturbances.

Because performance efficiency and health are affected, circadian rhythmicity has become a major concern not only for industrial shift work. This AGARDograph, together with those previously published on "Operational aspects of variations in alertness" (131) and "The operational consequences of sleep deprivation and sleep deficit" (159) as well as the Lecture Series on "Sleep, wakefulness, and circadian rhythm" (232) should present a useful source for planning and managing aerospace operations in harmony with human functional capacity.

1. STATEMENT OF THE PROBLEM

Conflicts of aerospace operations with circadian rhythms can principally arise in several ways: (1) when duty has to be performed as night- or as shiftwork, (2) when an abrupt phase shift in the environmental timing system occurs, (3) when the Zeitgebers in the environment change their period length, are weakened or disappear completely. The first condition relates to the fact that aerospace operations are frequently required during unusual hours of the 24-hour rest-activity cycle or at irregular time intervals. The encountered problems are not specific for air and space operations, but are associated with shiftwork in general. The second condition always appears when time zones are traversed, resulting in effects which are specific for air operations due to the inherent high meridian crossing speed. The third condition mainly concerns space operations, but in principle also occurs in any other situations of partial or total deprivation from external periodic inputs, such as living in the Arctic, in social isolation, or in the confinement of a shelter. In the aerospace environment all three conditions may become effective, singly or in combination, but producing always the same effect: a disturbance of the biological timing system. When the biological rhythm disturbances affect physical and mental performance or health, they become operationally significant. It is obvious that a discussion of the operational significance of circadian rhythm has also to consider the consequences of sleep disturbances and sleep deficit, as well as of fatigue resulting from sustained operations.

The focus may differ as to whether conclusions are to be drawn with regard to aerospace operations in the civilian or in the military field. Even within the military community the implications may be weighted differently considering which group is being emphasized, for instance active (aircrew) versus passive (passenger) participants, fighter pilots versus crews of cargo aircraft. In contrast with transport aircraft, fighters rarely participate in long-haul missions; the more common practice is to fly multiple short-duration missions separated by periods of non-flying activity. If this sequence deviates considerably from normal rest-activity cycles or continues round the clock, it gives rise to rhythm disturbances which are similar to those caused by long-haul missions involving time zone displacements.

1.1 Principles of the Circadian System

To understand better the underlying mechanisms producing disturbances in the circadian system, a brief description of the physical and biological determinants involved is given in the following sections.

1.1.1 The Environmental Timing System

One of the main factors involved in desynchronization is the environmental timing system which is based on the periodic variation of light and darkness. Due to earth rotation, daylight travels within 4 minutes from one meridian to the next, thus covering 15 meridians in one hour (Figure 1). The globe is devided into 24 time zones each of which corresponds to 15 meridians. When air operations are performed along latitudes, the time of day changes: After eastbound flights the day shortens, i. e. the clock must be set ahead for as many hours as time zones have been crossed; after westbound flights, in contrast, the clock has to be set back, since the day is extended. Flying eastward is associated with an "advance shift", going westward leads to a "delay shift" in the environmental timing system.

The alteration of light and darkness is the most consistent oscillation resulting from the passage of day and night. It follows a very different course in different parts of the globe, from the equator regions with a constant L(12):D(12) with little annual variation to the poles, where conditions are always LL or DD and the annual cycle of climatic variation is dominant. The amplitude of the 24-hour periodicity of light is maximal in equatorial and minimal in polar regions. In contrast, the amplitude of the 365-day periodicity of light is maximal in polar and minimal in equatorial regions, thus resulting in an almost constant 24-hour photoperiod in the equatorial regions, whereas a seasonal variation of sunrise and sunset hours is found in the other regions.
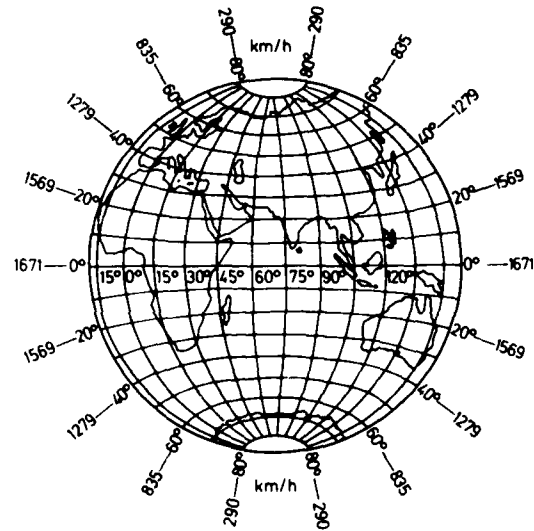

Figure 1: Globe with meridian intervals equivalent to one hour time difference or one time zone. Numbers beside latitude degrees indicate speed of daylight proceeding around the world.
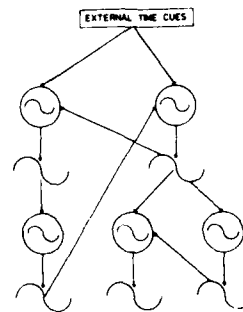

Figure 2: Non-hierarchical multi-oscillator model.

1.1.2 The Biological Timing System

The temporal structure of the environment in 24-hour periods corresponds to the periodic oscillation of physiological functions and behaviour which has been defined as the circadian rhythm. Often different rhythmic functions exhibit diverse curves with respect to the temporal positions of minima and maxima as well as to the magnitude of their amplitudes. Under constant conditions, i.e. during isolation from the environmental timing system, biological rhythms oscillate with spontaneous period lengths deviating from 24 hours (14, 27). At the same time different functional systems, such as body temperature and activity, may fluctuate with divergent frequencies, a phenomenon which has been labled "internal desynchronization". Persistence of rhythms under constant conditions and the phenomenon of internal desynchronization suggest the hypothesis that biological circadian rhythms are endogenous in origin, selfsustained and controlled by more than one "internal clock" (29, 340). Several models have been developed to describe the circadian timing system (14, 338, 340) of which the non-hierarchical multi-oscillatory model (221) best explains the presently known facts (Figure 2).

1.1.3. Interrelationships

The fact that under normal conditions biological rhythms concordantly show periods corresponding exactly with the length of one day, has been explained with the influence of environmental synchronizers or Zeitgebers. For plants and animals these are in particular the oscillations of light and temperature directly related to earth rotation. For man much evidence was gained that knowledge of the clock-hour and daytime-related social activities (23), such as meal timing (100, 102, 115, 134, 258), work and rest scheduling, and particularly sleep-begin and sleep-end (318) appear to be of greater influence as temporal reference than the natural light-dark cycle. In addition, electromagnetic fields in the 10 Hz range may act as synchronizers in the living organism (336).

It is the inability of the endogenous rhythms to adapt to a sudden shift of external synchronizers which causes a transistory desynchronization or dysrhythmia of body and environment.

1.2 Disturbances of the Circadian System

Disturbances of the circadian rhythm become manifest by changes in one, several or all of the parameters defining its regular oscillation, i.e. cycle length, phase, amplitude, level and shape of curve. Basicly, they are induced through modulations of the interrelationship between the internal and external timing systems. These modulations are the direct consequences of alterations in the rhythm characteristics of the environment, be it a phase shift or the deprivation of Zeitgebers, which may again be total or partial, occurring naturally or being manipulated artificially. They also result, when the biological system is shifted in relation to a stable environment, thus also disrupting the habitual synchrony between both systems, as it happens, for instance, in shiftworkers switching from day- to nightwork. In the following two sections a brief description is given of disrhythmic disturbances most frequently observed after experimental and "natural" (i.e. non-manipulated) induction.

1.2.1 Experimental Manipulations

Probably the most extensive body of data with significance for the exploration of the human circadian system was obtained from studies in deep caves, underground bunkers and isolation chambers (34, 66, 94, 110, 214, 215, 285). The advantages of these facilities are evident: They allow an almost perfect isolation of an individual from natural time cues normally entraining his circadian rhythm to a period of 24 hours. Furthermore, they present the possibility to substitute the habitual timing system by one or several artificial Zeitgebers which then can be easily manipulated, thus providing a variety of well-controlled experimental conditions. The most prominent form of manipulation has been the substitution of all external periodic inputs through constant light or constant darkness. The response of the human circadian system to such a constant environment is the well-known free-running state which is characterized by the persistence of the oscillation, but with a different cycle length, most subjects showing a spontaneous period close to 25 hours (66, 215, 216, 338, 342). It is interesting that out of more than 150 subjects with presumably free-running rhythms, only two subjects showed periods shorter than 24 hours (342).

In the free-running state all measured variables usually oscillate synchronously, i.e. different rhythms are internally synchronized (18, 125, 342). Some of the subjects, however, show internal desynchronization (different variables oscillate with different cycle lengths). Most frequently in these cases, rhythms of rectal temperature hold a period close to 25 hours, whereas activity rhythms alter their periods considerably, demonstrating cycle lengths in the range between 30 and 40 hours (342). Long-term cave experiments probably were the first where the existence of even longer activity periods were demonstrated, amounting to 48-50 hours (285); because they comprise two circadian cycles they have been labeled "bi-circadian" or, more appropriately, "circa-bi-dian" (342). Some discussion has been raised as to whether the phenomenon could be utilized in the military field. A sequence of about 36 hours of sustained activity and of about 12 hours sleep may have indeed strategic advantages for certain military operations. However, only some individuals have the capacity to free-run with a circa-bi-dian activity rhythm. Additionally, upon returning to the natural 24-hour timing system these individuals rapidly convert their activity cycle to "normal". Thus, it seems rather difficult to achieve such an extension of the cycle length in the habitual environment, not to mention potential consequences upon performance and health.

A further kind of manipulation was performed by adding specified external stimuli. These, of course, were easier introduced in a bunker or isolation unit than in underground caves. Summarizing the results, obtained from controlled environment facilities with constant conditions, it can be stated that several stimuli have been identified which have the potential to modify autonomous circadian rhythms of man. These are as different as light (intensity), temperature, psychical stress, and social contacts (342). When applied in a constant manner during the free-running state, they all lengthen the autonomous period, with the exeption of electromagnetic fields which were shown to shorten it.

By alteration of the external stimuli in a cyclic manner, artificial Zeitgebers were installed, allowing investigations of various problems with practical implications, such as strength and capacity of different time cues, range of periods to which the circadian system can be synchronized, and effects of abrupt phase shifts (34, 110, 214, 331). From the results so far obtained it can be concluded that human circadian rhythms can be synchronized by artificial Zeitgebers, but with periods varying only within a limited range of entrainment (18). There are different kinds of external periodicities generating different strength of synchronization: For man, physical Zeitgebers are less

effective than those including a component of social contact. The ranges of entrainment of the physical synchronizers are also smaller than those of the social time cues (342). Sudden phase shifts of the controlling Zeitgeber usually induce corresponding phase shifts of the biological rhythms. However, the circadian system does not shift immediately, but instead shows a certain "inertia" in achieving the new rhythm. The duration of this transient state is different in the rhythms of different variables (18, 66, 214, 216).

Somewhat less rigorous attempts to manipulate the external timing system have been undertaken by experiments with individuals remaining under normal environmental periodicity, but subjected to changes of one or several non-environmental timegivers. Shifting meal- or sleep-times, as well as depriving subjects of sleep or social contacts, are typical examples of this kind of experimental manipulation. Extensive data were obtained from bedrest studies which, although originally designed to investigate the effects of simulated weightlessness, were also considered as experiments manipulating the circadian system (222, 313, 347, 348, 349, 350, 351). Due to the steady state in supine posture, the subjects were deprived of at least two factors supposed to have time cue functions, i.e. the activity cycle and the periodic change in body posture (349,350). In fact, evidence was provided for rhythm disturbances under these circumstances: different variables phase-shifted, wheras other systems appeared to be unaffected. Exercise performed daily in the supine position did not influence these phase shifts. It was therefore suggested that change of posture would exert more synchronizing strength than activity (349).

1.2.2 Natural Interferences

The term "natural" in this section is used in the sense of not being manipulated or occurring without the application of artificial Zeitgebers. The main areas under this aspect are the interferences of shiftwork and transmeridian flights with the circadian system. Both have in common a desynchronization of the biological and environmental timing systems, but they also show a distinct difference. All synchronizing inputs are phase-shifted after transmeridian flights; however, the external timing system remains unchanged in shift work, but due to the inherent changes in work-rest cycles the biological system is also out of phase with the environment. Shiftwork results in a state of almost permanently conflicting Zeitgebers, and therefore, re-entrainment during shiftwork is accomplished slower and less completely than after time-zone flights. Since these aspects are directly related to aerospace operations, further details will be discussed later as they become relevant.

Though of minor practical implication, living in the Arctic (or Antarctic) should be also mentioned as a source of natural interferences (66, 110, 156, 202, 288). The Arctic and Subarctic provide an environment where constant conditions prevail for parts of the year and where individuals frequently are separated from time cues associated with the normal routine of human society. This constellation gave rise to investigations of the circadian system in individuals permanently living in this area, as well as in inhabitants of temperate zones living there only temporarily. Earlier findings in Eskimos and Indians suggested poorly developed rhythmicity, pronounced irregularities, diminished amplitudes and other disturbances (66, 202, 288). Vanishing rhythms (66, 202) as well as symptoms of the free-running state (156) were observed in visiting white individuals. In contrast, more recent findings in Eskimo children indicate well developed and maintained circadian rhythms, except during summer time, when they became disorganized (202). Newer studies in adult natives have also failed to show significant deviations from "normal" rhythmicity (156, 288). The differences to the earlier observations have been explained with the dramatic changes in life-style caused by a rapid recent urbanization. As a consequence, the regular daily routines of the social environment may override the influences of the natural environment. However, in the summer, when children are not going to school and continuous daylight enables activity at any time during the 24-hour cycle, the irregular life-style would dominate and thus induce the observed disturbances of the circadian rhythm (202).

Finally, blindness has also been considered as a source of interferences with biological timing (25, 212, 241). Despite some earlier findings to the contrary the present state of knowledge allows the conclusion that the majority of totally blind subjects do have circadian rhythms. However, under normal conditions, the rhythm amplitude may be smaller and the phase seems more variable, as compared with sighted subjects. Free-running rhythms have also been reported (212). These observations support the hypothesis that - at least in the long run - the light-dark cycle has some more controlling effects upon the human circadian system than previous bunker experiments with artificial light-dark cycles and otherwise constant conditions may suggest (25).

2. CIRCADIAN RHYTHMS OF PERFORMANCE AND RESISTANCE

Man's functional capacity during mental and physical activity is the result of multiple endogenous and exogenous determinants, one of them being their daytime-related oscillation. It has been documented that circadian rhythmicity as a basic principle of biological systems does not only control physiological functioning at rest but also the response of the body during loading, thus involving performance and efficiency.

Already more than 20 years ago, a certain section of the circadian cycle had been characterized as the "minimum of readiness for efficiency" (197) and as the "hours of diminished resistance" (109). In animals, it was shown that even death and survival in an hazardous environment could be made experimentally a function of circadian system phase (133). In 1967, we first presented data demonstrating for man rhythms in indices of physical fitness and operational stress resistance (182). Since then, the applied aspect of variations and oscillations of human performance efficiency has been subject of extensive research and analysis (33, 56, 58, 131, 146, 173, 181). It is the purpose of this chapter to summarize and update information on this topic and discuss its significance for human operations.

2.1 Mental Performance Efficiency

In the beginning of research irregular findings with respect to the shape of the 24 hours performance curve - often due to poor methodology and inappropriate techniques - caused scepticism as to the genuineness and significance of the relation between time of day and mental performance. Then, in well-controlled studies, using relatively short and simple tests Kleitman (186) established an association of diurnal variations of human performance with body temperature which appeared so close that temperature for a while was used as an indirect measure of performance efficiency in studies on circadian rhythm and shift work. However, in the last decade it became increasingly clear that this relationship does not hold for mental performance in general, but different tasks show different circadian variations in terms of "shape", or better phase and amplitude of rhythm, and that - where such a relationship originally exists - it may dissociate as consequence of changes in the temporal organization of the environment or in response to shift work. Recently, again it has been shown that there is no direct causal effect between body temperature and performance level (158).

2.1.1 "Normal" Rhythms

It is obvious from Figure 3 that body temperature as well the scores of performance tests, with some variations, rise during the day to a peak, or kind of a plateau, between 1200 and 2100 hours and decline to a minimum which usually occurs between 0300 hours and 0600 hours. This is true for flying an F-104 simulator (167, 168), for cancelling symbols or adding two-digit numbers (184), and for the highly paced psychomotor performance on the "kugeltest" (183). Similar curves have been described for many other tasks (151), like latency and detections in a vigilance test, for card sorting, and for the scores in a choice reaction test, to mention only a few.

Figure 3: Circadian rhythms of behaviour 1 and physiologic functioning in percent of the 24 hour mean, body temperature in $^{\circ}$C. (F-values for within day variation; for further explanation, see figure 5.)

The range of oscillation, i.e. the difference between the maximum and minimum score within a circadian cycle, for mental performance measured under standarized laboratory conditions, varies (for the group averages) between 10 % and 30 % of the 24-hour mean (7, 24, 38, 57, 148, 151, 168, 184, 186, 204, 273).

2.1.2 Factors Controlling or Modifying Performance Rhythms

Some factors of an internal, operational or environmental character have been identified to control or modify mental performance rhythms of which the following have proved to be the most significant: sleep, task variables, personality, motivation, sustained operation, physical exertion, and changes in the relationship between the temporal organization of the body and the environment.

Sleep. If subjects are not aroused from sleep for testing but stay awake during the night, the phase of rhythm drifts towards later hours. The range of oscillation, in comparison with controls, during the first night awake is smaller but becomes increasingly larger as sleep deprivation continues; at the same time the 24-hour mean of performance decreases (7, 85). (For sleep loss effects see also "Sustained Operation" in this section and "Sleep-Wake Cycle", section 3.1.4).

Task variables. Blake (38) seems to be the first who presented evidence for the assumption, that memory - with respect to the phase of the circadian curve - may be a "notable exception" (151) since the peak score in a memory task inversely to body temperature, occured in the morning and scores dropped off steadily during the day (59), thus resembling more the variation of some stress-related hormones like 17-OHCS, or evenmore, adrenaline (Figure 3).
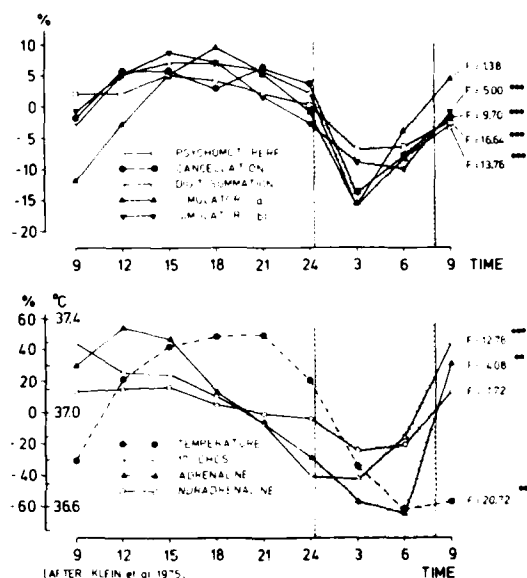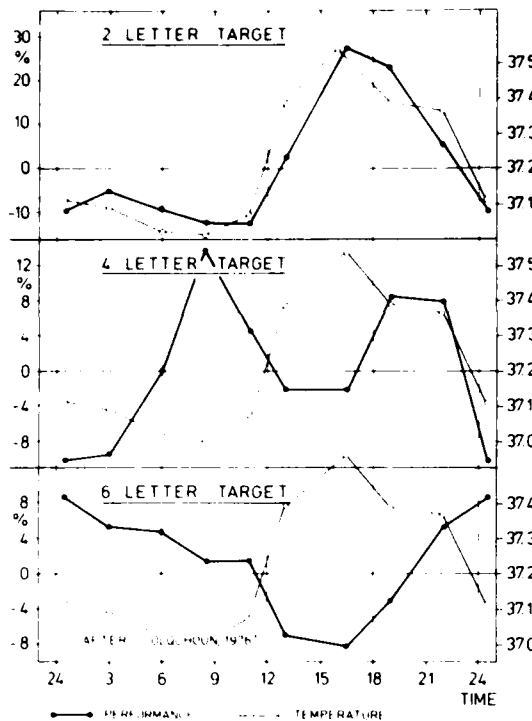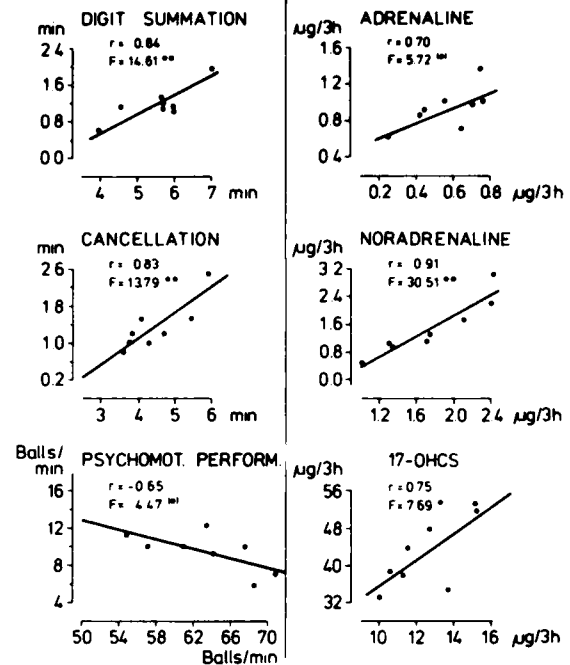
Figure 4: Rhythm of performance at three levels of memory load and body temperature rhythm.

Figure 5: Correlation of circadian range of oscillation and 24-h mean for behavioural and physiologic rhythms. (F-ratio for significance of correlation; $(*)p \leq 0.1$; $*p \leq 0.05$; $**p \leq 0.01$; $***p \leq 0.001$).

Later, some authors have established that " immediate memory" peaks in the morning, deteriorates through the early afternoon (1400 to 1500 hours) and rises again to the evening (122, 219). Others found the correlation between performance rhythm and temperature rhythm to change from a significant positive value to a significant negative one as the memory load of the task was increased (87, 89). An example for this relationship is shown in Figure 4.

