MIND, BRAIN, AND EDUCATION

Rhythms of Mental Performance

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ABSTRACT—Cognitive performance is affected by an individual's characteristics and the environment, as well as by the nature of the task and the amount of practice at it. Mental performance tests range in complexity and include subjective estimates of mood, simple objective tests (reaction time), and measures of complex performance that require decisions to be made and priorities set. Mental performance tasks show 2 components, a circadian rhythm and the effects of time awake. The circadian rhythm is in phase with the rhythm of core temperature and there is evidence for a causal link. Increasing time awake results in performance deterioration and is attributed to fatigue. The relative contribution of these 2 components depends upon the task under consideration; simple tasks generally show smaller effects due to increasing time awake. These contributions have been assessed by constant routines and forced desynchronization protocols and have formed the basis of several mathematical models that attempt to predict performance in a variety of field conditions. Mental performance is negatively affected by sleep loss; although short naps are beneficial, sleep inertia limits their value immediately after waking. The processes involved in cognition include attention (tonic and phasic alertness, and selective and sustained attention), working memory (phonological, used for speech, reading, and writing; and visuospatial, used for spatial processing, drawing, and mathematics), and executive function (initiative, decision making, and problem solving). These processes are illuminated by analysis of the regions of the brain involved, the presence of circadian rhythmicity, and the effects of sleep loss. The results from such laboratory- and field-based observations are relevant to the issue of learning in schoolchildren and lead to suggestions for improving their performance.

INTRODUCTION

There is a large body of research that considers biological factors that are associated with accidents or errors in the workplace, the aim being to develop strategies that minimize such occurrences. This approach has been complemented by laboratory-based studies that investigate the factors that affect mental performance, the basic argument being that poor performance is more likely to result in errors which, if uncorrected, lead to accidents (reviewed in Åkerstedt, 1995, 2007; Dinges, 1995; Folkard, 1990; Horne & Reyner, 1995; Waterhouse, Minors, Åkerstedt, Reilly, & Atkinson, 2001, for example). In the present context, "mental performance" can be defined operationally as the outcome of a task, effort, or activity that engages the central nervous system (CNS).

The combined result of these studies is that many of the factors that influence a person's ability to perform a task successfully are known. These factors include ambient conditions, food intake, practice effects, chronotype, and the nature of the performance task. Additional factors, which will be considered in more detail, include the effects of time of day (circadian rhythmicity), time awake, sleep loss, and naps.

SOME FACTORS AFFECTING MENTAL PERFORMANCE

Ambient Conditions, Food Intake, Practice Effects, and Chronotype

Environmental conditions that affect performance (Wojtczak-Jaroszowa & Jarosz, 1987) include lighting, temperature, and noise. Performance deteriorates if individuals feel uncomfortable, are distracted, or the conditions are unsuitable for the task in hand. Decreasing noise levels is one obvious solution, but levels that are too low might become soporific. The effect of brightening the light can be complex. On the one hand, it produces a general activation of the CNS and improves visual acuity; on the other, when it is too bright, it can be disturbing and render visual display units difficult to read.

The CNS receives its energy almost entirely from the metabolism of glucose, this molecule overcoming the potential problem posed by the blood–brain barrier by being transported across the cerebral capillaries by facilitated diffusion. The CNS has only a very limited store of glucose, sufficient for only 2–3 min of normal brain activity, but it is important to ensure that brain function is not compromised by inadequate glucose intake and low levels of plasma glucose. Cognitive function is compromised if plasma concentrations of glucose

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fall to around 2.8 mmol/L, the normal range during nocturnal fasting being 3.9–6.1 mmol/L (Ganong, 1999). Plasma glucose levels are maintained during the night by "glucose sparing" (Jarrett, 1979). In this phenomenon, the body (excluding the CNS) metabolizes fats, and the liver produces glucose from noncarbohydrate sources. The hormones glucagon, adrenaline, growth hormone, and glucocorticoids play a major role in controlling this phenomenon (Armstrong, 1980). Glucose ingestion promotes a rise in plasma glucose, which stimulates the secretion of insulin. Insulin switches the metabolism of the body from lipids to glucose and the storage of excess glucose as glycogen, the result of which is that plasma glucose levels return to normal values.

Under normal circumstances, therefore, glucose levels do not fall low enough to compromise brain function. However, mental performance is compromised in subjects suffering from hypoglycemia, and ingesting glucose counteracts this. It is less clear if complex carbohydrates (starch and cane sugar, for example) are as effective as glucose or whether the ingestion of proteins or fats can be of value (Dye, Lluch, & Blundell, 2000).