Memory functions not only exhibit peculiarities in phase but also lower ranges of oscillation (219). This is of particular interest in view of the negative correlation between amplitude and speed of adjustment of physiologic rhythms to shift work (262) and to shifts of artificial "Zeitgebers" (341). In fact, it was demonstrated (219) that a higher memory load task adapted faster to night work conditions simulated in a laboratory and to time shift following transmeridian flight.

Personality. Several investigators have described an influence of habit and personality factors on behavioural periodicity (39, 40, 186, 233, 236, 238). The results may be summarized as follows: In extraverts as compared with introverts (and similar in evening types against morning types) maximum and minimum of performance efficiency came later within the circadian cycle and the spontaneous period in the free running state is longer. If extraverts and introverts are tested in one group, circadian rhythms are synchronized and the differences are masked (60). In addition, "neuroticism", as compared to "stability", seems to increase the rate of internal desynchronization in isolation from time cues (339), as well as to hasten phase adjustment during shift from day to night work or after transmeridian flight (61).

Motivation. In their extensive studies on various demanding work-rest schedules, Alluisi, Chiles and their collaborators (7, 8, 51) demonstrated that motivation may reduce circadian variation of mental performance through "extra effort". They concluded that together with motivation, workload, that is the stress imposed by the task, had determined the extent of cycling in so far, that the range of oscillation was low if motivation was good or the task simple; or, on the other hand, periodicity was pronounced when motivation was low or the task very complex. In context with the load of the task, the reduction of the circadian amplitude during practicing (8, 92) and its increase during sleep deprivation (51, 85) can be understood as effects of relative workload alterations.

Changes in the range of oscillation, as just described, must alter the 24-hour mean. Since, in general, the trough of the circadian cycle is more susceptible to influences of the kind mentioned above, the 24-hour mean will be inversely related to the range of oscillation. Indeed, we have been able to demonstrate such an inverse relationship for the performance level of pilots in a flight simulator (168), as well as for some other mental performance tasks (181) for which the regression lines and correlation coefficients (together with those for some "stress-related" hormones) are shown in Figure 5. Since practicing on the task was finished and each subject had reached his optimal level of performance, the interpretation of this phenomenon leaves open two possibilities: the reason could be seen in different levels of motivation; but also a particular "disposition" manifesting itself as a higher susceptibility to the performance depressing influence during the night could have been the cause for the higher range of oscillation in individuals with the lower performance level.
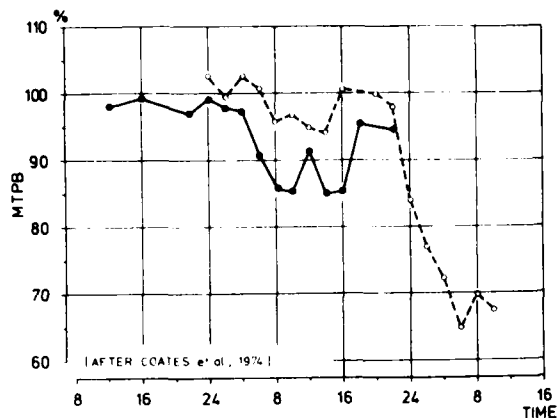
Figure 6: Sustained operation and circadian performance rhythm: Dependence on starting time.
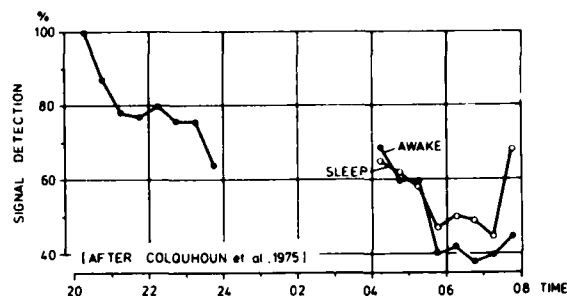
Figure 7: Effect of sleep injection into a period of sustained operation (relative changes in auditory vigilance).

Sustained-operation. Of particular interest are the interaction of circadian cycling of performance efficiency with the behavioural effects of sustained activity or sleep deprivation. As was shown earlier (7, 55), and recently was demonstrated again (9), the extent of performance degradation caused by sustained operation depends on the actual phase of the circadian cycle it coincides with (Figure 6). When an extended duty period began at noon, the performance degradation (commencing in this group of subjects after about 16 hours of operational activity), amounted to −10 % to −15 %, while, when the same operation began at midnight, the maximum decrement of performance amounted to −35 %. In the first case the effect of fatigue was obviously compensated in part by the increasing level of arousal during the day; in the latter case operational fatigue evidently added to the depression of alterness naturally occurring at night. It is of interest that Hartman (130) came to similar results measuring ILS-approach performance in simulated transport flights starting at different times of the day: It was only if the time of the mission upon reaching the low phase of circadian periodicity extended 16-18 hours that a considerable performance degradation was observed . It is clear that in managing human operations one should prevent whenever possible a coincidence of the final section of a long-haul activity period with the nocturnal low of behavioural rhythms.

Colquhoun (62) has proven the benefit of the injection of a sleep section into a period of sustained operation (Figure 7): Two operational periods which took place between 2000 and 2400 hours and 0400 and 0800 hours were separated in one case by a (non-operational) wake period, in the other case by a sleep section. The difference between the two conditions, obviously caused by sleep, was (a) a reduction in performance degradation at the circadian trough of about 10 %, and (b) a "normal" increase of performance in the early morning hours, leading to a difference of more than 20 % in performance efficiency at 0800 nours. The significance for crew management, for instance, in reinforced crew operation is once more obvious.
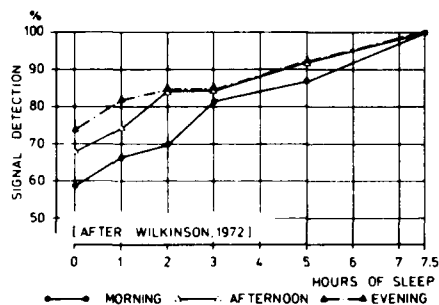
Figure 8: Sleep deprivation effect on performance depending on the time of day.
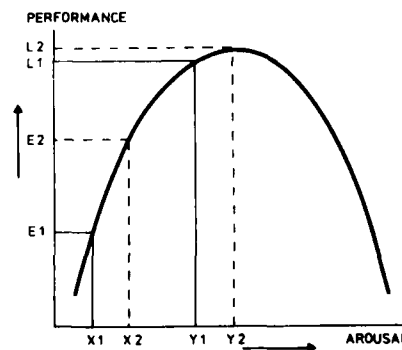
Figure 9: Postulated relationship between level of arousal and performance efficiency.

As Wilkinson (343) has shown, the effect of sleep reduction is also dependent on the time of day (Figure 8): if sleep was reduced by only 2.5 hours in each of two consecutive nights, for instance, impairment of performance on a vigilance task was 13 % in the morning, but only 8 % in the afternoon and evening of the following day; the daytime dependent difference in performance degradation was the more pronounced the more the sleep was reduced.

Physical exertion. Physical activity may influence mental performance through changes in the level of arousal: Light to moderate physical work increases it, heavy work has the opposite effect. It has recently been demonstrated (357) that this effect depends on time of day as well as on task speciality. A physical load of about 30 % of the maximum aerobic work capacity improved the scores of a visual-motor coordination test in the morning and afternoon but not in the late evening and early night. However, the same exercise regimen impaired performance in a memory test at all hours of the day, in comparison with (non-exercise) control conditions. The results were explained with differences in the relative load of physical exertion: the load seemed to be beyond the optimum of arousal for memory functions in general, and for psychomotor coordination performance at the specific time of the day. (The relativity of physical exercise load in dependence on the time of day is further discussed in section 3.1.3, "Physical Performance".)

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2.1.3 The Arousal Theory

The modification of behavioural rhythm can be explained quite well by the "inverted-U" shaped relation between arousal and mental efficiency (Figure 9). Colquhoun (57) has pointed to the fact that a given fluctuation in arousal will result in a more pronounced variation in performance efficiency when the overall level of arousal is low than when it is relatively high or even near the optimal point. Accordingly, increase of arousal by task-complexity and/or by higher motivation will decrease the circadian range of oscillation of performance rhythms while a reduction in arousal through loss of sleep, lack of interest, etc. will have the opposite effect. Arousal beyond the optimum (hyperarousal), for instance through extreme motivation and/or task overload, increasingly enhances circadian oscillation the more arousal is shifting towards the (opposite) end of the curve.

2.1.4 Field Studies

Behavioural rhythms evaluted in field studies like work output, frequency of failures and number of errors (37, 44, 127, 149, 255), in principle follow the circadian characteristics observed in laboratory research on human performance efficiency; there are, however, at least two differences worth mentioning (Figure 10): (a) the range of oscillation is much higher and often comes up to 100 % of the 24-hour mean, or more, and (b) a second (minor) peak of performance degradation, the post-lunch dip", is often found shortly after noon. The pronounced circadian oscillation is usually explained with the fatigue caused by continuous duty and its interaction with the circadian depression at night. Other reasons could well be lack of interest and/or motivation, or, in comparison with the laboratory, unfavourable environmental conditions, for instance with respect to noise or temperature levels.

The "post-lunch" phenomenon is not necessarily related to the meal usually taken at that time of the day (57). It has been attributed also to the duration of the preceding duty period; however, this does not explain, why the performance increases again towards later hours, even during continuous activity. It has been speculated (149) that a 12-hour rhythm of "susceptibility" or "readiness" for mental performance might be superimposed on the basic 24-hour cycle and could be responsible for the accumulation of performance failures in the early afternoon. In this context it is of interest to know that the post-lunch depression of performance, contrary to the responses at night, is not accompanied by a decrease in body temperature.

Behavioural circadian rhythmycity may favour an accumulation of nocturnal mishaps. As Harris (127) demonstrated recently, this is the case in single-vehicle road accidents, in particular if "dozing" of drivers was reported (Figure 10). In analyzing the situation leading to accidents of that kind for which "coming off the road" is typical, he emphasized that "the truck driving task is likely to be one of the most demanding vigilance tasks "where the driver must maintain a "continual vigil", "keep his truck positioned in a traffic lane", "constantly monitor the lane", and "a momentary lapse of attention could have and often has had disasterous consequences". Harris, in the same material confirmed the effect of fatigue: fewer accidents than expected occurred early in trips and more than expected during second half of trips; the "crossover" from less than expected to more than expected occurred between the fourth or fifth hour of driving time. Thus, there was evidence again for an interaction or a superimposition of the natural decrease of arousal through circadian rhythmicity as well as the operationally induced fatigue effect causing a depression of arousal.

Circadian influence could hardly be demonstrated for accidents in which a vehicle crashed into the rear end of another one (127): the percentage followed rather closely the "exposure" data, i.e. the relative number of trucks on the highway by time of day, though accident rates are slightly higher than expected by exposure between midnight and 0800 hours (Figure 11).
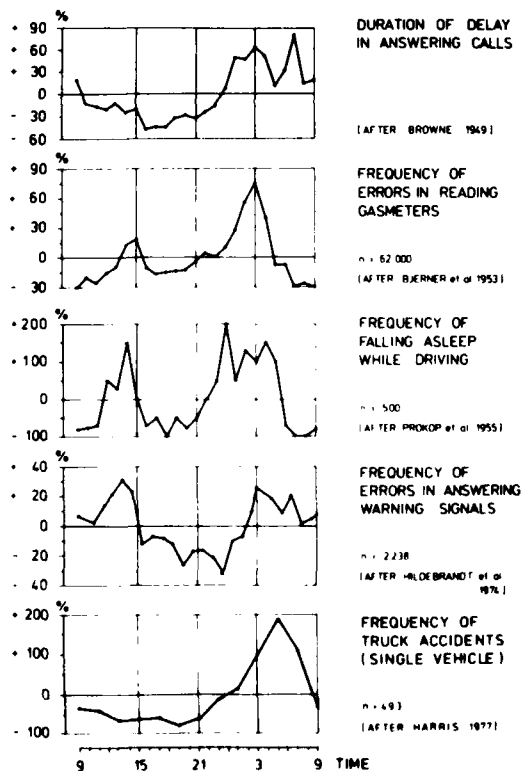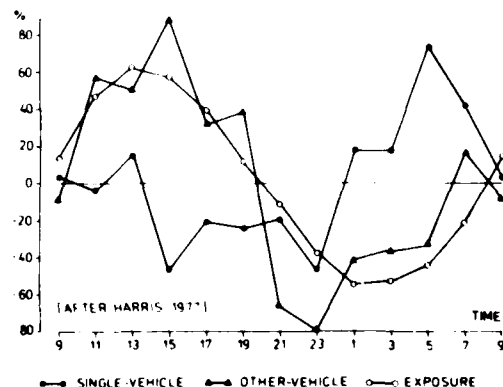

Figure 10:Behavioural circadian rhythmicity in field studies.

Figure 11:Percentage of accidents by time of day and type of accident. (Exposure: Normalized percentage of trucks on the highway for a random sample of interstate drivers).

2.2 Physical Performance

It seems that we were the first to experimentally repeat standardized physical fitness tests around the clock. We found cardiovascular responses at mild (166) and medium (182) exercise intensities to be subject to periodic variations: heart rates and blood pressure were lowest between 0300 - 0600 hours and highest at 1200 - 1800 hours. If exercise heart rates were used in the conventional manner to predict maximal oxygen uptake ($\dot{V}O_2$max) by means of nomograms we came to the result that aerobic work capacity was higher at night than during the day. This finding was unexpected but inevitable since the prediction of $\dot{V}O_2$max from exercise heart rates rests on the assumption of an inverse proportional relationship between the two parameters according to which lower heart rates at a given work intensity indicate a higher aerobic work capacity. This principle has been proven to be valid in comparison of individuals with different work capacities, i.e. trained and untrained subjects, and, intraindividually, if muscular exercise capacity, in parallel to $\dot{V}O_2$max, increased in the course of an athletic training. However, we have always expressed doubts (166, 182, 183) that this principle was applicable to intraindividual differences in exercise heart rate response due to circadian cycling, and have pointed to the fact that older and starving individuals have lower heart rates without having higher work capacities, at the same time.

In recent years, circadian differences of cardiovascular responses - mainly heart rates - were confirmed for various tests (Leistungspulsindex, Physical Work Capacity 170, ect.) at different submaximal exercise levels (68, 314, 315). At the same time, it became obvious that oxygen consumption oscillates with the time of day only at rest and at mild exercise loads; no day-time dependent $\dot{V}O_2$-differences were found at submaximal work intensities (68, 315). In 1971, the status of knowledge induced the statement (145): "The maximum of physical efficiency is not found during the day but around 3 a.m. at night".

Up to that time however, direct measurements of aerobic capacity at different day times were still lacking. Then, between 1973 - 1975, five papers from different groups of investigators were published on this topic (70, 155, 316, 320, 356). Additionally, it was demonstrated that actual athletic performance was significantly better between 1600 and 1800 hours as compared with 0700 - 0800 hours (67, 266); the same was shown for exercise training effects (31).

In one of the laboratory studies (70) maximal aerobic work capacities compared at 0800 and 1800 hours were not different. For the other experiments, with respect to day-night differences, the results can be summarized as follows:

-Maximal oxygen uptake was not different (316), was 3.9 % higher at night (320), was 5.7 % (155) and 5.2 % (356), respectively, higher around noon, all differences being statistically significant.
- Maximal work output was higher by 1.1 % (320) and by 12.4 % (155), respectively, during the day as compared with the night, both differences were significant.
- Maximal heart rate was not significantly different in most studies (316, 320, 356); in one case (155) it was 3.4 % higher during the day.

Figure 12: Linear regression of oxygen uptake on workload, as evaluated at night (dashed line) and during day (solid line).

Figure 13: Intraindividual day-night differences in heart rate, respiration and oxygen uptake under different workloads (o-o day, +-+ night).

For the evaluation of circadian differences of physical work capacity it is of particular interest that in the two studies, where it was indicated, work output was higher during the day than at night. From the figures given in these papers we have computed for the circadian extremes of work output the ratio of oxygen consumption to work output and found that "efficiency" was 5 % lower at 0400 hours as compared with 1600 hours (320) and was 11 % lower at 0300 hours than at 0700 hours (155). For rest and mild exercise levels in principle data suggest the opposite: a higher efficiency at night, since oxygen consumption under these conditions shows a clear cut circadian rhythm with a maximum during the day and a minimum at night. The differences of "efficiency" for physical labour performed either at 1600 or at 0400 hours are best demonstrated through the linear regression of oxygen consumption on workload (Figure 12) : At 11 mkp/s, e.g. oxygen consumption is 3.6 % higher during the day, in the medium range of workload (at about 14 mkp/s - 16 mkp/s) there is no day-night difference, and at 27 mkp/s the oxygen consumption is 4.6 % higher during the night. These figures are taken from an investigation performed in our laboratory on 16 untrained students (320); since "workload" is also a relative term, the absolute values of this correlation may depend on properties of the subjects, like status of training, age, etc. Typical intraindividual differences in the physiological responses to an increasing workload observed in one subject in a day-and night-test are

presented in Figure 13.

In the context of the subject discussed here, Östberg and Svensson (236) recently pointed to the fact that older individuals have lower heart rates but perceive workload higher than younger ones; they compared this with day and night responses to physical exercise and concluded that the "functional age " increases during the night. They took this phenomenon as an indication of reduced efficiency of man for physical work at night.

As for mental efficiency, there is also for physical performance an interaction between the effects of sustained operation and time of day (355): If subjects pedaled on an ergometer continuously for an 8 hours shift with a workload of 30 % of $\dot{V}O_2max$, there was no significant difference in oxygen uptake 30 min after commencement of shift at 0830 hours, 1630 hours or 0030 hours; however at the end of shift, oxygen uptake was higher than at the beginning, for 2.7 % at 1600 hours, for 11.5 % at midnight and for 4.9 % at 0800 hours, thus efficiency for a medium workload was lowest at midnight.

The present knowledge on circadian variations of physiological responses to physical work is best summarized and interpreted as follows (Figure 14):

- Heart rates at rest (in parallel to other cardiovascular and metabolic variables) show a circadian oscillation with a difference of about 8 - 12 % between the diurnal maximum and nocturnal minimum. This difference becomes smaller with increasing workload and approaches zero at maximum effort. The day-night difference in heart rate is not identical with the trained-untrained difference (Figure 15); it is therefore not possible to predict aerobic work capacity correctly from heart rate level at submaximal exercise with nomograms set up in sports medicine.
- Similar as with heart rate, oxygen uptake at night as compared to the day, is lower at rest and at mild exercise; however, there is no circadian difference anymore at medium workload, and at submaximal and maximal work output nocturnal oxygen consumption seems to be higher (Figure 14). This is also different from what was observed as typical for trained and untrained subjects (Figure 15).
- In accordance with the nocturnal low of "readiness for efficiency" spontaneous maximal work output or maximal oxygen consumption seems to be somewhat lower at night; however, depending likely on motivation, it is possible to reach the same level of maximal oxygen uptake at night as during the day through "extra effort".
- "Efficiency", that is oxygen consumption in relation to work output, at maximum efforts, is significantly lower at night, consequently equivalent work outputs as during the day can only be produced with higher "physiological cost"; this is in the order of magnitude of 5 - 10 % extra oxygen uptake. The lower efficieny could explain the feeling of temporary night workers that nocturnal labour is relatively more stressful.

2.3 Susceptibility and Resistance

Susceptibility to noxious stimuli. Rhythms of susceptibility or resistance have been investigated mostly in animals. Many authors were able to demonstrate circadian cycling already more than 15 years ago for a variety of noxious stimuli like ethanol (135), anaesthetics (71, 240), bacterial endotoxine (109), ouabain (113), and for convulsions experimentally induced through audogenic (125) and chemical (72) stimulation or electroshock (354). Also, a circadian sensitivity of mice and rats to irradiation has been shown (248), with a possible relation to periodic hemopoetic cell responses (136, 249, 312) and to the circadian amplitude of hypophyseoadrenal activity (74).

Figure 14: Circadian rhythms of heart rate and oxygen uptake during hypokinesis, rest, and physical exercise of different loads.
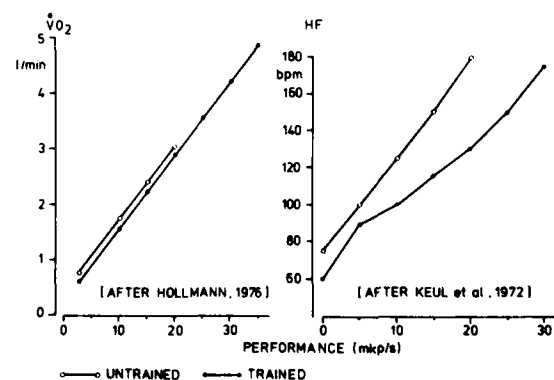
Figure 15: Dependence of heart rate and oxygen uptake on workload in untrained and trained subjects.

Though phase differences were quite obvious among drug susceptibility rhythms, it seemed that the lowest resistance for a standard dose in the lethal range frequently was more easily obtained in the natural activity period, while during the same period the largest dose was needed to produce the specific therapeutic drug effect (e.g. anaesthesia with an anaesthetic); thus, the therapeutic index seems to be the lowest during the activity, and the highest during the resting period of rodents. Meanwhile circadian periodicities in toxicology and pharmacology have been intensively explored and implications are being introduced into clinical practice for man (111, 220, 261, 299).
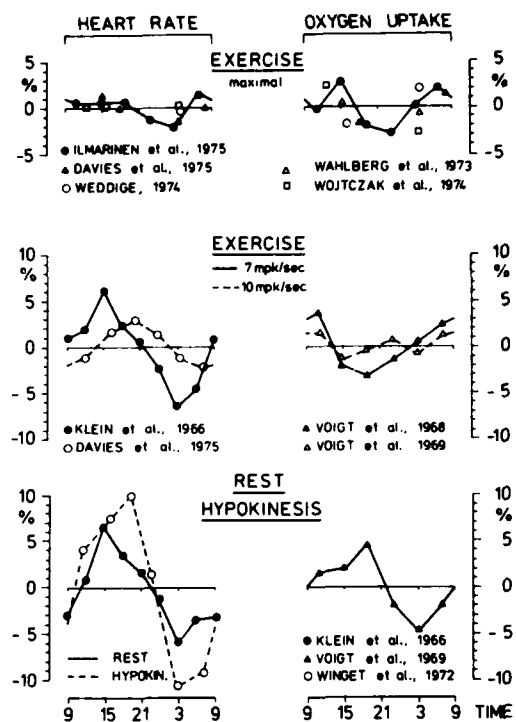
Decompression sickness. More than the therapy-oriented susceptibility rhythms, the periodic oscillations of resistance to environmental stressors seem to be of significcance for aerospace operations; and here, indeed, exist some observations on man. Already in 1944, a dependency on the time of day of the frequency of symptoms of decompression sickness in man during altitude chamber rides has been observed (54): Between 0900 and 1200 hours 41 % out of approximately 2 000 subjects experienced signs of decompression sickness while between 1300 and 1600 hours only 29 % out of a similar number of subjects suffered from the same symptoms. Differences in peripheral blood flow which is higher in the afternoon (162) could be the reason.

Altitude/hypoxia tolerance. We evaluated human tolerance to decreased PO_2 (hypoxia), measuring the time of useful consciousness (TUC) in healthy male subjects in an altitude chamber at a barometric pressure of 287 mm Hg or 7.500 m (182): With a TUC of 6.3 min at 0300 hours, altitude tolerance was about 34 % better at night than at 1500 hours (TUC = 4.7 min) and 1800 hours (TUC = 4.8 min) during the day (Figure 16). In mice (300) mortality during exposure to a hypoxic gas mixture of 5.5 % oxygen in nitrogen was significantly higher (66.7 %) in the dark (activity period) than in the light span (36.1 %). Independently of the time of day, mortality was always higher when mice came from the dark (activity) before being exposed to hypoxic conditions (301), so that the circadian rest activity cycle seems to be one strong determinant of hypoxic resistance.

In man altitude tolerance is highly correlated in a negative way with the individual response of the adrenal cortex to an acute altitude exposure (322): Higher resting values and smaller responses of the 17-OHCS plasma level were found in relation to relatively better altitude tolerances in unadapted (170, 172, 322, 326, 329), as well as in altitude-adapted (160, 171) subjects. This is exactly the functional state of the adrenal cortex during the night in man with normal social habits: A higher level of 17-OHCS and a smaller response of the same hormone to a standardized stress or ACTH dose, so that the circadian periodicity in the activity and reactivity of the adrenal cortex in connection with the circadian rhythm of basic oxygen consumption could be the reason for the particular day-night fluctuations found in the altitude tolerance.

Oxygen toxicity. A circadian rhythm has also been established for susceptibility to oxygen toxicity seizures (152): In rats during exposure to hyperbaric oxygen the time preceding the first convulsion, was more than 100 % longer between 0700 and 1100 hours, i.e. during the early sleep phase than at the other times of the 24-hour cycle; it was speculated that the protective mechanism against cerebral oxygen toxicity effects might be seen either in a decrease in sympathetic tone due to a decrease in epinephrine, or in the circadian rhythm of the CNS level of serotonin which is high at the onset of sleep (332).

Orthostatic tolerance. Another physical factor for which circadian rhythmicity of tolerance has been demonstrated in man is orthostasis (Figure 16). Pulse pressure during tilt (182) as well as an "Index of Orthostatic Tolerance" (22) computed from heart rate and blood pressure responses to tilt were more favourable in the afternoon and evening than between 0300 and 0600 hours; waking up sleeping subjects between tests during the nocturnal period seemed to increase the differences. The reason was seen in the nightly trough of cardiac output and of venous pressure at the lower extremities which is accompanied by a peak of the extracellular fluid volume (22).

Figure 16: Circadian rhythm of susceptibility to stressors in man.

Acceleration tolerance. On the same line, we should see preliminary data obtained in our laboratory by Vogt (unpublished results), which indicate central light loss (CLL) during $+G_z$ centrifugation to occur at an acceleration level about 0.8 G higher in the early afternoon than at night (Figure 16). However, whether this finding reflects a "true" circadian rhythmicity of cardiovascular responses to a $+G_z$ stimulus is difficult to decide, at present, since the light-threshold itself shows a similar periodicity without centrifugation.

2.4 Synopsis

There can be not doubt that endogenous circadian rhythmicity is one determinant of mental performance, physical exercise capacity and the resistance to noxious hazards.

With the exception of altitude (hypoxic) tolerance - which peaks at night when tonic physiologic levels are set for sleep - performance efficiency is found to be best in man during the day. However, for mental performance there is a dependency on task specifity: Memory load tasks peak earlier than psychomotor or vigilance oriented elements of mental efficiency.

Amplitude of efficiency rhythms is smaller when subjects stay awake than when they are aroused from sleep. The same is true if an individual is more disposed, better trained and more highly motivated for a task. By motivation, mental as well as physical performance at night may be brought up to similar levels than those encountered during the day; this requires "extra effort" and higher physiological costs.

Fatigue, as consequence of sustained operation and sleep loss, intensifies circadian rhythmicity of mental efficiency. This seems to be one reason that in field studies the nocturnal maximum of human failures and errors is much more pronounced than in comparable laboratory research; differences in motivation and in interest for the task as well as unfavourable environmental conditions "at the work bench" might be other factors.

As observed in road traffic, a heavy continuous call on vigilance in an otherwise monotonous environment may give rise to a higher nocturnal accident rate by way of interaction of fatigue and the circadian variation of arousal.

Moderate exercise as well as injection of sleep sections into periods of sustained operation seem to be beneficial with respect to fatigue and circadian effects on arousal.

3. CIRCADIAN RHYTHMS IN TRANSMERIDIAN AIR OPERATIONS

When air operations involve geographical displacements along latitudes, they introduce rapid and often large time-zone changes with specific consequences for the human organism. Since typical, the resulting effects have been labeled "Desynchronosis" (297), "Transmeridian Dyschronism" (114), or simply "Jet Lag" or "Jet Lag Syndrome". This terminology can be deceiving, as it may suggest some kind of illness. There is, however, no evidence as yet that any serious illness is directly associated. Thus, purely descriptive terms, such as "Desynchronization" or "Dysrhythmia", may be more appropriate. On the other hand, there is no doubt that various symptoms of impaired well-being occur and distinct degradations in mental and physical performance are observed, even if only subjectively.

3.1 Post-Transmeridian Desynchronization

After transmeridian flights a certain percentage of individuals suffer impairment of well-being mainly manifested by vegetative functions which, like hunger, wakefulness and sleepiness, and defecation, are daytime dependent: Due to the persistence of biological rhythms, in relation to the environment, they appear at unusual and unconvenient hours. Independent of the presence of subjective symptoms, post-transmeridian desynchronization is objectively demonstrable in numerous psycho-physiological variables. Strughold (294) seems to be the first to publish a scientific paper on this subject.

3.1.1 Physiological Variables

Postflight desynchronization of human physiological rhythms has been described during the last 20 years in a series of investigations, mainly for body temperature, cardiovascular and metabolic variables, hormone and electrolyte excretion (50, 63, 64, 69, 73, 76, 79, 80, 86, 97, 99, 101, 104, 114, 115, 132, 137, 139, 140, 180, 184, 191, 193, 213, 256, 257, 278, 281, 283, 321, 330, 335).

From our own research on various groups of 8 young males, each transported on the North Atlantic route, example; of postflight rhythm changes are presented for 17-OHCS excretion (73, 321) in Figure 17, and for heart rate response to submaximal exercise on a bicycle ergometer (335) in Figure 18; they exhibit some features typical for desynchronization, though not all of them are necessarily specific and appear simultaneously:

- a displacement of the curve to the left after westbound transportation and to the right following eastbound flights (shift of rhythm into the normal position occurring gradually);
- an alteration in the range of oscillation (sometimes, resulting in disappearence of rhythm);
- a change in the 24-hour mean;
- lower functional values (than preflight) at certain times of day, higher values at other hours of the circadian cycle, the position of higher and lower postflight values depending on flight direction.

Through continuous pre-, in-, and postflight measurements (178) it is possible to demonstrate some additional modifications of circadian rhythm (Figure 19):

- speed differences in shift of maximum and minium (278, 321);
- alterations of the "form-factor", the ratio of the length of the inclining section to the length of the declining section of the circadian curve (337).

The changes are dependent on flight direction: Data from another study (Figure 20) demonstrate earlier and farther shift of the maximum as compared with the minimum after westbound transportation, whereas the opposite is true for eastbound flights.

Continuous measurements show also that circadian rhythm of body temperature, immediately after an 8-hour flight across 6 time zones, is still entrained to preflight environmental periodicities, and shift commences not before onset of the first sleep period in the new time zone (Figure 19). This finding suggests that faster means of long-range transportation, like supersonic flight, with return on the same day, would avoid shifts of biological rhythms; otherwise the degree of "jet lag" will not change,
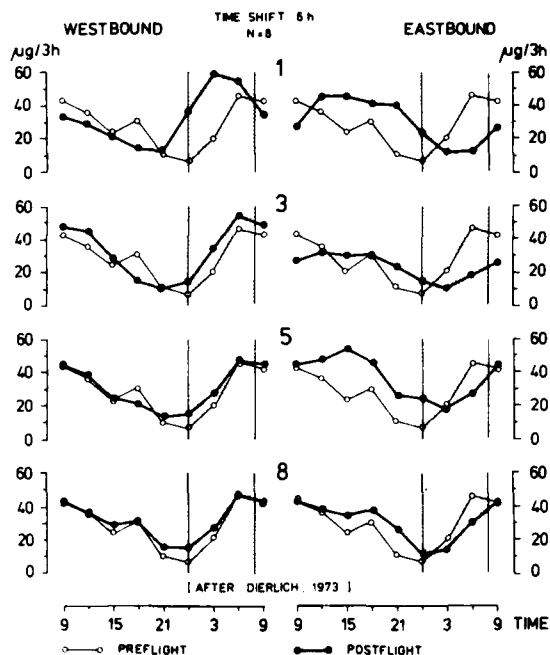
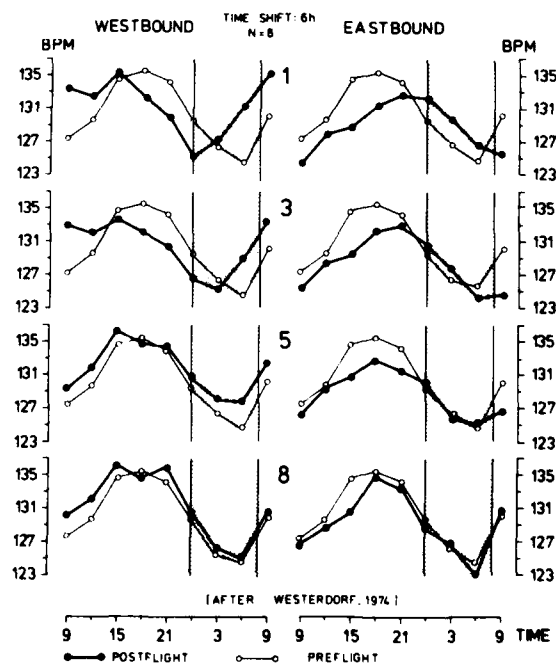Figure 17: Urinary 17-OHCS excretion after transmeridian flights.

Figure 18: Heart rate response to submaximal exercise after transmeridian flights.

since it is maximal with subsonic speed of flight already. On the other hand, it was shown before that speed of travel not resulting in more than 30 min time shift per day, for instance by ship, permits complete adjustment of body temperature rhythm already during the journey (278).

Figure 20: Differences in resynchronization rate of maximum and minimum in dependence on flight direction (phase angles of body temperature rhythm).
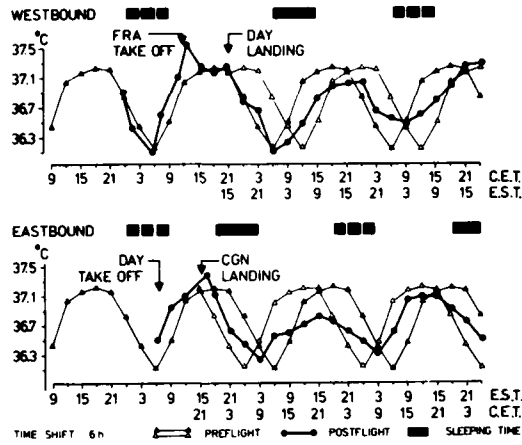
Figure 19: Continuous measurements of body temperature. (Preflight rhythm hypothetically shifted into the postflight position expected after completion of resynchronization.)

Finally, it should be mentioned that control investigations have shown displacement of biological rhythm (phase shifting), indeed, to be the specific consequence of a disturbance in the temporal relationship of body and environment; while other changes of the 24-hour rhythm, including those of amplitude and 24-hour mean, may also result from other forms of human activity, such as strenuous flights in north-south direction or vice versa (98, 99, 141, 283).

3.1.2 Mental Performance

In principle, mental performance rhythms, desynchronize in a similar way as just described for physiological parameters (167, 168, 176, 184, 286, 327). In fact, some task variables like psychomotor performance respond to a rapid phase-shifting of the environmental Zeitgebers in close analogy to the rhythm of body temperature (Figure 21). The changes typical for a post-transmeridian desynchronization are again: displacement of rhythm, modification of amplitude and 24-hour mean, and lower functional values at certain hours, higher values at other times of day (Figure 22). For instance, on the first day after crossing 6 time zones performance degradation became obvious in the late afternoon and early night after a westbound flight, and in the morning and afternoon when travelling had been in the opposite direction. On the average, impairment at the "typical" hours reached maximally -8 % and -10 % of the corresponding preflight levels when computed for westbound or eastbound transportation, respectively (Figure 23). It was often demonstrable for up to 5 cycles; but statistical significance usually was lacking by the 3rd postflight day. In view of the fact that by high motivation and extra effort, circadian cycling of mental performance may be overcome (see "Mental Performance" in section 2), we must conclude that the above mentioned periods of the circadian cycle are those times, where it will be at least more difficult to obtain the preflight performance level.

Figure 21: Body temperature and psychomotor performance rhythms following an eastbound flight. (24-hour mean is indicated through horizontal lines.)

As an indication of total performance efficiency, the 24-hour mean is of particular operational significance. We were able to prove a postflight degradation of performance for several task variables; however, it was small, and statistical significance was reached only after eastbound transportation (Figure 24). Halberg et al. (114, 117) also demonstrated deterioration of performance only following eastbound flights, while Hauty and Adams (139, 140) found a remarkable impairment only after westbound travel which, however, was related with time in transition of 23.5 hours contrary to 15.5 hours after eastbound transportation.

Figure 22: Psychomotor performance after transmeridian flights.

Figure 23: Three performance tests after transmeridian flights. (Time difference: 6 hours; for further explanation, see figure 5.)

Figure 24: 24-hour means of temperature and performance rhythms after transmeridian flights. (For further explanation, see figure 5.)

To what degree disruption of rhythm, or other causes, such as flight stress and fatigue, contribute to the deterioration of the overall level of mental performance is not easy to decide. The decrease of performance in airline personnel (253, 254) and in animals (268) following simulated time zone flights indicate just as much a direct effect of internally disturbed time structure, as the finding of Taub and Berger (303) who demonstrated a performance degradation after shifts of sleep periods without changes of prior sleep length or any specific alteration in the electrophysiological patterns of sleep. On the other hand desynchronization (displacement) of performance rhythms in man (280) and resistance rhythms in animals (227) without alteration of the 24-hour mean indicate that a change in the overall level of rhythm is not a compulsory aftermath of rhythm disruption.

3.1.3 Physical Performance

During international sportive competitions, athletes' subjective complaints about sleep loss and fatigue and observations of impaired performance after transmeridian flights have been related to the "jet lag syndrome" (274, 358). Unfortunately, postflight measurements round the clock of physical performance variables are almost completely lacking. We know only of the evaluation of "grip strength" (256) and of our own assessment of heart rate responses to submaximal exercise loads (Figure 18) which could be taken as an indirect measure of aerobic performance capacity.

Indeed, exercise heart rate revealed desynchronization (335); but in view of the somewhat complex circadian relationship between heart rate, oxygen uptake and exercise capacity (179) it seems difficult to predict from the data available, to what degree and in what way performance efficiency might be impaired. From the fact that (similar to mental performance) physical efficiency during the night is lower than during the day, one could speculate that (in dependence on flight direction) a decrement or an increment of physical performance variables might be expected at similar times, as observed in psychomotor performance.
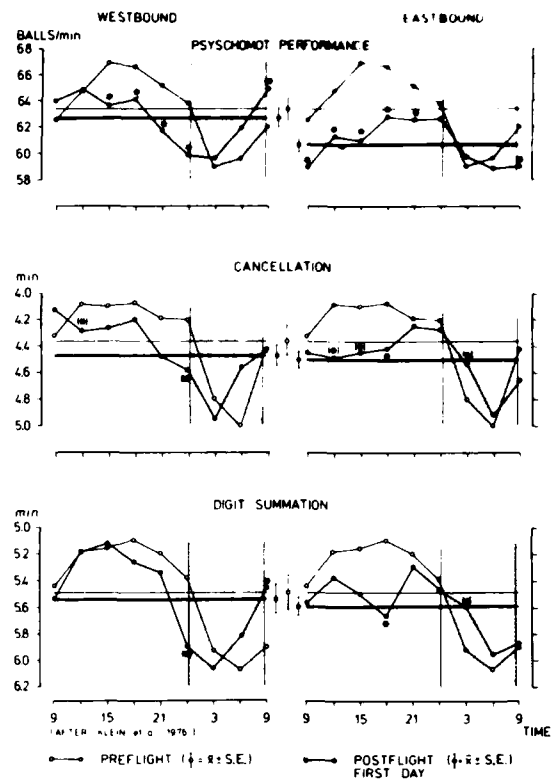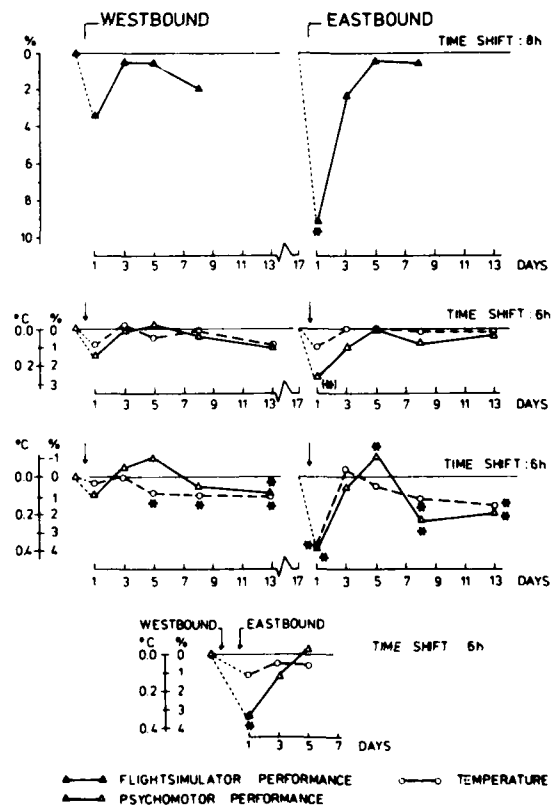
Basing on the heart rate responses (Figure 18) we would assume that it might be more difficult to produce preflight performance between 1500 hours and 0300 hours after a westbound flight across 6 time zones, and between 0700 hours and 1900 hours following an eastward flight. A prediction as to the order of magnitude of these changes, as to their duration and as to the response of the overall level of performance (24-hour mean) is, however, beyond any reasonable speculation.

3.1.4 Sleep-Wake Cycle

The sleep-wake cycle is part of the circadian timing complex, it, therefore, participates in the desynchronization of body and environment. Normally, the desire to sleep coincides with the environmental phenomenon "night" which is not just darkness but rather the socially related period of relative inactivity. After transmeridian flights the elementary disposition to be active or not, with relation to the environmental cycle, exists at unusual and inappropriate times of the day. This is the reason that sleep disturbance is one of the major subjective complaints of transmeridian air travellers. Difficulty in falling asleep, repeated spontaneous awakening during the night, and abbreviation of sleep by early morning wakening are symptoms which have been substantiated by sleep charts and diaries.

Sleep duration and sleep pattern. The view has been expressed that the most common cause of fatigue amongst pilots, generally, is not getting enough sleep. In view of this statement the small amount of research on this subject is surprising. Even though results are not consistent, they suggest that the problem may be a real one.

From an inquiry on 312 crew members of an European airline (194) it became obvious that during flights on the Atlantic route, 55 % subjectively experienced a shorter sleep than normal. Individual differences seemed considerable. Around one fourth reported to sleep normally from the first night on, between 40 to 45 % had this feeling not before the second night, and sleep disturbance lasted even longer in 25 to 35 % of those questioned. Twenty percent admitted to use hypnotics when on flights, contrary to only 5 % during duty free periods at home; in stewardesses this figure was highest with 44 %. A somewhat similar result, with respect to the use of hypnotics by flight crews, was obtained in a recent study through personal interview technique on 358 crew members (142): Only 54 % declared never to use hypnotics on route, whereas at home this figure was 87 %; of those admitting use of sleeping medication, 21 % did so "rarely", the same percentage "sometimes", and 4 % "frequently". In the same study similar figures were given for alcohol as an aid to sleep with the difference that 11 % took alcohol "rarely", but 11 % also "frequently". Of particular interest were the answers with respect to the practice in taking hypnotics: Though 6 to 8 hours before duty were the more frequent figure, use of up to 4 hours before duty was admitted; in 86 % Nitrazepam (Mogadan) was taken.

Preston and coworkers, in the early 70s, studied sleep with the use of sleep logs and of subjective assessments of fatigue (251, 252, 254). The results obtained in aircrews operating on world-wide schedules may be summarized as follows.

In comparison with normal pattern and duration, sleep on route
- was disrupted and broken into many periods;
- was well below the individual normal amount at home, average differences per 24 hours occasionally being as high as 2.5 to 3.0 hours;

Figure 25: Cumulative sleep loss during a world-wide flight schedule.

- resulted in a cumulative sleep loss; this was during a 15-day-flight operation in the magnitude of almost 30 hours at the maximum and 10 hours at the minimum, the older crew members experiencing the greater sleep deficit (Figure 25).

Air cabin crews, mainly investigated on transatlantic routes, showed a consistent sleep loss of five to six hours per night flight, or of about one hour per day on route; loss of sleep in this study seemed mainly associated with the number of night flights at local time, but hardly with time zone changes (254). Also, in a longitudinal study over 3 months on 23 crew members operating in patterns of 3 and 5 days on the Tokyo-Moscow (Western Europe) route, a sleep loss of 6 to 10 hours on night flights was recorded amounting to 1.5 to 2.5 hours per day on route (30). It was concluded that several days were necessary for recovery.