One aspect of measuring mental performance that needs to be incorporated into an experimental protocol is that of the effect of practice (Blatter & Cajochen, 2007). As one becomes familiar with any task, the speed and accuracy with which it can be performed increase. For many mental performance tasks, particularly those involving central processing, it is also necessary to develop a suitable strategy, and this acquisition requires practice. The effects of practice will complicate the interpretation of results from an investigation of other factors that might be of more interest—the effect of time of day or time awake, for example—and so suitable protocols to remove the effects of practice need to be developed. Three methods have been used (Blatter & Cajochen, 2007). The first requires the subjects to perform the task often enough before the main investigation begins for any practice effects to have disappeared (the subject being fully trained in the task). This familiarization process can be rather time consuming. A second method, which is often used in investigations of rhythmic changes in performance during the course of the 24 hr, is to divide the group of subjects into several subgroups; each subgroup starts its sequence of 24-hr measurements at a different time of day (24:00, 04:00, 08:00, 12:00, 16:00, and 20:00 hr, for example). In this way, the mean performance at each time of day *for group as a whole* will contain the same mixture of practice effects, and the rhythm in performance will be superimposed upon the noise due to these practice effects. A third method is to compare the results with a control group whose members have had the same amount of practice but not undergone the manipulation under investigation (sleep deprivation, for example).

Individuals differ in their preferred habits with respect to times of sleep, times when they feel most or least able to perform mentally or physically demanding tasks, and times when they prefer to be relaxing. This is assessed through a questionnaire from which a score measuring chronotype is derived (Horne & Ostberg, 1976). Increasing scores indicate the individual's position on a continuum from "extreme evening type" through "intermediate type" to "extreme morning type." The questionnaire has been translated into several languages, and it has been claimed that each of the questionnaires has been validated by the results it has given. There is evidence that the detailed interpretation of individuals' scores requires knowledge of their cultural surroundings because some cultures routinely rise earlier in the morning than others, for example. It has been a consistent finding that morning types are less suited to night work (but more suited to the morning shift) than are evening types and that they have an earlier phasing of the circadian rhythms of core temperature, cardiovascular parameters, and mental performance (Kerkhof, 1985; Vidacek, Kaliterna, Radosevic-Vidacek, & Folkard, 1988). The direct applicability of the questionnaire to schoolchildren, whose sleep hours might be expected to differ from those of adults, is unclear, but suitable rewording of some component questions would be expected to correct for this difference.

Nature of the Task

Measuring mental performance in the field can be difficult. The task might not be readily quantified (decision making, for example), or it might not have an obvious end point (watchkeeping on board a ship, for example). The conditions under which the task is being carried out might vary, in the case of driving or outdoor work in general, or noise might act as a distracting influence. The work being performed might also be variable in nature, standardization of the overall task being difficult to achieve. Also, the workforce itself might be heterogeneous with regard to sleep loss, for example.

Hildebrandt, Rohmert, and Rutenfranz (1975) summarized the earlier studies. Their general conclusions were that errors were higher at night than during the daytime (but there was a transient dip in performance in the early afternoon), performance was worse in the second half of the shift, and external factors played an important role.

Many of the difficulties found in field experiments can be controlled, at least partially, in laboratory-based investigations. There can be more control over the nature of the task, the conditions under which it is performed, and the subject's lifestyle. Early tasks were often pencil-and-paper tests that had to be scored by hand; nowadays, the tests are more likely to be presented on desktop or portable computers and the results scored electronically. These have been summarized in several reviews (Adan, 1993; Folkard, 1990; Folkard & Monk, 1985; Waterhouse et al., 2001). It is not appropriate to consider all mental performance tests, but the following assessments and types of task have been used quite commonly.

Assessments of Self-Rated Subjective Feelings

In response to a question like: "How alert do you feel?," the subject might be required to tick an appropriate description from a list of possibilities ("very alert," "fairly alert," etc.) or to make a mark somewhere on a line, the ends of which are labeled "Not at all" or "As much as possible."

Objective Assessments

A real task will comprise several of the following components: a sensory input, vigilance, the use of short-term and long-term memories, logical reasoning, and a motor output. Some laboratory-based tests have concentrated on a few of these components, thus simplifying the situation. To give a few examples from the many that have been used:

- The requirement to find a target letter in a block of random letters would be an example of a test dominated by sensory input and attention.
- Manipulative skill might be assessed by threading beads onto a string.
- Short-term memory has been assessed by a search and memory test (Folkard & Monk, 1985); in this test, a block of random letters is given and each line has to be scanned separately for a target of between two and six letters. As the length of the target increases, so does the extent to which short-term memory is required to accomplish the task.
- Simple reaction time can be measured as the delay between receiving an auditory or visual signal and responding to it, generally by pressing a button. This task can be made more complex by requiring the subject to respond to only one of several stimuli or to respond differently to different stimuli. In addition, a variable amount of warning can be given before each presentation.
- Logical reasoning can be assessed by presenting the pair of letters, A and B, in either order and requiring the subject to assess the truth of a statement such as "B is not followed by A."

Increasing the Reality of the Tests

The above tasks have the advantages that they can be standardized, and performance scores from them can be calculated and used to compare performance under different circumstances. However, their relevance to real tasks—their external validity—can be called into question.

It is to combat this criticism that tasks can be modified in various ways. These modifications include making the task more difficult by involving more processing by the CNS (working memory), by requiring a combination of skills, and/or by giving competing tasks. For example:

- The number of digits involved in a test of mental arithmetic can be increased, or the processes involved can include subtraction as well as addition. In general, increases in complexity mean that the subject sacrifices speed for accuracy or vice versa—or the test requires that one of these options be set as the priority by the experimenters.
- A moving target is required to be tracked (requiring attention, visual input, and manipulative skill); the speed of movement of the target, or the amount of randomness in the movement, can be increased.
- A battery of tasks, the components of which might remain simple, can be mixed together, multitasking (Gillooly, Smolensky, Albright, Hsi, & Thorne, 1990; Szlyk, Myers, Zhang, Wetzel, & Shapiro, 2002). In addition, time constraints can be placed on the individuals and, again, priorities can be set when several tasks are performed simultaneously. With the appropriate combination of tasks and instructions to the subject as to what is required, workload and executive control (decision making, setting priorities) can be introduced. As the workload increases, the element of stress begins to appear, and it can be important to assess how this causes a decrement in performance. Introducing an (often distracting) secondary task and investigating its effect upon performance at the primary task is a method that is commonly used to replicate the situation found in field conditions (Young & Stanton, 2007).

Vigilance is often a component of mental performance, the subject being required to react to an abnormal or missing stimulus among repetitive stimuli that form a background. Vigilance tasks are slightly different from many other measures of mental performance in that they last for extended periods of time, several minutes or a few hours. Their importance is that vigilance has become a key component in the requirements of a modern workforce that acts as a machine minder.

Technological advances have meant that the use of video games has been advocated (Kennedy, Bittner, Harbeson, & Jones, 1982), with separate scores being kept of the various skills demanded by the game. Portable electronic devices that set and score several tasks are also used (e.g., Nouguier-Soule, Nouguier, Bicakova-Rocher, Gorceix, & Reinberg, 1999). It is then only a small step to use driving (Szlyk et al., 2002) and flight simulators, a possibility that approximates closely to field studies.

An alternative approach has been to measure neurophysiological variables that have been shown to correlate with actual mental performance (see, e.g., Ryu & Myung, 2005). These variables include the electroencephalogram (for measuring the power of the alpha rhythm), the electrooculogram (for measuring eyeblink intervals), and the electrocardiogram (for measuring heart rate variability and parasympathetic tone). These measures have the advantage that they are objective, but the exact link between the results of such measurements and the actual mental performance is not always clear, and it might depend upon the circumstances in which performance is being measured.

More generally, it must always be borne in mind that the exact links between the results of laboratory-based tests, whatever their nature, and the tasks required in field circumstances are rarely fully understood. This caveat applies to the assimilation of new information in a school environment. Poor learning ability by a pupil might reflect any or all the circumstances in which the information is given, the mental state of the pupil at the time of presentation, or the clarity with which the teacher imparts the information in the first place. Similar problems exist also when a pupil is required to disseminate information; a poor performance at answering questions correctly might reflect inauspicious conditions for doing so, lack of clarity from the teacher as to what is required, a fatigued or bored pupil, or a lack of the information required (or sufficient understanding of it).

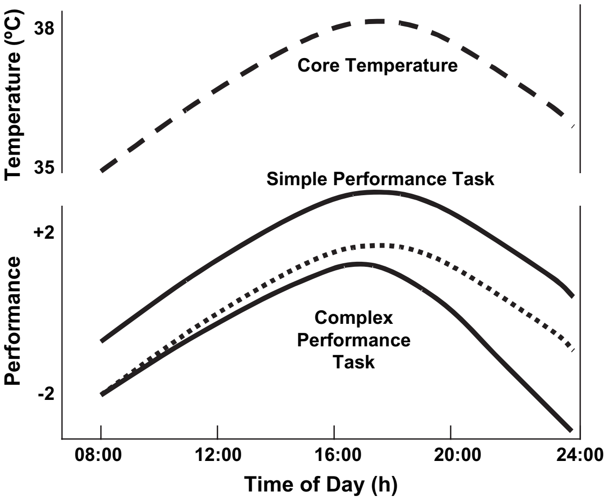

Fig. 1. Diagrammatic illustration of the diurnal rhythms of, top, core temperature (dashed line) and, bottom, simple and complex performance tasks (full lines). For the complex performance task, the dotted line shows the time course of a complex performance test in the absence of the effects of fatigue. Performance is expressed as the deviation from the daily mean (represented by 0) in terms of the standard deviation (calculated from all values obtained over the course of the 24 hr). The size of the standard deviation and the absolute value of the zero depend upon the particular task.