The concept of a cumulative sleep loss implies that for recovery the same amount of sleep as was lost is necessary. This may not be true, however, since from sleep deprivation studies it is generally believed that one night of somewhat extended sleep of about 13 hours usually makes the symptoms disappear in most individuals (271).

The average sleep loss evaluated in flight studies is comparable with that quoted for night or rotating shift workers: 0.5 - 2.0 hours per day; however, if naps were taken into account, the sleep deficit was less (278). The situation seems to be similar in the aerospace environment.

Nicholson (228, 230), following the sleep patterns of aircrews operating on world-wide routes, suggested that with acceptable schedules sleep disturbance arising from irregular duty periods and from adaptation to time zone change, rather than sleep deprivation, was the main problem. He concluded that there was no overall sleep loss as long as the total sleep over each 3 days period preceding any duty period was similar to that observed under normal conditons. Short periods of sleep (naps) were observed both, during rest and duty periods, when the workload was not demanding. The occurrence of inflight sleep of cockpit crew members was meanwhile confirmed through micro-sleep EEG patterns during the over-night parts of flights with the aeroplane on autopilot (49).
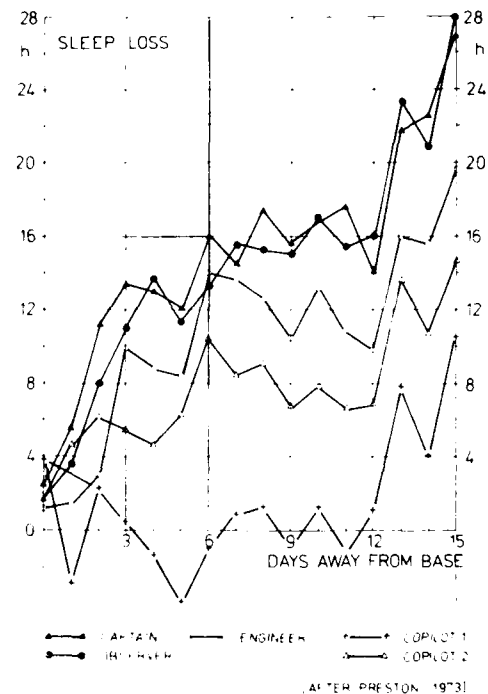
Also from 100 military missions on transmeridian routes, naps were reported reasonably often (128). On average, during the multi-day missions, sleep was not reduced in comparison with the pre-mission period. Nevertheless, on post-mission days 1, 2 and 3 sleep duration was longer (i.e. 9.9, 9.2, and 8.9 hours, respectively). The "dramatic change" was interpreted as a demonstration of a physiological debt developed during the mission through factors as "the mission work, the 30-hour day, circadian conflicts, altered sleep schedules, off-duty activities, variation in sleep environments, the situational stress of time-zone translocation". The author emphasizes that "continuing attention must be given to sleep and rest problems in the airlift environment".

According to Nicholson, for pilots on route "naps appeared to play an important part in maintaining the necessary balance of sleep and activity". He concluded from observations on a few individuals only, that "personal modification of the natural need to sleep plays an important part in the overall strategy of sleep planning and, therefore, in minimizing tiredness during duty". Indeed, some of the sleep studies mentioned above, revealed considerable individual difference not only in the ability to sleep on route during rest periods, but also in the ability to take sleep while on duty (30, 142, 252). Though naps seem to reduce impairment of efficiency caused by sleep deficit (158), we are left with the decision wether naps on duty should deliberately be incorporated into the system.

Sleep structure. Accordingly to differences in the electrical activity of the brain (EEG), the eyes (EOG) and the muscles (EMG), sleep has been divided into stages: stage 1 to stage 4 (orthodox) sleep and REM (Rapid Eye Movement, or paradoxical) sleep. From sleep onset the stages do not emerge in a random order but are distributed across the total sleep period in a characteristic manner: Stage 3 and Stage 4 sleep (high amplitude slow-way sleep) predominates in the early part, while REM sleep does so in the later; there are 2-3 periods of stage 4 and 4-5 periods of REM sleep. Also, sleep stage percentage is reproducible in different nights, though it varies between individuals and changes with age; so does sleep length (317).

It has been speculated that sleep as part of a basic rest-activity cycle, in addition to the intrasleep characteristics, might have time of day related circadian aspects. This hypothesis was supported through an obviously circadian distribution of sleep stages: if sleep was interjected into different time periods of the circadian cycle, the proportion of stage 3 and stage 4 sleep decreased from a maximum in the early hours of the night to a minimum between 0400 and 0800 o'clock in the morning and increased again during the day; REM sleep showed an almost specular course (83, 317). Others (334) hold that REM sleep is time of day dependent, while stage 3 and 4 sleep is more related to "time awake" or "time since last 3 and 4 stage sleep". Also it was established by autocorrelation analysis that there is no consistent circadian influence on the duration of REM intervals but rather the REM cycle is a sleep-dependent rhythm hardly related to the time of day of sleep (223, 224).

Sleep displacement into different segments of the 24-hour cycle modifies prior wakefulness, time of day of sleep onset and length of sleep; these factors are known to affect the structure of sleep. This may be the reason why the results from transmeridian studies (81, 83, 176, 190, 218, 311), like those from shift workers or sleep inversion in the laboratory (75, 91, 157, 190, 303, 304, 305, 306, 317, 319, 333) are not very consistent. An example from own investigations is presented in Figure 26.

The attempt to compile the findings reads as follows:

- Sleep latency is often reduced, if prior wakefulness was long and stressful; this is more consistently observed during the first postflight night and after eastward time shift; later, sleep latency may be prolonged;
- awakenings and transitions between sleep stages occur more often; the increase in awake time may cause a reduction in total sleep time, in particular if time in bed is limited by defined work-rest schedules;

Figure 26: Sleep structure after an eastbound flight (60 years old woman).

- delay to the first REM period is often reduced, REM sleep occurs earlier;
- absolute duration of REM sleep may be reduced, this was reported after delay and advance shifts (westbound and eastbound transportation) and for the first postflight sleep period which is particularly affected by the stress and fatigue of flying;
- sleep structure seems to adapt fast to shifts of the environmental time cues; in general, it normalizes within a few days.

Consequences of sleep disturbance. The interrelation between sleep, sustained operation and circadian rhythm has been described in section 2.1.2. In this paragraph we shall deal with changes of performance efficiency, which might be caused by sleep reduction or sleep fragmentation in consequence of post-transmeridian desynchronization and/or irregular work-rest schedules. We will base our summary on recent reviews published by Johnson and Naitoh (159) and Johnson (158), the essence of which reads as follows:

- In operational studies no consistent performance changes have been found within the 36-48 hours range of total sleep loss.
- In the laboratory significant impairment of performance was observed in consequence of one (or more) night(s) of total sleep deprivation. Several factors have been identified which determine sleep loss induced performance decrements: some enhance it, such as duration, difficulty and pace of task as well as requirement of short-term memory; others reduce it, such as knowledge of results (feedback), proficiency in task performance and high interest (motivation).

- Gradually reducing sleep to 6.5 - 6.0 hours per night (partial sleep loss) induced increase of the subjective feeling of sleepiness, fatigue and discomfort, but no changes in objective performance tests; good performance seemed to be maintained, however, with higher physiological cost.
- If total sleep time is not reduced, but sleep is fragmented, i.e. intersleep intervals vary, under operational conditions performance seemed to be impaired, while in the laboratory little performance decrement was found.
- Deprivation of stage REM and stage 3 and 4 sleep apparently has no detrimental effect on performance.

Hypnotics. In view of the long lasting residual effects of most hypnotics, including Nitrazepam, on human performance (165, 231), the practice of an uncontrolled consumption by aircrews is precarious. In two studies, some drugs have been identified which seemed relativeley harmless: in one case (231) it was Diazepam (10 mg) and Methaquolon hydrochloride (400 mg), in the other (126) Flurazepam (30 mg). Recently, however, long lasting performance degradation has been reported for Flurazepam (53, 233) and polyneuropathy as effect of Methaqualon, so that both must be eliminated from those hypnotics which under certain conditions could be recommended for use by aircrews; namely, if (a) relief is requested by an individual because of serious sleep problems while on route with irregular patterns, and if (b) the potential user is instructed to observe the following rules (126):

- try the drug in a low dose several nights before using it on a regular trip;
- do not use the drug during layover time if "hangover" is significant during the trial use;
- do not use the drug if the layover time is less than 12 hours.

In comparison with Diazepam, Temazepam (10-20 mg) seems to be even more favourable: It has not only a short lasting effect on performance, but also no long-acting metabolite, so that "daily ingestion is unlikely to be contraindicated", while Diazepam medication should not be repeated at intervals less than 48 hours or given more than twice in seven days, "though it is particularly useful for sleep at unusual times of the day" (233).

3.2 Post-Transmeridian Re-Entrainment

The terms "re-entrainment" or "resynchronization" in the context of this chapter refer to the transition of a circadian rhythm from the preflight to the postflight steady state. Quantitatively, it is described by shift rates per day and by the total time needed for completion. Resynchronization curves represent phase angles of consecutive 24-h sections of the resynchronizing rhythms, or phase angle differences between the circadian rhythm in transition and in the pre- or postflight steady state. The course of resynchronization, in general, is non-linear and is modified by various influences.

Synchronization of circadian rhythms in man occurs to a high degree under the influence of social time cues. During night and shift work, environmental and social synchronizers diverge; this seems to be one reason, why night- and shiftworkers often are in a continuous state of circadian desynchronization. Transmeridian flights favour re-entrainment of biological rhythms since all components of the temporal environment are shifted at once. Nevertheless it takes days to weeks before the biological timing system is completely re-adjusted. The rate of resynchronization is affected by flight direction, is divergent between physiological rhythms, depends on the characteristics of time cues, and may be different between individuals.

3.2.1 Circadian Asymmetry

In an early study (169) on 75 aircrew members flying transatlantic shuttle, subjective estimations of load as well as objectively measured changes in psychophysiological variables were more pronounced after eastbound flights than after flights in westbound direction. A higher number of flight legs contributed to the results in the expected manner, but did not affect the outcome with respect to flight direction. However, since westbound flights always were outgoing and day flights, eastward flights always homegoing and night flights, and in addition, layover times had been 30 hours only, the results could hardly be conclusively associated with the direction of time shift.

Later, it became obvious that retardation and acceleration of the "internal clocks" occur with different speed: Nearly all flight experiments indicated a faster shift of rhythms after east to west flights in comparison with west to east flights (104, 112, 117, 137, 139, 140, 168, 194, 256, 279, 321). Through several experiments in which German and U.S.A. residents served as subjects and flights in both directions occurred during daytime, we then excluded time of day of flight and homegoing/outgoing as main contributing factors for the circadian asymmetry (Figure 27).
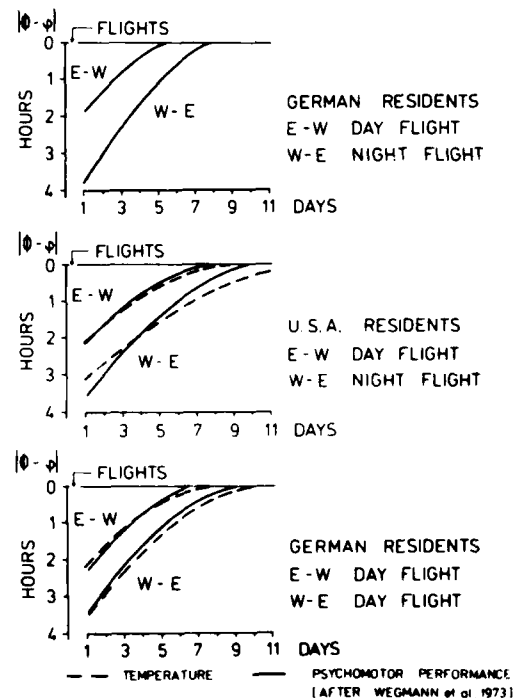
Figure 27: Resynchronization of phase angles in 3 different groups of subjects showing circadian asymmetry being independent from relative flight direction and time of day of flight. (Time difference: 6 hours; ϕ - ϕ : phase angle difference between environmental synchronizers, represented through local time ϕ , and the biological rhythms ϕ ; zero indicates a relationship between the two being identical with that before the flight.)

PSYCHOMOTOR PERFORMANCE
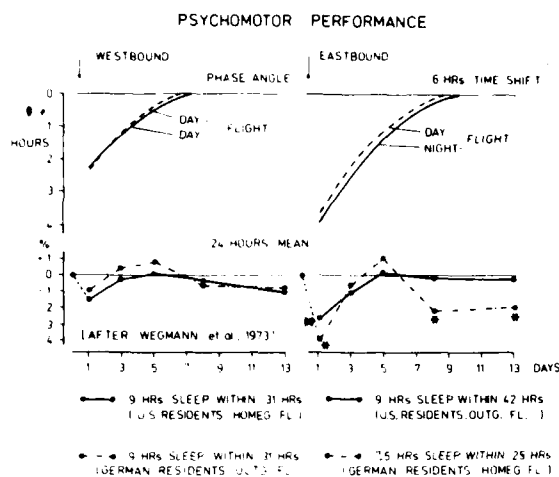
Figure 28: Independence of resynchronization from relative flight direction and lenght of preceding wake period. (For further explanation, see figures 5 and 27.)

Also, the hypothesis was supported by experimental results (327) that a variation of the length of the wake period, as caused by different flight schedules, does not affect the course of de- and resynchronization as long as a sleep period of normal length precedes the following duty period (Figure 28): It was insignificant for the response of the 24-hour mean and for resynchronization of phase angles whether the transmeridian transportation required a period of 33 hours of wakefulness followed by 9 hours of sleep (eastbound night flight), or whether subjects had to stay awake for only 17.5 hours, and then slept for 7.5 hours before they were tested (eastbound day flight).

Figure 29: "Resynchronization by partition" in one group of subjects after an eastbound flight.

In our results resynchronization on a total average was faster by about 50 % following the westbound flight: In several assessments of various psycho-physiological variables, including heart rate, body temperature, catecholamines, 17-OHCS, and various mental performance tasks (each one evaluated from 8 subjects on flights in both directions), re-entrainment occurred with a rate of 88 min/day and 56 min/day as consequence of westbound and eastbound transportation, respectively.

It was shown earlier that the direction of the circadian asymmetry varies with the species and with the natural length of the circadian period: In birds (28) and in man, if the period length was shorter than 24 hours (15, 337), resynchronization was faster after an advance shift of time cues corresponding to an eastward transportation; in species with period lengths usually longer than 24 hours (including man) the opposite was true (82). However, for man there are remarkable exceptions: in some isolation experiments, re-entrainment after advance shift of artificial Zeitgeber with 80 min/day was faster than after delay shift with 57 min/day (19), even if the circadian period was longer than 24 hours (337). As possible reasons for the difference to flight experiments, knowledge of the purpose of the study and strength of time cues have been discussed (25, 342).

3.2.2 Antidromic Phase Response and Re-entrainment by Partition

Usually, biological rhythms re-entrain by shifting in the same direction as the environmental Zeitgebers. However, several cases have become known in which the opposite was true: a so-called "antidromic" phase response (124, 173). Mostly, this process does not occur simultaneously in all psycho-physiological functions, but rather a "re-entrainment by partition" (19) is observed. This phenomenon meanwhile was found during a 12-hour delay shift of sleep time in a hospital (199), as consequence of a 6-hour advance shift in an isolation unit (341) and after a 9 hour advance shift following transmeridian flights. Figure 29 illustrates this phenomenon for the latter case: 8 subjects resynchronized body temperature, psychomotor performance and 17-OHCS rhythm after a westbound flight by a delay shift; after eastward transportation all subjects re-entrained rhythms of performance and 17-OHCS by an advance shift, but only 4 subjects did so with body temperature, whereas the other 4 subjects delay-shifted the temperature rhythm despite of the fact that this resulted in a shift across 15 instead of 9 hours.

Aschoff (17, 20, 21) has pointed to the fact that the probability of partition occurrence is greater after advance-shifts (eastbound flights) and increases with the magnitude of shifts or the number of time zones crossed. We have speculatively related the preference of man for delay shifting with his easier adaptation to this direction due to spontaneous periods longer than 24 hours (184). But as possible reason for this phenomenon free-running cycling due to weakness of Zeitgebers has been discussed (82).
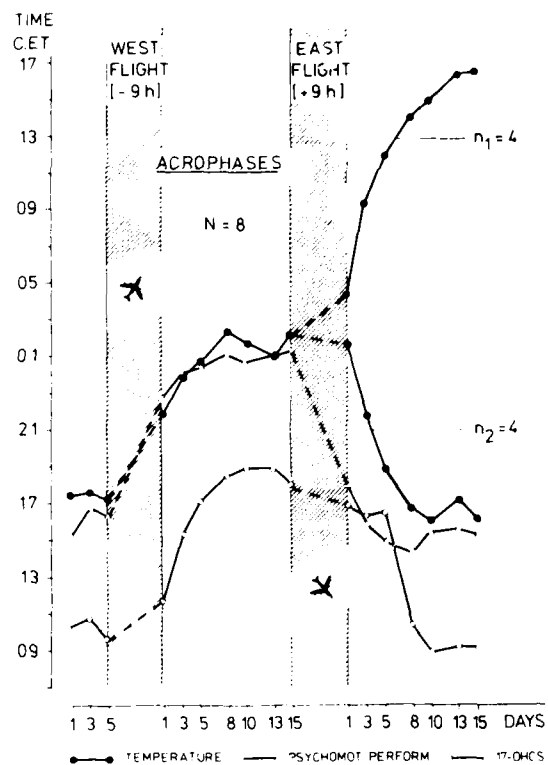
Table 1: Shift Rates after Transmeridian Flights in Minutes per Day

Function	Westbound	Eastbound
Catecholamines (Urinary)	135	90
Adrenaline	90	60
Noradrenaline	180	120
Mental Performance	93	57
Psychomotor Perf.	52	38
Reaktion Time		
(Vigilance)	150	74
Heart Rate	90	60
Body Temperature	60	39
17-OHCS (Urinary)	47	32
Average	88	56

immediately after shift of time cues, and slower later on. In addition, the extent of daily shift was proportional to the number of time zones crossed, i.e. it was the higher, the larger the phase angle differences between the environmental and biological timing systems. (For a more extensive discussion, see "Formulas", section 3.2.6).

It is not clear yet, what causes internal dissociation. It was postulated earlier that higher nervous processes adapt faster than vegetative ones to an abnormal temporal routine (95); however, we know now that this is not generally the case. Also the complexity of the task seems to be of importance for mental performance rhythms (139, 140, 167). In addition, there may be a "specifity" in task variables which affects the speed of resynchronization: It has been demonstrated (30) that a higher memory loading task adapted faster to night work conditions simulated in a laboratory and to time shift following transmeridian flights.

Otherwise, one can observe that the more persistent (slower adapting) rhythms are those which under control conditions often show significant circadian oscillation; in particular, that was true for temperature, 17-OHCS, and psychomotor performance. On the other hand, the variation of the fast entraining noradrenaline rarely reached the level of statistical significance (see Figure 3). In another study (5) noradrenaline allowed only a poor fit to a sine curve, so that one has the impression that the endogenous circadian component of this hormone is weak or even lacking, and variation might reflect merely responses to changes of the environment. This could well be the case in other abrupt adapting rhythms.

3.2.4 Characteristics of Time Cues

For animals a negative correlation between the strength of Zeitgebers (light intensity or range of temperature cycling) and the time needed for re-entrainment of rhythms has been established (25, 82, 153). For man a similar relation seems to exist between social time cues and speed of resynchronization (Figure 31): In a group of passengers who were kept in the relative isolation of hotel rooms, time for 95 % resynchronization of psychomotor performance rhythms was about 50 % longer on average than in passengers who were allowed to leave the accommodations for outdoor activities every second day (33, 174, 175). Since both groups were aware of the preceding time shift as well as the local time, the higher degree of social contact, related to the divergent activities, should be the reason for the differences in shift rates.

3.2.3 Internal Dissociation

Different circadian rhythms resynchronize with divergent speeds; this is true for physiological functions, as well as for mental task variables (Figure 30). The different rates in rhythm adjustment lead transitorily to an abnormal phase relationship between the functional systems, thus causing "internal dissociation". If the average figures, given above for delay and advance resynchronization, are broken up for different circadian rhythms, divergent shift rates result (Table 1).

In other studies on man, divergencies of resynchronization speed for different functional rhythms have also been observed which, in general, agree well with those demonstrated by our findings. From these studies, in addition to the differentiation shown in the table, blood pressure as well as urinary sodium, calcium and chloride excretion must be rated as fast adapting, while urinary potassium and serotonin are slow (112, 134, 194, 201, 205, 213, 260, 289, 339).

However, the figures listed in Table 1 do not yet reflect the fact that re-entrainment occurred very often in a non-linear way (167, 177), being faster
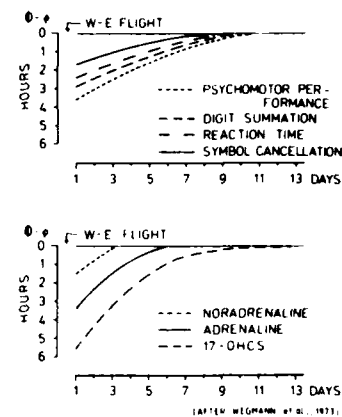

Figure 30: Difference in rate of resynchronization of rhythms after transmeridian flights: internal dissociation. (For further explanation, see figure 27.)
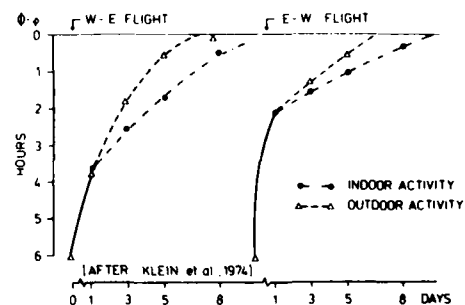

Figure 31: Difference in rate of resynchronization of performance rhythm depending on mode of activity. (Time difference: 6 hours.)

Endeavours to hasten post-transmeridian resynchronization by a corticosteroid-like substance (52, 200) or by a tranquilizer (287) have failed so far. On the other hand, timing of food intake is among the social Zeitgebers which have been shown to control circadian variables. In animals, controlled access to food could be made either to oppose or to augment effects of synchronization by lighting regimen (115). In addition, composition of food was found to have Zeitgeber characteristic (77, 78, 102, 208, 242). On these results "a diet plan for shift workers and transmeridian travellers" was developed (76) which is based upon (a) the chronobiotic (=synchronizing) action of tea (theophylline) and coffee (caffeine); (b) the operation of food as a Zeitgeber in a feeding program with a prolonged starvation phase (presumably acting through glycogen depletion); and (c) the tendency of a high protein meal to favour synthesis of catecholamines, and of a meal high in carbohydrates to favour the synthesis of serotonine (according to normal circadian variation, the first should be high during the active phase, the second during the inactive phase of the circadian cycle). Through preflight alternation of "feast" days (large meals) and "fast" days (light meals) in combination with food timing synchronized with that at the flight destination, and programmed intake of coffee or tea, an acceleration of phase shift of biological rhythms is attempted. On base of subjective results, trials with humans are supposed to be highly successful (76). Objective measurements taken from humans following the diet plan have been reported, and apparently show positive results (101).

3.2.5 Individual Differences

From differences in subjective sensitivity it was predicted that 25 % to 30 % of the transmeridian travellers would have no or only minor difficulties in adjusting to the sudden displacement of external time cues; about the same percentage was estimated not to adjust at all (209, 297). A figure of 20 % was also given for the non-adapting group from experiences with shiftworkers (45, 309), however, this figure is considered somewhat conservative since it is based on officially recognized transferees.

Using resynchronization time of psychomotor performance rhythms as an indicator of the ease or difficulty of time zone adjustment, we have demonstrated (173) individual differences for 14 subjects of one age group (Figure 32): Resynchronization times for the westbound direction distributed in a range between 1.7 and 6.0 days, corresponding to a rate of shift between 210 min/day and 60 min/day. Travel in the opposite direction resulted in resynchronization times ranging between 2.9 to 11.3 days; this corresponded to a shift rate of 125 min/day. Finally, there were 3 individuals out of 14 who required between 14.3 days and 17.9 days to advance shift their psychomotor performance rhythm across 6 hours. With an average rate of shift of 22 min/day, resynchronization for psychomotor performance was so unusually slow that one could consider them to be examples for the individuals who "adapt only with considerable difficulty". Their number (22 %) matches well with the figures mentioned above for the group with a high subjective sensitivity; however, it is remarkable that they become evident only in connection with eastbound transportation.

Meanwhile, there have been some factors identified which may be responsible for individual differences in speed of resynchronization.

Characteristics of rhythms. It has been demonstrated that the individual resistance to displace body temperature rhythm, in response to a shift of time cues in an isolation unit, is proportional to the amplitude of rhythm before shift; the negative correlation between the amplitude and the duration of re-entrainment was higher for the advance than for the delay shift (341). This relationship has been confirmed recently for shift workers after delay shifts, where it was significant for oral temperature, urinary 17 OHCS and peak expiratory flow (262). It was found for temperature rhythm again after sleep inversion by Foret, Benoit and Merle (Personal communication, 1979).

Also the standard deviation (SD) of temperature rhythm, computed from measurements on 12 consecutive cycles, was used for a stability (low SD)/lability (high SD) characterization of circadian variation (61). Through the negative correlation between SD and the personality factor "introversion" there was a relationship established between stability and lower rate of shift, and lability and higher shift rate.

FREQUENCY

WESTBOUND FLIGHTS (N = 14)

EASTBOUND FLIGHTS (N = 14)

TIME SHIFT 6 HRS

(AFTER KLEIN et al 1977, ADAPTED FROM BELJAN, 1972)
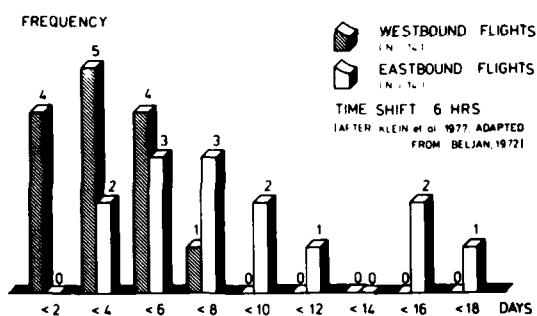
Figure 32: Frequency distribution of the resynchronization time of psychomotor performance rhythm.

In shift workers a higher temperature amplitude was associated with good subjective and clinical tolerance, while a low amplitude could be related to poor tolerance; the differences were statistically highly significant (259, 262). Considering the negative correlation between amplitude and speed of resynchronization the results suggest that slow adaptation of temperature rhythm indicates good tolerance to shift work.

Personality. "Morning" and "Evening" types of individuals, and in a similar manner "Introverts" and "Extraverts", have been related with early and late peaking of circadian rhythms (like body temperature, catecholamines, mental performance and behaviour), and with shorter and longer periods of cycles, respectively, while isolated from time cues (4, 39, 40, 60, 88, 90, 186, 203, 234, 235, 238).

These relationships encouraged the hypothesis that ease of shift of body rhythm might depend on personality factors. It was supported through subjective rating in industrial shiftworkers that extraverts (with longer circadian periods) adapt about 50 % faster to a delay shift than to an advance shift (239). This again is in agreement with the more recent finding that evening types, as compared to morning types, do not experience sleep deficiency and tend to increase duration of sleep easier, when sleep onset is shifted to later hours (42); on the other hand, they sustain sleep latencies longer than morning types, if sleep onset is advanced. In the same study, a better adaptability to delay shifts was demonstrated for subjects with a lower ratio of pulse and respiration frequency (for the significance of this quotient see ref. 144, 147). Also, it was predicted from investigations on industrial workers that morning types cope better with the early day shift while evening types adapt easier to permanent night-shift (244).

Colquhoun and Folkard (61) found (a) that the difference in temperature rhythms between introverts and extraverts was much more pronounced in the subgroup "neurotic" subjects, while in the subgroup "stable" subjects it actually did not exist, and (b) that in re-analyzed figures from a previous transmeridian flight study the resynchronization rate between the groups decreased in the following order: neurotic extraverts, stable extraverts, stable introverts and neurotic introverts.

Introverts and highly "neurotic" people have been identified as those who quit shift work after a shorter time (150, 225). The assumption that this might be so because of greater difficulties in adapting to the abnormal temporal routine is backed by the finding that "neuroticism" is related to a higher degree with internal desynchronization of different circadian systems, if subjects are isolated from external time cues; the same was true for older people (339).

Age. It appears that older people subjectively have greater difficulties in adapting to changes in the temporal relationship of body and environment (4, 45). This could partly be caused by susceptibility to sleep disturbances, obviously increasing with age (317). (See also Figure 25). But age-related differences of circadian rhythms have also been verified. In animals, aging caused a decrease in amplitude and a slower adjustment of temperature rhythm following a change in lighting routines (115). In man, increased age also retarded phase shift of temperature rhythm in shiftwork (260) and of urinary potassium cycling in response to a simulated delay shift of time cues (287). Also, advanced age in combination with a reduced temperature amplitude indicated a lower tolerance to shift work (259). Wever (339), in the study mentioned above, not only demonstrated a higher rate of internal desynchronization of older people in a time cue free environment but also established speculatively a "threshold age" of about 40 years from which on the tendency to a "decoupling" of rhythms significantly increases. It seems, however, that this phenomenon as well as others of the described age effects need additional confirmation through studies with higher numbers of observations. Nevertheless, it is of interest that sleep over the age of 40 years in healthy man becomes increasingly disturbed.

3.2.6 Formulas

Utilizing the findings of several studies conducted by our laboratory in recent years (167, 173, 177, 181, 327), we developed a concept which allows us to appraise the average resynchronization time for any day after arrival in a new time zone. The course of adaptation is non-linear and re-entrainment occurs in relation to the number of time zones crossed. Based on mean values computed from the re-entrainment of body temperature and mental performance rhythms after transmeridian flights crossing 6 time zones, the resynchronization rate is evaluated as follows: 50 % of the difference in pre- and postflight local time is shifted within 36 - 48 hours after arrival; again 50 % of the residual phase lag is shifted within the following 48 hours; the same applies to the next two days, and so on. As an example, after a flight involving a time displacement of 6 hours, circadian rhythm has shifted 50 % or 3 hours on the second day, 75 % or 4.5 hours on the fourth day, and on the sixth day after arrival 88.5 % or 5.25 hours. Mathematically, these relations can be comprised in the formula: $R=f(t)= \Delta \Phi \cdot 2^{-\alpha t}$, where R is the resynchronization in hours yet to be accomplished, $\Delta \Phi$ is the number of traversed time zones, t is time after arrival in days, and α denominates the time constant. Of course, the equation represents a more generalized form of the concept outlined above. Strictly speaking, it has been experimentally validated only for these specific conditions, i.e. a time displacement of 6 hours. However, a more recent study which we conducted to investigate the effects of a time shift of 9 hours after transmeridian flights, revealed evidence that an extrapolation to more

$$t_R = \Delta \Phi \cdot 2^{-\frac{1}{2}}$$

- o———o $\Delta \Phi$ = 12 h
- •———• $\Delta \Phi$ = 9 h
- +———+ $\Delta \Phi$ = 6 h

Figure 33: Resynchronization curves as predicted by the model for different time displacements after transmeridian flights.

than 6 time zones may be permitted (Wegmann and Klein, unpublished data). Applying the formula after evaluation of an average value for the time constant of $\alpha = 0.5$, we have calculated the resynchronization courses depending on the traverse of 12, 9, and 6 time zones. Figure 33 gives a graphical presentation of the results. As can be seen from the curves, the model predicts initial resynchronization rates being higher the more time zones were crossed. On the other hand, with progressing time after arrival it foresees that differences in the residual resynchronization very soon become neglectibly small, thus making a differentiation almost impossible already on the 6th day. This effect is interesting in so far that it would result in t o t a l resynchronization times being essentially the same, whether 6, 9 or 12 time zones were crossed. As an example, the formula predicts for the 6th day after arrival in the new time zone remaining phase angle differences of 0.75, 1.13 and 1.5 hours, respectively, between the biological and environmental timing system.

It is obvious that introducing an average value of $\alpha = 0.5$ for the time constant disregards the differences in resynchronization existing between individuals, body functions and flight directions. For scheduling of transmeridian air operations, however, it offers a reasonable compromise of sufficient precision and easy applicability. Its advantage is that it is derived from empirical values based on a considerable amount of experimental data and that it covers not only physiological variables, but also performance rhythms.

Inferring from theoretical considerations, Sasaki (279) conceived a model which also permits an estimation of the resynchronization status in dependence on the time spent in a new time zone. In accordance with our findings, he postulates that re-entrainment does not proceed linearly, but rather asymptotically. Under the assumption that the rate of resynchronization is proportional to the number of traversed time zones, a differential equation is derived (for a detailed description see Appendix 1). Its solution for the condition that the traveller remains at the same location, as is the case for stopovers or for arrival at the destination, provides a relative simple formula, combining exponential and linear components. For operational purposes its applicability seems to be not much less convenient than that of our empirical formula. It also allows the prediction of the resynchronization status any time after arrival and for one as well as multiple transit stops. However, for the time being it has the disadvantage that a broader experimental validation is lacking. Thus, its feasibility has been tested only for a few observations on body temperature rhythms, and empirical values for the time constant have not been derived from other rhythms.
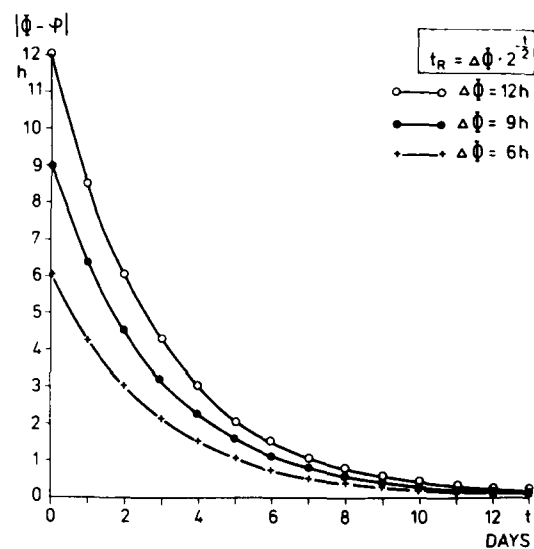
3.3 Rapid Round Trip

Often aircrew duty is such, that an outgoing transmeridian flight, after a short sojourn in the new time zone, is followed by a return flight to the home base. With respect to desynchronization of circadian rhythm such flights have been investigated only rarely; in addition, different variables have been followed, which makes conclusions difficult. In one study, the layover in the new time zone was two hours only; as a result, there was a reduction of the amplitude of the rhythm in urinary electrolyte excretion on the first day after the return to the homebase, but no further changes for instance of phase angles (97). This seems not surprising in view of the finding mentioned above that only with the first sleep period in the new time zone does shift of biological rhythms commence.

This prerequisite was certainly fulfilled in a previous study on 8 subjects who, on a round-trip between Paris and Alaska, stayed 20 hours in Anchorage before returning to France (193). According to the authors, the variations of 17-OHCS and potassium excretion immediately became concordant with the reference circadian curves on return to Paris; however, for analyses, statistical models apparently have not been applied. Also Buck (46), measuring psychomotor performance on pilots (over 2 - 3 min once immediately before and after transmeridian flights), concluded that "subjects remained adapted to local time at the home base", if layover time in the new time zone was only 24 hours. Contradicting, in a study performed by our own group (132, 191, 281, 330), circadian rhythms of 17-OHCS, body temperature and psychomotor performance in comparison to pre-flight positions showed a significant phase shift in the magnitude of 1.5 to 2.0 hours on return to the home base, which on the 3rd day was reduced to about 1 hour (Figure 34). Curves of catecholamines and reaction time were not displaced. A significant reduction of the 24-hour mean was evaluated for all variables except noradrenaline; also the amplitudes were significantly altered in some rhythms.

Layover times abroad were 2 - 3 days in a Japanese investigation on a round trip between Tokyo and San Francisco (283). Under this condition circadian rhythms were disturbed while on route; normalization after returning to the home base took between 1 day for 17-OHCS and 17-KS, and 4 - 5 days for heart rate and body temperature. The authors concluded that a short-stay flight pattern, because of shorter resynchronization times, minimizes the ill effects of the time zone flights. Similar conclusions have been drawn for rapid rotating shift work (105, 187).
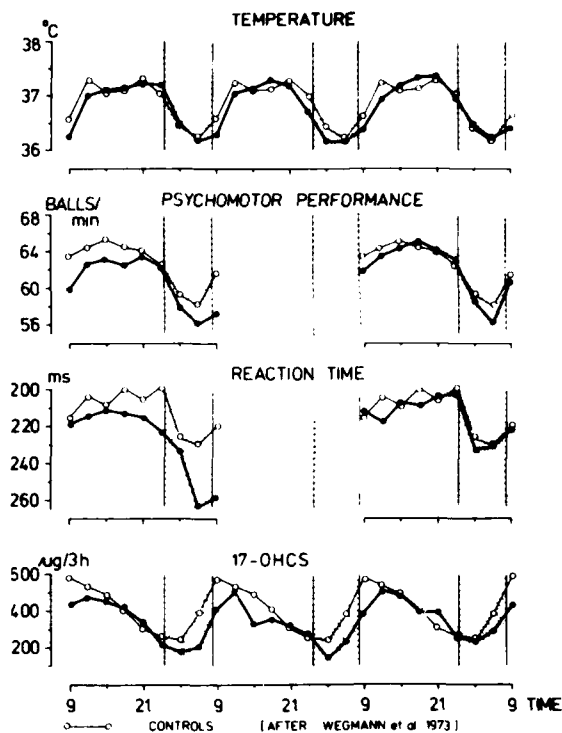
Figure 34: Circadian rhythms before and after a rapid transmeridian round trip Frankfurt-Chicago-Frankfurt. (Time difference: 6 hours; layover time: 24 hours.)

3.4 Repetitive Desynchronization

Shifts in time references give rise to external desynchronization and internal dissociation of circadian systems which may continue for days or weeks, depending on the circumstances. In workers on rotating or night shifts, or in aircrews on long-haul transmeridian routes it could become a permanent state for prolonged time periods. Therefore, it is essential to address the question of psycho-physiologic long-term effects of repetitive circadian desynchronization.

Experiments with insects and rodents have been conducted (26, 115, 116, 143, 247) in which shifts of lighting regimen, varying in extent, direction and repetition pattern, were introduced and the resulting changes of longevity or life span were measured. The results were inconsistent and somewhat surprising: Some experimental conditions caused a significant reduction of life span; others had no effect, some even led to a prolongation. Speculatively, it was concluded that age at the introduction of repeated shift regimen (earlier in life better than later), pattern of shifting (twice a week better than weekly), or inhibition of maturing processes could be responsible for the fact that repeated schedule shifts were life-shortening, harmless, or even life-lengthening. Considering the extremity of these experiments one must conclude that animal research as yet has not been very helpful in defining or predicting chronic desynchronization effects in man.

The extensive information available from shiftwork has been repeatedly reviewed in recent years (1, 4, 6, 45, 65, 188, 211, 272, 302, 307, 308, 309). It has been considered to be rather inconclusive, the reason being a selection process involved in the recruitment or retaining of shiftworkers. In brief, the results can be summarized as follows.

In shiftworkers as compared to dayworkers there are
- an abnormal frequency of sleep problems;
- more often tiredness, restlessness, and minor nervous disturbances of transitory character;
- a higher number of digestive problems and gastro-intestinal disturbances (reported in some studies only);
- both, lower and higher absenteeism;
- no higher mortality rate.

More recent investigations revealed that most of the disturbances associated with shiftwork
- had come into existence in the early periods of shiftwork;
- developed in predisposed individuals who often showed indications of similar symptomatology (sleep complaints, sensitivity to noise, gastro-intestinal irritability), before commencing shiftwork;
- were reduced, and well-being increased in "drop-outs" from shiftwork.

Some authors believe that statistics underestimate the problem, because individuals unable to cope with shiftwork transfer to day work (self-selection). They conclude that shiftwork is a risk factor for pre-disposed individuals. They also propose to exclude from irregular working pattern those individuals whose personal histories indicate a disposition for sleep disturbance, digestive and intestinal problems, and other symptoms of psychosomatic disorder.

Questionnaire studies of aircrews report also on a high incidence of sleep disturbances and gastro-intestinal symptomatology (48, 194). However, health surveys often failed to confirm objectively psychosomatic diseases being a major factor for grounding or deviating significantly in rate from the general population; they neither discovered sickness trends attributable to irregular work patterns or rhythm disruption (3, 32, 41, 250). One is inclined to assume that the difference to the industrial shiftwork situation could be due to the intense medical preselection of the aircrew population. Nevertheless, a specific screening procedure able to predict an individual's aptitude to cope with irregular work-rest schedules might still reduce the number and intensity of short- and long-term disturbances.

3.5 Models

Based on extensive studies in which urinary biochemical responses were measured in military air crews during a great variety of experimental and operational stress exposures, Hale et al. (119, 120, 121) developed the concept of "physiological cost" of flying. This concept has been reviewed recently by Hartman (129) and was incorporated into considerations for management of irregular rest and activity (130). Differentiating between primary aircrew stressors, like sleep disturbances, and secondary stressors, like day-night cycles or time zone transitions impacting on man only if primary stressors are already taking their toll, he emphasized among others the necessity of provisions for good sleep and some balance of local and home base time. Probably because of the complexity of the interrelationship of the different factors, he did not formulate his findings in a mathematical form.

Realizing that circadian rhythms in air operations may well have impact upon flight crew efficiency and therefore flight safety in general, several attempts have been made to assess the effects in computable forms and incorporate them into formulas of a broader validity. Based on data from field studies, the formulas so far developed have covered besides the effect of desynchronization such factors as rest period time (47, 96, 284), the potential physiologic load (217), and the optimal or maximal workload (230). A general description of the various models is given in the following sections, a more detailed listing of the pertaining formulas is presented in Appendix 1. Examples of application and a general comparison of the outcome will be given in Appendix 2.

Rest period time. Buley's formula (47) for determining rest periods on long-distance air travel considers several factors as significant for the physiological and psychological state of the air traveler after arrival. Those available for computation are included in his model: flight duration, local times of departure and arrival, and time zones in excess of 4. It is obvious that by insertion of departure and arrival time, as well as number of time zones, circadian rhythmicity gains some weighting in this formula. In part it was derived from earlier studies (284) and in its improved form was applied to long-distance air travels by members of ICAO. As it has evolved, the equation reads: Rest period = Flight duration/2 + Time zones in excess of 4 + Departure time coefficient + Arrival time coefficient; or in symbolic form: $R = T/2 + (Z-4) + C_D + C_A$.

The coefficients are defined by dividing the 24-hour day in 5 sections and scoring them by numbers from 0 to 4 depending on their expected fatiguing effects. The validity of the formula has been tested by routine application, and the results were regarded as subjectively satisfactory. However, it has been stated that its applicability cannot be extended on air crew scheduling, but rather remains restricted to the business traveler.

On the basis of Buley's formula, Gerathewohl developed "a simple calculator for determining the physiological rest period after jet flights involving time zone shifts" (96). The underlying formula includes, in addition to the components of Buley's model, three more factors: age, flight direction (eastbound versus westbound displacement), and also traversed time zones less than four. The extended formula reads: Rest period = Travel time (in hours) + Departure time coefficient + Number of time zones + Arrival time coefficient + Geodirectional coefficient + Age coefficient; or reduced to the symbolic form: $R = T + C_D + N_{tz} + C_A + G_C + A_C$.

The geodirectional coefficient takes into account the different resynchronization rates observed between east- and westbound flights. Hence, traveling from West to East contributes twice as many credit points to the summation. The age coefficient ranges from 1 to 4 corresponding to classifications with increasing age. Credit for time shifts is already given with 1 time zone crossed and then "is graded as a cyclic function" with more time zones added.

Physiologic load. A different approach was chosen by Mohler (217) in 1976. Utilizing the data which he derived from airline pilots on world-wide flights, he developed a multiplicative and additive formula resulting in a "physiological index" giving the predicted overall flight pattern level of difficulty and pointing to critical segments within the pattern. The purpose of this index was to serve as an aid in constructing flight patterns, indicating when a pattern or segment has the potential of imposing high physiological loads. As major critical tiring factors in long-distance flights the following are included in the formula a) multiple night flights (necessitating day sleep), b) number of time zones and c) layover after an evening arrival. Multiple transits, patterns exceeding 7 days, flights in eastbound direction and the first flight of a pattern are also considered significant enough to contribute to the computation of the index. The calculation procedure is performed in 5 steps, each with many detailed conditions. Thus, a condensation to a simple symbolic form appears rather difficult, though, no doubt, the computation per se can easily be handled. As preliminary empirical criteria for the grade of load, empirical values are given reflecting easy, heavy, and definitely severe indices. At its present status, we hesitate to recommend a general application of this model, remembering the fact that the baselines were derived from very specific airline flight patterns with many segments. Thus, when applying the formula for instance to a rapid round trip between Frankfurt and Los Angeles, the resulting index did not reflect satisfactorily the high load on the crew of such a flight. This consideration does not question the validity of the model for other patterns. On the contrary, it may be seen as a start in the right direction and as a promising step in quantifying factors contributing to fatigue which otherwise are neglected or under-estimated.

Optimal/maximal workload. Nicholson (230) has developed an approach to quantify optimal and maximal workload for flight patterns including several segments and for aircrews operating world-wide.The workload is obtained from the duty periods and the number of days on route; time zones remain unregarded. Optimum workload is defined as the cumulated duty hours for days on route above which sleep difficulties may be encountered; maximum workload is reached when cumulated duty hours do not allow acceptable sleep patterns. Nicholson claims that during world-wide flights many factors may affect well-being and efficiency of aircrews, but that of prime importance is the maintenance of an acceptable sleep pattern which can be achieved only through an appropriate timing of duty periods. In his formula, calculation of workload is given by multiplying the days en route (+ 1) with the average duty hours per day. Thus, for flight patterns with several days en route, a table is derived indicating optimum and maximum of the accumulated duty hours for each day of the tour. Nicholson claims that the effects of irregular duty hours and time zone changes receive sufficient weighting in his formula as reflected by the reduction of the average workload for the whole tour with increasing duration.

3.6 Rest/Duty Regulations

Constructors of flight patterns are basically confronted with two aspects of the involvement of circadian rhythms in air operations. Simply, they may be called: shifted work and shifted time. The first aspect implies flight duty to be performed at abnormal daytimes within the 24-hour rest/activity cycle. The second aspect must be considered, when flight patterns include transmeridian routes.

There is general agreement that flying at unusual daytimes is more stressing than doing the same operations during normal hours, and probably there are no rest/duty regulations, issued by airlines or legislators, which do not take into account that this is one of the major fatiguing factors. To compensate for its impairing effects, all official regulations principally have incorporated the same expedients: reduction of flight duty hours, elongation of the subsequent rest period, and limitation of the number of night flights.

Some disagreement only exists in defining night flights, i.e. in stipulating what is the beginning and what is the end of the night, or how many flight hours have to be spent during night so that the flight will be conceded as night duty time. There are also minor divergencies where the 24-hour period is divided into sections and gradually differentiated with respect to causing more or less fatigue. Thus, the number of sections may differ between some regulations, amounting from 2 to 5 per day, and the beginning of the time period considered as most fatiguing may vary between 22.00 and 24.00 hours. As stated above, all these differences are minor and do not question the general acceptance of circadian rhythmicity as a factor potentially influencing performance and efficiency, when operations are conducted as night- or shiftwork. As far as literature on rest/duty regulations is available, it suggests the conclusion that this aspect is taken seriously and is sufficiently considered.

In view of this fact, it seems somewhat surprising that only few of the national and international rest/duty regulations, presently in force, seem to cover the aspect of circadian rhythmicity specifically evolving from operations on transmeridian routes. There are some reasons, however, conceivably responsible for this denial. First, considering the enormous variety of flight chedules and routes all over the world, it becomes obvious that a regulation satisfying the need for practicality and the demand for general validity appears rather difficult to develop. Secondly, regulations reflect a compromise regarding the various and sometimes divergent interests of the parties involved. Third, there is not yet unanimity among experts as to the extent these factors may affect flight safety through impairing crew efficiency.

To give an example, how the aspect of circadian rhythmicity in transmeridian operations is incorporated into legislation, the German rest/duty regulations are cited (11).

As a general rule for flight crews on transmeridian routes, the regulations imply that resynchronization to a new time zone must not be enforced but instead aircrews return as fast as possible to their home base. This applies only on the premises that sufficient rest time is provided within each 24-hour period away from home. To prevent sleep deficits, 14 hours rest time are considered the minimum under these conditions, and the operator is obliged to supply quarters which can be shielded from light and noise during local daylight hours. Upon returning to home base, the minimum rest period will be extended, if one or more flight segments have been spent in time zones differing from home base by 4 or more hours. The additional rest period required by regulation, will then be calculated by multiplying the largest time zone difference while on duty with the factor 8. Thus, if the largest difference has been 6 for instance, the additional rest period will be $6 \times 8 = 48$ hours; or with the largest difference being 12 time zones, the rest period requires additional $12 \times 8 = 96$ hours. The factor is primarily established on findings with respect to resynchronization times based on body temperature rhythm; it allows normalization of the circadian system for at least 50 % at the home base. Beginning a new duty period, the conditions with respect to the residual desynchronization are equal and independent of the number of time zones crossed before. In applying these principles, the regulations pursue the following objectives: (a) to keep shifting of circadian rhythms at a minimum while on duty in time zones different from home base; (b) to grant a rest time upon return with sufficient resynchronization of the biological timing system to avoid possible consequences on efficiency and health.

3.7 Synopsis

Since air operations occur around the clock and over many time zones, they interfere with the synchronization of the environmental and biological circadian timing systems. Subjectively, the post-transmeridian desynchronization may become manifest in a disturbance of those vegetative functions which like hunger, wakefulness and sleepiness, and defecation are strongly daytime-related: They appear at unusual and unconvenient hours. Objectively, the "jet lag phenomenon" is characterized through transient changes of the circadian oscillation of body functions, the most significant of which are: displacement of rhythm on the temporal axis, change in the oscillation range, and alteration of the 24-hour mean. For mental and physical performance rhythms, these changes mean lower functional values - i.e. a depression of the "readiness for efficiency" - at certain sections of the 24-hour cycle, and sometimes higher functional values at other times of day. Where the readiness for efficiency is degraded, preflight performance level, if at all, may be obtained only with extra effort and higher physiological costs.

Table 2: Factors Affecting Relative Rate of Post-Transme-
ridian Resynchronization

Faster	Slower
Evening Types	Morning Types
Extraversion	Introversion
Low neuroticism score	High neuroticism score
Younger	Older
Low pulse-respiration ratio	High pulse-respiration ratio
Labile (non-significant) rythms	Stable (significant) rhythms
Strong time cues	Weak time cues
Low amplitude	High amplitude
Delay (westward) shift	Advanced (eastward) shift

The following factors have been identified to affect the speed of re-entrainment (normalization) of biological rhythms: direction of flight, nature of function, characteristic of time cues, and individual features like personality and age (Table 2). Moreover, it was demonstrated that rapid return to the home base minimize the disadvantageous effects of time zone flights because of shorter resynchronization times.

Long-termed professional activity on transmeridian routes subjectively may cause a higher incidence of sleep problems, nervous disturbances and gastro-intestine complaints, particularly in female crew members. Objectively, however, the rate of psychomatic diseases shows no deviation from general population and seems to be no major factor for grounding; in addition, health surveys, so far, do not demonstrate sickness trends attributable to irregular working pattern or rhythm disruption. This seems to be different from the industrial shiftwork situation; the reason must be seen in the intense medical/psychological preselection and supervision of the aircrew population.

4. CIRCADIAN RHYTHMS IN SPACE OPERATIONS

The potential disturbance of circadian rhythmicity in the space environment and its consequences for performance efficiency and well-being of crew members were among the principal concerns expressed in the early phases of manned space missions (12, 13, 43, 108, 109, 138, 185, 198, 295). Though some of the apprehensions were not confirmed during actual flights, many questions posed at the beginning of the sixties have not been answered yet. Through recent reviews of several authors (10, 16, 293, 298) on the current status of "space biorhythmology" it became obvious that four aspects are still of major interest: 1. circadian rhythms of susceptibility to environmental agents, 2. consequences of change or lack of external circadian time givers, 3. effects of abnormal time schedules and shifts of rest-duty cycles, and 4. significance of the absence of gravity.

Since physiologic circadian rhythmicity as a source of variation in responses and susceptibility to environmental factors as well as the general effects of abnormal scheduling and shift work have been discussed in preceding sections, in this chapter only specific information will be reviewed which directly refers to space operations. Before going into further details, it may be helpful to recall briefly a description which has been given of the photic environment in space with respect to the "Zeitgeber" characteristics (295).

During orbital flights the length of the light-dark cycle depends on the altitude; below the van Allen radiation belt its duration is between 80 and 130 min, about 30 - 40 % of this period comprising darkness, i.e. earth shadow time. En route to the moon or to a planetary target the environment becomes non-periodic with permanent sunshine. On the moon itself a sunshine period of about two weeks is followed by a dark period of the same duration, while on Mars the day-night cycle is only 37 min longer than on earth.

For practical reasons, it seems opportune to discuss further the significance of circadian rhythms for space operations separately, considering first the sleep-wake cycle and thereafter rhythms of other physiological variables.

4.1 Sleep-Wake Cycle

There have been doubts expressed as to the possibility of an undisturbed sleep in space. Early flights confirmed these concerns: Repeatedly, astronauts and cosmonauts complained about poor sleep and sleep loss resulting partly in an accumulation of fatigue while in orbit. Irregularities of the sleep-wake cycle were held responsible for these symptoms which were often more pronounced during the first days of a mission. In some instances sleep difficulties apparently caused performance decrements; in others they led to the use of hypnotic drugs to promote sleep, and of an amphetamine-type medication to increase alertness following sleeplessness (93). Besides changes of environmental factors, like gravity and light-dark cycling, several operationally related reasons have been offered as explanation for the development of sleep disturbances (10, 35, 36, 298): 1. abnormal length of working periods (high work load effect); 2. continuous deviation of the sleep-wake cycle duration from 24 hours ("migrating day" effect); 3. phase shift of sleep periods in comparison with ground based sleeping time (night- and shift-work effect); 4. cyclic noise disturbances resulting from thruster firings, communications or movements in the spacecraft.

4.1.1 Space Flights

Recordings of an electroencephalogram in orbit during the Gemini VII mission allowed the first objective evaluation of the characteristics of two sleep periods (2, 207). Though recordings suffered from technical difficulties, it became obvious that one of the observed "nights" was inadequate in terms of duration and quality of sleep while the other one seemed to be fairly normal.

With regard to the work-rest cycles for space crews, Aschoff (13) stated in 1964: "Whatever schedule will be chosen, the basic phenomena of circadian rhythmicity cannot be disregarded". In fact, it turned out that sleep difficulties diminished whenever the flight protocol was subordinated to this principle. Corresponding measures included amelioration of work-rest scheduling as well as elimination of other external sleep disturbing factors, such as timing of communication with the ground and arranging the sleep for several crew members simultaneously but in individual compartments. These improvements finally allowed an approach to evaluate the "pure" effects of weightlessness on sleep in the Skylab flights.

Electroencephalogram and electrooculogram have been monitored in one crew member of each of the three manned Skylab missions (93). In orbit, recording began between the 3rd and 7th day and was performed during 9 to 20 selected nights. The most significant results can be summarized as follows: Inflight sleep EEG characteristics in general corresponded well with preflight findings; there were, however, some remarkable exceptions: In one astronaut (28-day mission) total sleep time, as compared with pre- and postflight averages, was significantly reduced during the whole period in orbit; reduction was not due to sleep difficulties, but was based on a voluntarily reduced total time spent in bed. In contrast to this one of the two other astronauts (284day mission) experienced "real" sleep difficulties in the initial part of the flight; they were of a magnitude that they could have interfered with performance capabilities, and occasionally they required sleeping medication. Objectively, during the first 19 days in orbit, sleep latency was increased and total rest and sleep time were reduced in this subject. Values returned to levels typical for the preflight and postflight period during the later part of the mission. Another phenomenon observed was the reduction of the number of awakenings (93); it had been predicted and was explained by the idea that the loss of gravity might cause "fewer sleep-interrupting body movements than on earth due to the so-called pressure points" (296).

Postflight changes were generally characterized by a late increase in state REM and a decrease in REM latency; at least in one case these changes were preceeded by a phase of relative REM-suppression immediately at the beginning of the recovery period.

4.1.2 Simulation Experiments

Some of the results from the Skylab missions coincide well with the findings from sleep analysis during prolonged simulation of weightlessness (276, 277): total sleep time was reduced at the beginning of a six-day water immersion period; there was a tendency for lengthening in the second half of the simulation, but sleep duration never reached the pre-immersion level. In contrast with the findings in space however, the percentage of total sleep time spent in stage REM and stage 4 was also reduced in the first half of the immersion period; during the later half a gradual

normalization was observed. Finally, there was a REM-rebound in the immediate post-immersion period.

In a simulation of a future Spacelab mission irregularity and shift of work-rest periods were studied by sleep-EEG recordings (192, 323, 324, 325). The most prominent results were a distinct increase in awake time, a decline of the sleep efficiency index and a diminution of REM average length and latency; these symptoms were more pronounced at the beginning and gradually stabilizing toward the end of the mission (Figure 35).

4.1.3 Synopsis

The present data with respect to the sleep characteristics in the absence of gravity suggest the following statements. There seem to exist three types of responses, possibly depending on the susceptibility of the individual:

(a)   a continuous reduction of sleeping time related to a diminished requirement for rest, but with no adverse effects on well-being and efficiency; this has been explained by different hypotheses (10, 103, 359);

(b)   no systematic alteration of sleep characteristics, except a somewhat higher variability;

(c)   a pronounced disturbance of sleep lasting days or weeks with subjective difficulties, a reduction of total sleep time, a need for sleeping medication, and the potential risk of a transitory impairment of performance efficiency; later this symptomatology may turn into one of the states described in (a) and (b).

Figure 35:Changes of sleep characteristics during a simulated Spacelab mission compared with pre- and post-mission control periods (mean values of 4 Payload Specialists; dashed lines: normal values of a control group).

More information is required on sleep characteristics during the initial phase in the micro-g environment, since the results from space flights in this respect are either lacking or not consistent with those from ground-based simulation experiments.

After recovery from a prolonged period of weightlessness, there are alterations in the sleep stage characteristics which are not well defined yet; they seem to indicate a readaptation process to the one-g condition which lasts, at least, for several days.

With regard to work-rest scheduling, former space flights as well as recent simulation experiments have emphasized that circadian rhythmicity should not be disregarded, if sleep disturbances are to be prevented.

4.2 Physiological Variables

The expected changes of periodic time cues connected with earth rotation made biorhythmologists predict an internal desynchronization of circadian rhythms in space. The prediction was derived from the results of ground-based experiments in a constant environment or from investigations in natural or artificial light-dark cycles with period lengths deviating from 24 hours. In addition it was suggested that, as for sleep, absence of gravity, confinement or restricted activity , and alterations of rest-activity cycles would be factors initiating a disturbance of physiologic rhythmicity.

4.2.1 Space Flights

Unfortunately, up to the end of the Skylab flights "regardless of the theoretical problems posed by various studies, because of priorities established during earlier programs, no human inflight biorhythm studies were scheduled" (195). Analysis of cardiovascular and respiratory data collected only for medical monitoring of astronauts or cosmonauts in orbit (118, 270) revealed evidence of a circadian fluctuation which, in part, was closely related to the imposed activity cycle. However, operational constraints prevented specific data collection on man allowing a more detailed discussion of the basic mechanisms of circadian rhythm response to the space environment (269).

In contrast, the US Bio-Satellite III experiment was especially set up for this purpose (123). Analysis of physiological parameters obtained from the Macaca nemestrina monkey during days 2 - 8 in orbit, indicated for CO_2, body temperature, and heart rate a consistent periodicity greater than 24 hours, whereas the arterial blood pressure showed a rhythm of exactly the length of a terrestrial day (107). The findings allowed the conclusion of an external desynchronization of some physiological rhythms from the imposed environmental 24 hour day-night cycle as well as an internal desynchronization between arterial blood pressure and other physiological parameters. (In connection with the potential role of geomagnetism as a Zeitgeber in space it is of interest that measurements of the magnetic flux density in orbit displayed predominant periods of 1.6, 23.5 and 70.4 hours). Since the results observed in flight had never been encountered during simulation on earth, a possible existence of a gravity dependent mechanism in the control of circadian rhythm was considered (107). However, the conclusiveness of this statement suffers from the fact that considerable changes in the cardiovascular status and fluid balance of the animal (210) gave rise to a premature call down of the Satellite on orbital day 9 and caused the death of the monkey 12 hours after recovery. The pathological processes responsible for the death of the animal - and not the space environment per se - could as well have caused the observed derangement of circadian rhythms.

A study in which urine volume, sodium, potassium, and hydrocortisone were measured in three crew members prior to and after the Skylab II Mission did not reveal major postflight differences with respect to circadian rhythm
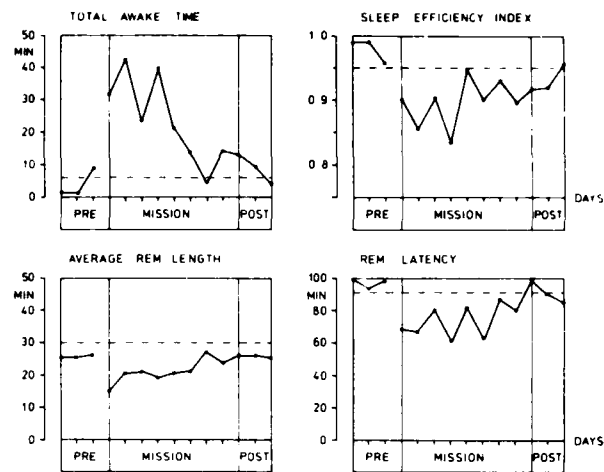
characteristics (195). In the opinion of the authors the results indicate that human physiologic rhythms remain synchronized in the absence of gravity as long as a well controlled 24-hour work-rest cycle is present as external Zeitgeber. They state that particularly in the case of the stable rhythm of potassium excretion one would not have expected the same phase relationship between pre- and postflight variation, if in orbit a disruption had occurred in the basic circadian control mechanism.

4.2.2 Simulation Experiments

Dysrhythmic changes similar to those observed in the monkey in space were found in man during earth-bound simulations of selected aspects of space operations, such as hypokinesis, confinement and isolation.

During 56 days of bed rest with controlled photoperiods, meals and activity, thyroid rhythms dissociated from cortisol rhythm as well as from light and activity schedules (313). Under the same conditions, the 24-hour mean and the amplitude increased in plasma ACTH rhythm but decreased in plasma cortisol (196). On the other hand, heart rate circadian variation was remarkably consistent, while body temperature exhibited a tendency to become desynchronized (349); in another bed rest study heart rate and body temperature phase-shifted in relation to each other and to the environment (350). Also plasma insulin rhythm shifted progressively and was apparently not associated with either light or meals regimen (346). Most parameters showed a prompt resynchronization in the post-experimental ambulatory period. Since muscular activity (exercise) during bed rest had no favourable effect on synchronization, a posture dependency of maintaining rhythm synchrony was concluded (351). It was speculated that the disturbances in the phase relationship of circadian rhythms might also be indirectly the consequence of changes in posture dependent factors, like hydrostatic pressure or distribution of body fluids and electrolytes (350). Confinement alone did not affect the phase of body temperature, as long as the photoperiod consisted of 16 hours of light followed by 8 hours of dark. Exposure to the presumed Skylab light environment, i.e. a constant low intensity light, resulted in free running rhythms (346, 347). In one group a phase shift of 12 min per 24 hours was observed, in another group the period length increased by 16 min per 24 hours. When isolated individually, subjects had phase-shifted differently, but living isolated in groups they were synchronized with each other, thus providing support for the suggestion that in man circadian cycles may be synchronized by group interaction (16, 346, 348).

During social isolation of 105 days duration in ambulatory subjects, an abrupt shift from a normal light-dark cycle of L(16):D(8) to a constant low intensity light condition (LL 24, 15 ft.c.) caused a significant augmentation of depression, aggressiveness and hostility as compared with controls and measured by selfrating scales and questionaires; at the same time, psychophysiologic awareness and psychosomatic complaints increased. Maximal changes occurred within 1 - 2 days after change of the illumination; return to baseline was achieved within 10 -12 days (264, 265).

In the Spacelab simulation study already mentioned in section 4.1.2 (192, 323, 325) analyses of the 24-hour rhythms of various physiological variables revealed internal dissociation due to shifts of sleep-wake schedules during the mission. As observed after transmeridian flights, rhythm of heart rate adjusted faster than body temperature, and both were faster than corticosteroid excretion (Figure 36).

4.2.3 Synopsis

The data presently available do not allow a definite statement as to the nature of responses of the human circadian system to space flights. Probably, this will be possible not before specific experiments on human subjects in space have been conducted. The present knowledge indicates, however, that (a) circadian rhythms persist in space, and (b) certain factors of the space environment and/or of space operations seem to favour the development of desynchronization between rhythms of one individual and possibly also between rhythms of individual members of a crew. Intraindividual desynchronization is considered as "physiological poorer" (16), "deleterious" (246), or "not compatible with good health and efficiency" (10). Desynchronization between individuals potentially creates problems for scheduling of work and rest within the team.

4.3 Discussion

Figure 36: Internal dissociation of circadian rhythms in different functional systems during a simulated Spacelab mission. Curves represent acrophases of the 24-hour cycles as averages from 4 Payload Specialists.

Adequacy of work-rest schedules is per se of high significance for both, normality of sleep in terms of length and quality, and for synchronization of circadian rhythms. Particularly in the absence of terrestrial physical periodicities the cycling alteration of rest and activity becomes a powerful regulator for the temporal structure of the organism. In isolation experiments, Russian researchers inversed circadian rhythms completely in a relatively short time through the appropriate work-rest schedule as a social synchronizer (291, 293). This can hardly be achieved through industrial night-work when at the same time the subject is continuously under the influence of the majority of conventional environmental time cues.

Adherence to a customary living schedule, i.e. a 24-hour day with a L(16):D(8) work-rest cycle, seems optimal for the entrainment of the circadian system (195) and is an aid for retaining good sleep (93). Circadian rhythms remain synchronized also under the conditions when several work and rest periods are comprised in 24 hours: synchronization by demultiplication (16). According to Stepanova (292) adaptation to a 23-hour day presents difficulties: "Daily migration of phase of the sleep-wakefulness rhythm counter-clockwise, equal to one hour, is by no means within the capacity of all persons, especially those over 30 years of age". Also Aschoff (16) considers an entrainment to a day shorter than 24 hours not easy. According to his experience shortening of the Zeitgeber period may cause loss of entrainment and subjectively unpleasant feelings. Because of the natural tendency of most persons towards periods somewhat longer than 24 hours, he suggests that the possibility should be tested to keep space crews on an artificial day with such a period length. The consequences of neglecting these considerations convinced medical supervisors in the U.S. that
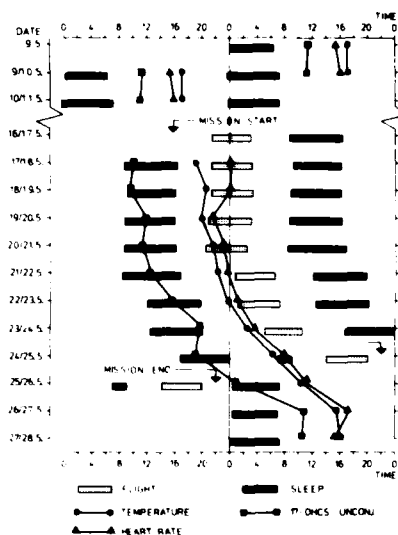
"efforts must be continued with flight planners to maintain the work day in flight at about 12 hours allowing 8 hours for sleep and 4 hours for leisure" (207). Russian psychophysiologists, however, have emphasized that the sequence of work and sleep will be subordinated to the task of the mission and will not have a close analogy with terrestrial activities (189); they even exclude for prolonged space flights the possibility of constructing 24-hour schedules (106) and demand a flexible approach to patterns of rest and activity.

In this context, Nicholson (229) has discussed the analogy of the work schedules for airline pilots on world-wide routes (see "Sleep-Wake Cycle", section 3.1.4) to the situation of space crews. Since pilots seemed to tolerate irregular duty hours taking naps both, during rest and duty periods, he recommends this system as a more realistic approach to the operational requirements of prolonged spaceflights than the demand that the work schedules must be constructed in such a way that the Zeitgeber period becomes a multiple of the 24-hour rhythm. As long as the workload permits an acceptable sleep pattern to emerge, irregular duty should be feasible. Space flight experience has itself shown that some of the irregular sleep and waking schedules were tolerated up to two weeks, but that by three or four weeks both, ground personnel and onboard crew, noted decreased efficiency under such irregular patterns. Nicholson supports the view that short duration high workload missions, asin the early days of space flight, may be more amenable to a random pattern of work and rest, whereas the long duration low workload missions of the Skylab type would be more amenable to the 24-hour cycling. In actual experience however, the first weeks of long duration missions were treated operationally just like short duration flights.

Indeed, a pattern allowing irregular sleep and duty hours to be commenced at any sidereal time would do away with many difficulties of flight planners. But there remain some questions to be answered and some comments to be stated.

(a)   Other researchers found adaptation to irregular sleep and waking schedules "not easy". Trials to adapt man to very unusual cycle lengths, i.e. 16-hour and 48-hour days, "ended in failure", because of development of marked neurotic disorders (10).

(b)   Irregularity of sleep and wakefulness results in desynchronization of the circadian system; the consequences have been discussed earlier (see "Sleep-Wake Cycle", section 3.1.4). In airline pilots the period of irregular patterns lasts for a limited time only, i.e. not more than 2 or 3 weeks, at the most; this phase is followed by a period of conventional 24-hour days at home which induce re-entrainment of biological rhythms. What happens if the irregular pattern lasts longer and adjustment through external synchronizers is lacking?

(c)   Split-period sleep involves the possibility of stage REM sleep deprivation; though sleep was not monitored in airline pilots, the pattern is considered as fully adapted since they had freedom to sleep often, even if only for very short periods (229). This raises the question: Will naps on duty in space be compatible a) with mission operations, b) with emotional stress?

d)   Finally, it should be realized that there are considerable individual differences with respect to tolerance to irregular work-rest schedules, to split-period sleep, to sustained wakefulness and sleep reduction.

As long as the impact of these factors for space operations is not clear, it seems advisable to establish a 24-hour sleep-wake cycle, unless operational considerations override.

5. RECOMMENDATIONS

The various problems of circadian rhythmicity in aerospace operations have been summarized at the end of each of the foregoing chapters. The recommendations given in this final chapter represent very condensed operational conclusions, as they can be derived from the present state of knowledge. Some of them apply to both air as well as space operations; some are relevant only for one of the areas.

Recommendations pertaining to air operations are given first, with each of the specifically affected group being adressed.

Passengers, whose goal is to hasten circadian resynchronization, should shift the rest-activity cycle, in particular the timing of sleep and meals, to local conditions immediately after arrival at the final destination. They should relax for the first 24 hours, but otherwise not isolate themselves from environmental time cues. Sufficient (extended) sleep during the first night seems essential; if necessary, this goal should be obtained using a hypnotic. Where possible, pre-adjustment in timing of sleep and meals before the flight can be helpful; this must be done, of course, in relation to the expected direction of time shift.

Aircrews aiming to avoid time zone adjustment should try to stay on home base pattern while en route and use any chance for sleep through naps and even short acting hypnotics; however, side effects of sleeping aids must be tested individually and intake should not be later than 12 hours before duty. Since night flying and irregular rest-activity patterns require extra effort, they should not add any additional stresses. After return to the home base it is essential to utilize off-duty time sufficiently for rest and recreation.

Management engaged in maintaining maximum flight safety, should consider the following factors as contributing to aircrew load when constructing work-rest schedules: duration of duty period, departure and arrival time, number of time zones crossed, number of night flights. (Hints for application of these factors in rest/duty regulations are given in various models; however, a solution of general validity has still to be found).

Night duty should only be commenced well rested. Since it is more stressful, maximum permissible night duty hours should be shortened. If possible, maximum efficiency (such as required during landing an aircraft after a long-haul flight) should not be demanded at the time of maximum behavioural depression at the circadian trough.

In addition, where transmeridian flights are involved, efforts should be taken to provide accomodation permitting crews en route to stay on home base patterns. As far as possible, schedules should be arranged for a rapid return to home base; extended rest periods should be granted at home to allow biological rhythms to resynchronize with the environment. Since irregular patterns seem to become more stressful with age, transmeridian flying should be reduced for crew members older than 50 years. Posting air crews overseas is an excellent solution for most of the medical problems arising from time zone flying.

Flight surgeons responsible for air crew health and efficiency should exclude from long-term duty on transmeridian routes individuals with a disposition of sleep disturbances, gastrointestinal disorders and other psychosomatic complaints.

Investigators searching to improve the overall situation, should try to develop objective criteria for selection of individuals fit for duty with irregular rest-activity patterns occurring in shiftwork and in flying on transmeridian routes.

It is obvious that for space operations some of the recommendations given above are also valid. The lack of circadian time cues in the natural space environment and the potential effects of weightlessness on biological rhythms and sleep give rise, however, to some additional statements.

Mission management should provide a 24-hour periodicity in scheduling work-rest cycles, taking into account the normal terrestrial rest/duty proportion of 1:2. Because of their time-giver characteristic, sleep-begin and sleep-end should be planned according to launch-site or mission control center time.

If possible, sleep for crew members should be arranged simultaneously, but in individual compartments. Care should be taken that individual sleep behaviour characteristics are matching, and combinations of "larks" and "owls" should be avoided. External sleep disturbing factors, including those caused by communication with the ground, must be eliminated. This is even more essential, when duty periods of crew members are phase-shifted against each other. In this case a separation of sleeping quarters from the working area is necessary.

Investigators, similar as for air operations, should develop more precise criteria for the adaptation capacity of the circadian system. Depending on mission characteristics and operation schedules, slow or rapid shifting of circadian rhythm may be required. Parameters or means of predicting the individual speed as well as the "ease" or "non-ease" in adjusting to changes of Zeitgebers are desirable.

APPENDIX 1

DETAILED DESCRIPTION OF FORMULAS AND MODELS

Sasaki's formula. The formula was developed to estimate the resynchronization status of the biological timing system after transportation across longitudes (278). Based on observations of body temperature resynchronization, it was postulated that the reduction in phase lag, i.e. time difference between biological and environmental timing system, proceeds asymptotically. From the fundamental assumption that the rate of phase lag reduction, dy/dt, is proportional to the phase lag at time t, the following equation was derived:

$$\frac{dy}{dt} = \frac{1}{\tau} \, [f(t) - y] \qquad (1)$$

y : longitude of biological rhythm
f(t) : longitude of aircraft position
f(t)-y : phase lag at time t (in days)
: time constant

Starting from a location λ_0 and traversing longitudes at a constant speed v, the aircraft position becomes

$$f(t) = vt + \lambda_0$$

and equation (1) is converted to

$$\frac{dy}{dt} + \frac{1}{\tau} \, y = \frac{1}{\tau} \, (vt + \lambda_0) \qquad (2)$$

Solving equation (2) for y, the following solution is obtained:

$$y = (y_0 - \lambda_0 + \tau v) e^{-\frac{t}{\tau}} + (vt + \lambda_0 + \tau v) \qquad (3)$$

y_0 : initial longitude of biological rhythm
λ_0 : longitude of starting point
v : angular velocity of aircraft along latitudes in degrees per day

For the condition that the traveler remains in the same location (λ_0) , as is the case for stopovers or for arrival at the destination, the aircraft position becomes f(t) = λ_0, and the solution (3) of the differential equation (2) is reduced to:

$$y = (y_0 - \lambda_0) e^{-\frac{t}{\tau}} + \lambda_0 \qquad (4)$$

Findings derived from studies on body temperature resynchronization revealed empirical values for the time constant ranging from 2.5 to 4.3 days. Variation was observed mainly between individuals and in dependence on flight direction, the average constant after eastbound flights being for instance τ = 4.0 days and after westbound flights τ = 2.8 days.

Buley's model. This model was conceived for the computation of rest periods on long-distance air travel (47). Basing on significant and easily-quantifiable stress factors and at the same time compromising between scientific accuracy and administrative expediency, the following formula was developed: Rest period = Flight duration/2 + Time zones in excess of 4 + Departure time coefficient + Arrival time coefficient; or reduced to the symbolic form:

$$R = T/2 + (Z - 4) + C_D + C_A$$

According to the author, some principal ground rules have to be followed for the application of the formula:
(a) The resulting R in tenths of a day is rounded to the next higher half of a day.
(b) Departure and arrival time are in local time.
(c) Stopovers exceeding 2 days constitute termination of a travel, the onward flight is considered as the beginning of a new journey.
(d) The maximum rest period allowable at any place en route is 2 days.

For the determination of the departure and arrival coefficients it was assumed that they should be predicated on the shape of a typical circadian performance curve and on the social pattern, i.e. in particular the sleep period, of the departure and arrival places. Therefore, the 24-hour period was devided into 5 sections and scored from 0 to 4 depending on the presumed fatiguing effect. The scores have been associated with the 24-hour sections as follows:

Coefficient	Departure Time	Arrival Time
0	0800 - 1159	1800 - 2159
1	1200 - 1759	2200 - 0059
2	- -	1200 - 1759
3	1800 - 2159	0100 - 0759
	0100 - 0759	- -
4	2200 - 0059	0800 - 1159

The author claims that if the sums of C_D and C_A for each 24-hour section are plotted above the midpoints of the sections, a curve is produced "which approximates the vertical mirror image of a typical circadian performance curve".

Gerathewohl's model. The underlying formula is principally an extension of Buley's model (96). In addition, it also considers traversed time zones less than four, flight direction (eastbound versus westbound) and the age of the traveller, thus comprising 6 main factors presumably associated with "jet-flight fatigue" in a simple summation. The extended formula reads: Rest period = Travel time + Number of time zones + Departure time coefficient + Arrival time coefficient + Geodirectional coefficient + Age coefficient; or in symbolic form:

$$R = T + N_t + C_D + C_A + G_C + A_C$$

For an easy and convenient computation of the rest period time a calculator was developed which basically resembles a circular slide rule and is operated in a similar fashion. It bears the scales of the various factors, relating 5 credit points to them in the following manner (TZ = time zones):

Credits	Departure-Time	Arrival-Time	Age	Flight-Direction	
				E – W	W – E
1	12.00 – 17.59	18.00 – 21.59	≤ 30	1 – 6 TZ	1 – 3 TZ
2	08.00 – 11.59	22.00 – 00.59	31 – 45	7 –12 TZ	4 – 6 TZ
3	18.00 – 21.59	12.00 – 17.59	46 – 60	– –	7 – 9 TZ
4	22.00 – 00.59	01.00 – 07.59	– ≥ 60	– –	10 –12 TZ
5	01.00 – 07.59	08.00 – 11.59	– –	– –	– –

The number of time zones is not included in the table, since they are weighted in a non-linear way and, as the author stated, "the time zone scale is graded as a cyclic function in accordance with circadian adjustment to local time after geographic displacement". Credit points approximately amount to 0.3 for one time zone up to 15.0 for 12 time zones.

As can be noticed from the figures above, the geodirectional coefficient is weighted differently in dependence on the flight direction, thus taking into account circadian asymmetry: Travelling from West to East contributes about twice as many credit points to the rest period calculation than flying in westbound direction. Finally, it is also note-worthy that the age of the traveler is considered in such a way that the older persons get more credit after long-distance flights than the younger persons.

Mohler's "physiological index". As an aid in constructing flight patterns, a multiplicative and additive formula was conceived enabling the computation of an index indicating low or high physiological demand of a pattern in total, or of its single segments (217). Basing on freshness/tiredness data derived from aircrews on world-wide flights, empirical values were defined reflecting the grade of demand as follows:

Indices lower than 1.75	: "easy"
Indices ranging from 1.75 to 2.30	: "heavy"
Indices exceeding 2.30	: "definitely severe"

Essentially eight factors are presumed to constitute the potential "load", the three major fatiguing factors in flight being: number of time zones traversed, multiple night flights in close sequence, and 24-hour layovers after night arrival. The remaining 5 factors are considered as moderately fatiguing and include: the first day of a pattern, multiple transits, day sleep, flight in easterly direction, patterns in excess of 7 days. The contribution of these factors to the overall demand of a flight pattern segment is graded by applying scores ranging from 1.0 to 2.2 in steps of 0.1, depending on the intended weighting. In five steps 5 scores are obtained which by multiplication result in the overall index of a flight pattern segment. The procedure is as follows:

Step 1.

Score 1.0 for a segment on days 2 through 7 of a flight pattern.
Score 1.1 for a segment on the first day and on days 8 and more of a flight pattern.

Step 2.

Depending on the duration of the layover period preceding the next departure, scoring is performed according to the following ranking:

Layover (hours): <12 12-17 18-20 21-27 28-43 44-52 53-59 ≥60
Score: 1.5⁺ 1.3   1.2   1.4⁺⁺ 1.0   1.0⁺⁺⁺ 1.1   1.3

⁺ Add 0.2, if day sleep required (between 0600 and 2100 local time).
⁺⁺ Add 0.3, if following departure is between 2100 and 0600 within the next 24 ± 3 hours local time.
⁺⁺⁺ Add 0.4, if following departure is between 2100 and 0600 local time.

Step 3.

(a) Score 1.7, if departure is between 2100 and 0600 local time.
(b) Add 0.1, if departure according to (a) was preceded within 72 hours by a night flight (any flight encompassing 4 or more hours between 2100 and 0600 local time).
(c) Score 1.0, if (a) and (b) not applicable.

Step 4.

(a) Score from 1.0 to 2.2, depending on number of traversed time zones. Score 1.0 if no time zone difference. Add 0.1 for each time zone differing between departure and destination up to a maximum of 12.
(b) Add 0.1, if time zones were traversed in eastbound direction.

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<u>Step 5.</u>

Score 1.0 and add 0.1 for each transit between two layover points in sequence.

Multiplication of the 5 scoring values as obtained in step 1 through 5 reveales the physiological index for the pattern segment under consideration. Regarding minimum and maximum values possible in each step, it becomes obvious that the lowest index will be 1.0 and the highest will equal the product: $1.1 \times 1.7 \times 1.8 \times 2.3 \times$ (1.0 plus 0.1 for each transit) = 7.74 or higher.

For calculating the total flight pattern index the segment indices are added and devided by the number of days away from home base, or more precisely by the quotient (hours away) /24.

Nicholson's model. Based on empirical data obtained from a study on airline pilots operating on world-wide routes, this model presents an approach to quantify low and high workload of flight patterns and its single segments (230). Workload was calculated as duty hours accumulated on route divided by (number of days on route + 1). The additional day in the denominator was given for the preparation activities during the 24 hours preceding the commencement of the flight schedule. Sleep patterns were evaluated and related to duty hours and number of days on route. Sleep patterns were considered acceptable, if the average sleep duration per 24 hours over 72 hours preceding duty was not below that observed during a control period of approximately one month during which the pilots were not involved in route flying. The graphical representation of the various relations led to the construction of a zone separating work load unlikely to lead to sleep difficulties from work load unlikely to maintain an acceptable sleep pattern. The borders of the zone have been termed the low and high workloads, respectively. From the results evidence was gained that "the workload compatible with an acceptable sleep pattern reduces in a logarithmic manner", as the number of days en route increases.

Duty hours representing low and high workload in dependence on days en route are listed below on the left side. On the right side values are given predicting the duration of flight schedules as to be considered of low or high workload when related to different amounts of total duty hours en route accomplished.

Days on Route	Duty Hours		Total Duty Hours	Schedule Duration (Hours)	
	Low Workload	High Workload		Low Workload	High Workload
2.0	26.0	29.5	30	64	–
3.0	32.0	36.0	40	109	88
4.0	37.5	42.0	50	165	138
5.0	42.0	47.0	60	237	202
6.0	46.0	51.0	70	312	280
7.0	50.5	55.0	80	–	368
8.0	54.0	58.5			
9.0	57.0	62.0			
10.0	60.5	65.0			
.	.	.			
.	.	.			
.	.	.			
16.0	79.0	82.0			

APPENDIX 2

APPLICATION AND COMPARISON OF MODELS

In order to see how the different models described in Appendix 1 can be applied, two typical flight schedules were chosen: (1) a 12-day "return schedule" between London and Honolulu with 9 flight legs, (2) a " round the world schedule" over 16 days, also with 9 flight legs and starting in London. All flight data are taken from Nicholson (228, 330) and presented in Tables 3 and 4.

Table 3: "Eastern Return Schedule" between London (LHR) and Honolulu (HNL): The eastward flight via Rome (FCO), Delhi (DEL), Hong Kong (HKG) and Tokyo (HND), the return flight via Tokyo, Hong Kong and Teheran (THR). [+]

Flight	Leg	Day on route	Dep	Arr	Flight duty		Layover period		Time zones
					h	min	h	min	
LHR - FCO	1	1.	15.oo	22.3o	6	3o	17	oo	1 E
FCO - DEL	2	2.	17.oo	o5.3o	9	oo	21	oo	3.5 E
DEL - HKG	3	3.	o4.oo	16.3o	9	oo	47	oo	3.5 E
HKG - HND	4	5.	16.oo	o2.oo	1o	oo	17	3o	0
HND - HNL	5	6.	21.oo	1o.35	8	35	23	35	5 E
HNL - HND	6	8.	11.4o	16.35	9	55	17	oo	5 W
HND - HKG	7	9.	11.o5	16.35	5	3o	21	55	0
HKG - THR	8	1o.	16.oo	23.3o	13	oo	25	oo	5.5 W
THR - LHR	9	12.	o2.oo	1o.4o	11	1o	--	--	2.5 W

[+] Data according to Nicholson (228, 23o).

Table 4: "Round the World Schedule" with all Flights in Westward Direction: From London (LHR), via New York (JFK), San Francisco (SFO), Honolulu (HNL), Nandi (NAN), Sidney (SYD), Singapore (SIN), Delhi (DEL), Teheran (THR), and back to London. [+]

Flight	Leg	Day on route	Dep	Arr	Flight duty		Layover period		Time zones
					h	min	h	min	
LHR - JFK	1	1.	13.45	18.2o	9	35	19	1o	5 W
JFK - SFO	2	2.	15.oo	19.45	7	45	21	15	3 W
SFO - HNL	3	3.	18.3o	23.5o	7	2o	21	25	2 W
HNL - NAN	4	4.	23.45	o5.2o	7	35	72	1o	2 W
NAN - SYD	5	8.	o7.oo	1o.55	5	25	47	o5	1.5 W
SYD - SIN	6	1o.	11.3o	19.4o	11	1o	74	1o	3 W
SIN - DEL	7	14.	23.2o	o3.4o	6	5o	21	o5	2.5 W
DEL - THR	8	15.	o2.15	o5.3o	4	45	2o	55	1.5 W
THR - LHR	9	16.	o3.55	12.2o	1o	55	--	--	2.5 W

[+] Data according to Nicholson (228, 23o).

For each flight leg the rest period time was calculated according to the models of Buley (Tables 3.1 and 4.1) and Gerathewohl (Tables 3.2 and 4.2). Credit points for time zones in Gerathewohl's model were taken from the illustration of the circular slide rule presented by the author (96). The actual flight duty time was used for the calculation of flight or travel time in both models, since flight duty time was considered more appropriate for application to flight personell than for passengers who remain passive.

Mohler's "physiological index" was also calculated for each single flight leg (Tables 3.3 and 4.3). In accordance with the author, layover periods were estimated by subtracting 1.5 hours ("block time") from the time between arrival and departure. Since both flight schedules did not contain a transit within any flight leg, the scoring of step 5 revealed 1.0 in all cases.

The accumulated duty hours and the total days on route in Tables 3.4 and 4.4 are taken from Nicholson (230). Subunits of low and high workload limits not given in the listings of the description of Nicholson's model in Appendix 1 were calculated by linear interpolation.

As to the a b s o l u t e level of demand of the various flight legs, a grading was possible only for the approaches of Mohler and Nicholson, since both authors relate their resulting values directly to defined limits. Thus, for the eastern return schedule Mohler's index indicates five flight legs being of "definitely severe", one of "heavy" and three of "easy" demand. For the same flight pattern Nicholson's model diagnosis high workload only for two legs (total duty hours beyond the limit for high workload), less than high but more than low demand for one, and a low workload for the remaining flight legs. Comparing the outcome of both models it can be stated that they conform very well in the classification for flight legs 1,4,8 and 9, fairly well for legs 2 and 7, but completely disagree in their estimates for legs 3, 5, and 6. The same comparison for the round the world schedule revealed better concurrence: Identical gradings for 6 out of 9 flight legs and disagreement in three cases (leg 4, 7 and 8). Taking the average for the total flight schedule,

both models come to the same result: easy demand with an average index of 1.33 or low workload with an average duty of 4.3 h per day. When Applying the same averaging to the eastern return schedule, Mohler's model indicates with a mean index of 1.88 a heavy demand and Nicholson's approach would predict a "high workload" with an average of 6.45 hours duty per day.

In order to make all four models comparable, a ranking from 1 to 9 according to the number of flight legs was introduced, rank 1 reflecting the lowest and rank 9 the highest demand. For Buley's and Gerathewohl's model the calculated rest period time was ranked, assuming that the lenght of this period is the resultant of the workload factors of the foregoing flight duty, as defined by the models. Thus, duration of the rest period becomes a direct, though only relative, demand estimate for the flight duty under consideration. For Mohler's approach the indices were ranked. For the ranking of Nicholson's model, the difference between the high workload limit and the accumulated duty time was calculated. The highest differences were scored with the lowest ranks, since they were considered to represent the lowest workload (the lowest values below the high workload limit). A negative difference indicates a workload beyond the high load limit and was assigned a higher rank the futher it was beyond this limit (e.g. legs 8 and 9 in Table 3.4).

Table 3.1: Evaluation of Rest Period Time by Buley's Model for Flight Schedule Given in Table 3

Leg	T/2	(Z-4)	C_D	C_A	Rest d	Rest h	Rank
1	3.3	–	1	1	0.53	12.7	2
2	4.5	–	1	3	0.85	20.4	4
3	4.5	–	3	2	0.95	22.8	6
4	5.0	–	1	3	0.90	21.6	5
5	4.3	1	3	4	1.23	29.5	8
6	5.0	1	0	2	0.80	19.2	3
7	2.8	–	0	2	0.48	11.5	1
8	6.5	1.5	1	1	1.00	24.0	7
9	5.6	–	3	4	1.26	30.2	9

Table 4.1: Evaluation of Rest Period Time by Buley's Model for Flight Schedule Given in Table 4

Leg	T/2	(Z-4)	C_D	C_A	Rest d	Rest h	Rank
1	4.8	2	1	0	0.78	18.7	4
2	3.9	–	1	0	0.49	11.8	1
3	3.7	–	3	1	0.77	18.5	3
4	3.8	–	4	3	1.08	25.9	9
5	2.7	–	3	4	0.97	23.3	6
6	5.6	–	0	0	0.56	13.4	2
7	3.4	–	4	3	1.04	25.0	7
8	2.4	–	3	3	0.84	20.2	5
9	5.5	–	3	2	1.05	25.2	8

Table 3.2: Evaluation of Rest Period Time by Gerathewohl's Model for Flight Schedule Given in Table 3

Leg	T	N_t	C_D	C_A	G_C	A_C^+	Rest (h)	Rank
1	6.5	0.3	1	2	1	3	13.8	2
2	9.0	1.7	1	4	2	3	20.7	4
3	9.0	1.7	5	3	2	3	23.7	6
4	10.0	0.0	1	4	0	3	18.0	3
5	8.6	3.1	3	5	2	3	24.7	8
6	9.9	3.1	2	3	1	3	22.0	5
7	5.5	0.0	2	3	0	3	13.5	1
8	13.0	3.8	1	2	1	3	23.8	7
9	11.2	0.9	5	5	1	3	26.1	9

+ According to Nicholson (230) the age of the pilot was in the fifth decade.

Table 4.2: Evaluation of Rest Period Time by Gerathewohl's Model for Flight Schedule Given in Table 4

Leg	T	N_t	C_D	C_A	G_C	A_C[+]	Rest (h)	Rank
1	9.6	3.1	1	1	1	3	18.7	4
2	7.8	1.3	1	1	1	3	15.1	1
3	7.3	o.7	3	2	1	3	17.o	2
4	7.6	o.7	4	4	1	3	2o.3	8
5	5.4	o.5	5	5	1	3	19.9	7
6	11.2	1.3	2	1	1	3	19.5	5
7	6.8	o.9	4	4	1	3	19.7	6
8	4.8	o.5	5	4	1	3	18.3	3
9	1o.9	o.9	5	3	1	3	23.8	9

[+] Explanation see Table 3.2.

Table 3.3: Evaluation of Mohler's Physiological Index for Flight Schedule Given in Table 3

Leg	Scoring according to step					Index[+]	Rank
	1	2	3	4	5		
1	1.1	–	1.o	1.2	1.o	1.32 *	2
2	1.o	1.3	1.o	1.45	1.o	1.89 **	4
3	1.o	1.7	1.7	1.45	1.o	4.19 ***	9
4	1.o	1.o	1.o	1.o	1.o	1.oo *	1
5	1.o	1.3	1.8	1.6	1.o	3.74 ***	7
6	1.1	1.4	1.o	1.5	1.o	2.31 ***	5
7	1.1	1.3	1.o	1.o	1.o	1.43 *	3
8	1.1	1.4	1.o	1.55	1.o	2.39 ***	6
9	1.1	1.7	1.7	1.25	1.o	3.97 ***	8

[+] By multiplication of scores from step 1-5, * easy, ** heavy, *** definitely severe demand.

Table 4.3: Evaluation of Mohler's Physiological Index for Flight Schedule Given in Table 4

Leg	Scoring according to step					Index[+]	Rank
	1	2	3	4	5		
1	1.1	–	1.o	1.5o	1.o	1.65 *	4
2	1.o	1.2	1.o	1.3o	1.o	1.56 *	2
3	1.o	1.4	1.o	1.2o	1.o	1.68 *	5
4	1.o	1.7	1.7	1.2o	1.o	3.47 ***	8
5	1.1	1.3	1.o	1.15	1.o	1.64 *	3
6	1.1	1.o	1.o	1.3o	1.o	1.43 *	1
7	1.1	1.3	1.7	1.25	1.o	3.o4 ***	7
8	1.1	1.7	1.8	1.15	1.o	3.87 ***	9
9	1.1	1.2	1.8	1.25	1.o	2.97 *	6

[+], *, *** Explanation see Table 3.3.

Table 3.4: Evaluation of Low and High Workload by Nicholson's Model for Flight Schedule Given in Table 3

Leg	Total hours duty	Total days on route	Duty hours[+] low	high	Difference[++]	Rank
1	6.5	~	—	—	—	1
2	15.5	1.4	22.o	25.o	9.5	2.5
3	24.5	2.7	3o.o	34.o	9.5	2.5
4	34.5	4.1	38.o	42.5	8.o	5
5	43.o	6.3	47.o	52.o	9.o	4
6	53.o	7.7	53.o	57.5	4.5	6
7	58.5	8.7	56.o	61.o	2.5	7
8	71.5	1o.3	61.o	66.o	− 5.5*	8
9	82.7	11.8	66.o	7o.5	− 12.2*	9

[+] Limits for low and high workload. [++] Difference between high workload limit and total hours duty. * High workload.

Table 4.4: Evaluation of Low and High Workload by Nicholson's Model for Flight Schedule Given in Table 4

Leg	Total hours duty	Total days on route	Duty hours[+] low	high	Difference[++]	Rank
1	9.6	—	—	—	—	1
2	17.4	1.6	23.5	26.5	9.1	9
3	24.7	2.9	31.5	35.5	1o.8	6
4	32.3	4.2	38.5	43.o	1o.7	7
5	38.2	7.5	52.o	57.o	18.8	3
6	48.9	1o.o	6o.5	65.o	16.1	5
7	55.2	13.4	71.o	75.o	19.8	2
8	6o.5	14.5	74.5	78.o	17.5	4
9	71.5	1ö.o	79.o	82.o	1o.5	8

[+], [++] Explanation see Table 3.4.

In this way, a procedure was obtained permitting the comparison of at least the r e l a t i v e gradings of all four models. The results are summarized for both flight schedules in Table 5.

A comparison of the ranks resulting from the four different models does not appear very encouraging with respect to conformity of the estimates for each flight leg. Only few cases demonstrate adequate congruity, i.e. for flight legs 1, 2, 8 and 9 of the eastern return schedule, and for leg No. 4 of the round the world schedule. The variance is rather high in all other cases, including a case of extreme discrepancy in which the lowest rank is combined with the highest one (leg 2 of the round the world schedule). In general, the agreement of all four models seems to be better for the return than for the round the world schedule. As could be expected, the comparison between Buley's and Gerathewohl's models reveals considerable conformity, since both are based on the same conceptual design. Agreement of these two models with Mohler's index is moderate but only less than moderate with Nicholson's model, which seems to be the "outsider" in this group of four approaches. Of course, these statements do not say anything about the validation of the approaches. The method giving the better workload estimate in a given situation, is unknown. The reasons for discrepancies are very complex. Thus, for instance, flight duration is taken into account by Buley, Gerathewohl and Nicholson, but not by Mohler. On the other hand, departure and arrival time are not considered by Nicholson, but they are by Buley and Gerathewohl, wereas only departure time is incorporated in Mohler's approach. Also, it should be pointed out that Buley's and Gerathewohl's model were originally developed for the flight passenger, especially the business traveller. But taking the estimated duration of the rest period as a quasi index for the workload of the preceding flight duty, both models may be applied to aircrew, as could be demonstrated in this chapter.

Further research in this area will be necessary to validate the predictors of the different models. The procedure outlined in this chapter may be seen as a first step in this direction Possibly, at the end a new approach could evolve which combines the most effective parts of the four models.

Table 5:   Comparison of Ranks Evaluated by the Different Models

Leg	Eastern Return Schedule				Round the World Schedule			
	Bu	Ge	Mo	Ni	Bu	Ge	Mo	Ni
1	2	2	2	1	4	4	4	1
2	4	4	4	2.5	1	1	2	9
3	6	6	9	2.5	3	2	5	6
4	5	3	1	5	9	8	8	7
5	8	8	7	4	6	7	3	3
6	3	5	5	6	2	5	1	5
7	1	1	3	7	7	6	7	2
8	7	7	6	8	5	3	9	4
9	9	9	8	9	8	9	6	8

Bu = Buley, Ge = Gerathewohl, Mo = Mohler, Ni = Nicholson.

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APPENDIX 3

THE "BIORHYTHM" THEORY

The concept of Biorhythm was first brought up at the end of the 19th and at the beginning of the 20th century by W.Fliess, a German ENT specialist in Berlin, H. Swoboda, an Austrian psychologist from Vienna, and by the engineer A. Teltscher from Innsbruck, Austria. In the thirties it was further developed mainly by mathematicians and engineers like A. Judt from Germany and H.R. Früh from Switzerland; it finally gained general public interest, in particular in the Anglo-American sphere, through G. Thommen's book (310) on "Biorhythm".

The concept claims that each human being's performance is governed by three basic cycles of different period lengths (Figure 37): a 23-day "male" or "physical" cycle involving changes in strength and endurance, a 28-day "female" or "emotional" cycle covering changes in sensitivity and emotional reactions, and a 33-day "intellectual" cycle comprising changes in intelligence, alertness or awareness. It pretends to be able to predict human behaviour in terms of "bad" or "good" days at any time of any person's life. This is done by a mathematical model which rests on a number of indispensable premises, some of the more important being the following:

- Each cycle is described by a sine curve having a positive and negative phase with two cross-over points.
- The cycling begins at the moment of birth always with a positive phase.
- In all individuals on earth, at all times, cycles must run with precisely the length of 23, 28 and 33 days; deviations of only minutes or even fractions of seconds from the assumed period length, through internal or external factors, are not compatible with the theory.
- The positive phase of all cycles corresponds to periods when performance is best, the negative phase indicates poorer performance; the cross-overs are termed "critical"; when two cycles cross the medium line criticality is doubled, and three curves crossing simultaneously is even more critical or dangerous.
- According to the theory, performance would be poor, vulnerability high, and accidents more likely on critical days, on days when more than one cycle is in a critical phase and the other cycle is in a negative phase, or on days when all cycles are in a negative phase.
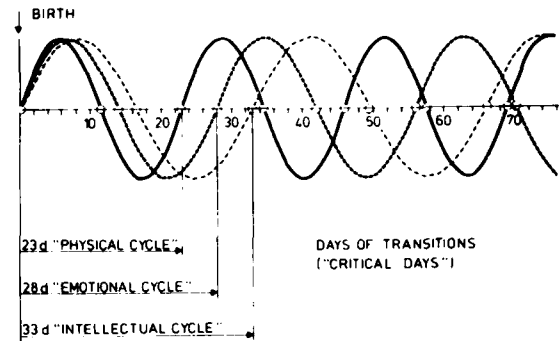

Figure 37: The "Biorhythm" concept (After Sacher, 1974).

The fascinating possibility of predicting human performance capacity was eagerly picked up by man-intensive industries in order to lower accident rates and/or increase efficiency and productivity. At the same time, Biorhythm companies grew up, offering consulting services for labour management or selling Biocalculators for computing one's "bad" or "good" days. The Biorhythm concept, thus, was commercialized before it had been tested seriously for its biological and mathematical foundations. It was in 1972 when G. Schönholzer stated (282): "Besides some recent expert statements which have not been published and, therefore, are not available, there is an endless number of press-releases, propaganda-brochures, mass-media commentaries, courtesy certificates etc. The very few regularly published papers which allow a scientific review more or less belong to the past. New sound and scientific publications do not exist. Therefore, there is no really controllable base".

Meanwhile the Biorhythm theory has been investigated independently in different scientific laboratories, mainly by comparison of actual events (accidents, deaths, athletic records etc.) with those expected by a random distribution. A second method applied was computing correlation of actual performance of a laboratory task with the phases of the Biorhythms' cycles. We have reviewed 15 reports, 13 of which appeared between 1971 and 1979; the results are briefly summarized.

Papaloizos et al. (237), Psychological Service d'Ebauches, Neuchâtel, Switzerland (1960): The theory was tested on 500 drivers who caused an accident; the occurrence of an accident could not be predicted by the theory better than by chance.

Kallina (161), Verkehrspsychologisches Institut des Kuratoriums für Verkehrssicherheit, Vienna, Austria (1961): From birth-dates of 100 drivers who caused accidents, the "Austrian Society for Biorhythm" calculated Biorhythm phases; the authors then correlated expected and actual frequency distribution of accidents and found that there were no significant differences; they concluded that there was no influence of Biorhythm phases on the disposition to cause an accident.

Mason (206), Workman's Compensation Board of British Columbia (1971): Over 13 000 industrial accidents have been investigated without a statistically significant correlation to Biorhythm phases.

Pircher (245), Fliegerärztliches Institut, Dübendorf, Switzerland (1972): More than 3 000 air and road accidents were investigated; the actual frequency was not significantly different from the expected frequency of accidents; it was concluded that Biorhythm is useless as a means for accident prevention.

Schönholzer et al. (282) Forschungsinstitut der Eidg.Turn- und Sportschule, Magglingen, Switzerland, and Sandoz-Wander, Inc., Hanover, New Jersey, USA (1972): The biorhythmic characteristics of more than 1 000 athletic records were calculated by the "Biorhythm Research Center, Switzerland"; then the authors computed the level of significance for differences between the actual events and their theoretical probability, special attention was given to the critical periods; the results demonstrated that Biorhythms have no influence on the frequency of such events; it was concluded that the idea of Biorhythm is a theory without biological and mathematical foundations.

Steinmetz (290), Master Thesis, Technical University Darmstadt (1972): The winner of Olympic records in track and field sports in 1968 and the German members of the European championship in track and field sports in 1971 were investigated; no correlation between physical athletic performance and Biorhythms' favourable and unfavourable periods were found; the hypothesis of proponents of the Biorhythm theory that the status of the physical cycles decides defeat or victory in a competition where athletes physically and technically are equal was not supported; the author quotes Russian investigations of 2 000 cases of World and Russian Records coming to the same results.

Sacher (275), Master Thesis, Naval Post Graduate School, Monterey, Calif., USA (1974): The author investigated the probability of biorhythmic criticality and its influence on human error and accidents based on data from more than 4 300 naval aircraft mishaps; by straightforward application of critical days or critical periods there was no significant influence from Biorhythms; however, a significant lower number of accidents than expected was found in pilots younger than 30 when a critical physical day was accompanied by a positive state of the emotional cycle (which is against the Biorhythm theory!), and in pilots older than 30 when physical critical days coincided with the negative state of the emotional cycle; with these results it is not easily understood why the author recommends "Biorhythmic Criticality" to be incorporated into a "Sortie System Safety Evaluation".

Rodgers et al. (267), Wyoming State Hospital and University of Wyoming, USA (1974): Predictive validity of Biorhythm theory was tested with three rating tests of a) general feeling b) job performance and c) sleep quantity and quality; critical days did not relate above chance to any test criterion; it was concluded that the critical days hypothesis was not shown to be a meaningful concept.

Feinleib et al. (84), National Heart, Lung and Blood Institute, Bethesda, MD, USA (1974): The hypothesis claimed in the literature that abnormally higher death rates occur on critical days was tested on 960 deaths from a long-term longitudinal study; the results appeared to contrast sharply with claims made by proponents of Biorhythm theory, they suggest that it is highly unlikely that biorhythmic cycles influence when men will die.

Rey et al. (263), Institut für mathematische Statistik und Versicherungslehre, Universität Bern, Switzerland (1976): More than 10 000 cases of suicide in Switzerland from 1961 to 1970 were used to test the hypothesis that Biorhythms cause differences in the frequencies of suicides at the various days of the cycles, in particular, at critical days; the results did not support the hypothesis; there was no indication of a verification of the Biorhythm theory.

Neil et al. (226), Man-Maschine System Desgin Laboratory, Naval Post Graduate School, Monterey, Calif., USA (1976): For 70 days, information processing was followed in 3 subjects; the set of performance data was subjected to Fast Fourier Transforms in an attempt to identify significant harmonics; from 12 significant harmonics 9 were found to be within one day of one of the cycles hypothesized by the theory of Biorhythms; the results were interpreted as suggesting the possibility of a biorhythmic influence in the performance of the tasks; however, no attempt was made to correlate these rhythms to birthdates.

Khalil et al. (164), Department of Industrial Engineering, University of Miami, Florida, USA (1977): In 63 aircraft accidents, 105 cases of unscreened death, 181 traffic accidents where a driver was at fault, performance and scores in 23 members of a swimming team and in 25 members of a bowling league, Biorhythm had no significant influence; it was concluded that no evidence in support of the theory of Biorhythm had been found.

Wolcott et al. (352), Aerospace Pathology Division, Armed Forces, Institute of Pathology, Washington, D.C., and National Transportation Safety Board, Washington, D.C.; Accident Investigation Branch, Office of Aviation Medicine, FAA, Washington D.C. (1977): In more than 5 000 "pilot-involved" accident cases, no correlation was found between any aspect of the Biorhythm theory and the occurrence of accidents.

Persinger et al. (243), Environmental Psychophysiology Laboratory, Department of Psychology, Laurentian University, Sodbury, Ontario, Kanada (1978): Analysis of 400 mining accidents demonstrated that the number of employees involved in accidents on their individual critical days of the different cycles did not differ significantly from chance expectancy; furthermore the number of employees involved in accidents when their cycles were in ascending phases did not differ significantly from the number of employees who were involved in accidents when their cycles were in the descending phases; neither empirical nor theoretical support for the Biorhythm model was found.

Wolcott et al. (353), Aerospace Pathology Division, Armed Forces, Institute of Pathology, Washington, D.C., USA (1979): In 10 individuals efficiency at a choice reaction time did not correlate with the phases of the Biorhythm cycle; it was concluded that performance was not influenced by Biorhythms.

The obviously complete failure to verify the Biorhythm theory with scientific methods contrasts to a certain degree with some reports on its successful application in reducing accident rates in industry (310, 344, 345). Where such conclusions are not due to a false use of mathematical models they bring up the question of a potential suggestive power of such a concept once the persons concerned have confidence in its (pretended) predictive power. In this context Schönholzer (282) has pointed out a possible "Placebo-effect" which might be positive or negative; he mentioned athletes who failed in competitions, obviously since Biorhythmic criticality had been suggested to them for this day, and others who performed very well in a kind of "stubborn" reaction since they knew they were supposed to be bad. Wolcott et al. (352) conclude their study with the warning: "Although it has been suggested by many advocates of the theory that briefing the theory to flying personnel might reduce accident rates, briefing a theory not proven by fact is fraught with danger. It could bring about a psychosis by association that, indeed, might make pilots reluctant to fly on a critical day, especially a multiple critical day. Individuals do have "good" and "bad" days; their occurrence, however, is not predictable by the Biorhythm theory". There is nothing to add to this statement.

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AG-247	ISBN 92-835-1378-9	UNCLASSIFIED

5. Originator
Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title
SIGNIFICANCE OF CIRCADIAN RHYTHMS IN AEROSPACE OPERATIONS

7. Presented at

8. Author(s)/Editor(s)	9. Date
Karl E.Klein, M.D. and Hans M.Wegmann, M.D.	December 1980

10. Author's/Editor's Address	11. Pages
DFVLR-Institut für Flugmedizin 5300 Bonn-Bad-Godesberg FRG	64

12. Distribution Statement
This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Circadian rhythms
Performance evaluation
Aerospace medicine
Sleep deprivation

14. Abstract

For over a century it has been recognised that the functional state of the human body is subject to periodic daytime-dependant oscillations which are called "Circadian Rhythms". Not only wakefulness and sleep alternate with the environmental light-dark cycle, for it has been established that most physiological, psychological and behavioural functions have an oscillatory nature. Certain hours of the 24 hour cycle have been identified as those where the tonic physiologic levels are set for sleep and "readiness for efficiency" is reduced. Though the underlying mechanisms for biologic circadian periodicity are as yet unknown, its relationship with the environment and with controlling endogenous and exogenous factors has become increasingly clear.

Because performance efficiency and health are affected, circadian rhythmicity has become a major concern not only for industrial shift work. This AGARDograph, together with those previously published on "Operational Aspects of Variations in Alertness" (No.131) and "The Operational Consequences of Sleep Deprivation and Sleep Deficit" (159), as well as the Lecture Series on "Sleep, Wakefulness and Circadian Rhythm" (232) should present a useful source for planning and managing aerospace operations in harmony with human functional capacity.

This AGARDograph was prepared at the request of the Aerospace Medical Panel of AGARD.

AGARD-AG-247

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AGARDograph No.247
Advisory Group for Aerospace Research and Development, NATO
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