CIRCADIAN RHYTHMS IN SELF-RATED SUBJECTIVE FEELINGS AND MENTAL PERFORMANCE

Changes in self-rated subjective feelings and many mental performance tasks have been measured diurnally in healthy subjects living a conventional sleep–activity schedule (for examples of these rhythms, see Blatter & Cajochen, 2007; Folkard, 1990). Rhythmic changes are present, with worse performance in the early morning and late evening and best performance somewhere in the middle of the daytime. It was realized early in such studies that the rhythms often showed a degree of parallelism with that of core temperature (Kleitman, 1939).

It is less common to measure performance during the nocturnal hours due to the problems associated with having subjects awake at this time. To achieve waking values at night either requires the subjects to remain awake or for them to be woken up. As will be described later, mental performance deteriorates in the presence of sleep loss (as would be the case if the subject remained awake, for example) and is transiently depressed after waking a subject from sleep ("sleep inertia"). Care has to be taken to correct for these effects. However, if self-rated subjective feelings and mental performance are measured during the nocturnal hours (Monk et al., 1997), values are lower than during the daytime; that is, there are negative effects when core temperature is near its minimum.

A closer inspection of the rhythms of self-rated subjective feelings and mental performance shows that they differ in detail when their time courses were considered, as does the degree of parallelism with the rhythm of core temperature. Typical diurnal changes are illustrated diagrammatically in Figure 1. The differences in time course can be considered to be variations in the rate at which a decrement occurs as a result of time elapsed since waking. As a general rule, the rhythm of a simpler task which requires the intake of information rather than much mental processing of it—visual search, for example—parallels the rhythm of core temperature more closely and does not decrement much until the end of the daytime. By contrast, as the amount of central processing increases, so does the amount of deterioration, this becoming clear soon after noon. This deterioration is often referred to as "fatigue" and has been found in field studies also (Åkerstedt, 2007; Hamelin, 1987; Pokorny, Blom, & Van Leeuwen, 1987; Wojtczak-Jaroszowa & Jarosz, 1987). A general conclusion from field and laboratory studies is that levels of self-rated subjective feelings and mental performance are largely determined by the interaction between circadian rhythms and time on task, and it is these two factors that dominate many models of these phenomena (see below).

In addition to the circadian rhythm in performance, there is a temporary decline in performance in the early afternoon—the "postlunch dip." The cause of this dip is unclear; it appears to be greater if lunch has been eaten, but it is still observed if an individual has fasted. There are also conflicting views as to whether other rhythms (e.g., that of adrenaline) are affected by this dip, and there seems to be considerable interindividual variation (Craig, Baer, & Diekmann, 1981; Monk, Buysse, Reynolds, & Kupfer, 1996; Smith & Miles, 1986).

Origins of the Rhythms in Mental Performance

Is the parallelism between mental performance and core temperature evidence of a causal link as was first suggested by

Kleitman (1939)? Certainly, such a link would be feasible because a raised temperature would promote the biochemical reactions occurring in the brain. Experiments in which body temperature has been raised or lowered are complex to interpret due to possible effects of stress (see Minors & Waterhouse, 1981). Thus, both producing a low-grade fever in individuals and cooling them by immersion in cold water are likely to change motivation in addition to any direct effects upon brain biochemistry.

It must also be borne in mind that a parallelism is also observed when the time courses of plasma catecholamines and mental performance tests are compared. Catecholamines are measures of the general activation of the body, and so there would be theoretical grounds for proposing such a link between these hormones and mental performance. In a broader context, the more general concept has arisen of "arousal," which might act as a link between body temperature, catecholamines, and mental performance. This link has traditionally been expressed as the "inverted U" relationship between arousal and mental performance (Yerkes–Dodson law).

The relationship between core temperature and mental performance has been reappraised in recent years. Three protocols have been used, two based upon the constant routine and one upon the forced desynchronization protocol.

In the constant routine (Mills, Minors, & Waterhouse, 1978), subjects are required to remain awake for a period of at least 24 hr in an environment where ambient temperature, lighting, and humidity are kept constant. In addition, physical activity is prohibited, subjects either sitting quietly or, preferably, lying down for the duration of the protocol. Further, identical snacks are given to the subjects at regular intervals (hourly or every 3 hr, for example). In such a protocol, the effects of rhythmic changes to the environment or individual's lifestyle have been removed, and any rhythm that remains has an endogenous origin and is attributed to the body clock.

When mental performance tasks are measured during such a protocol (Carrier & Monk, 2000; Johnson et al., 1992), they retain their rhythmicity, but this rhythmicity is superimposed upon a general decline in performance (illustrated diagrammatically in Figure 2A). Over the course of a circadian cycle, this decline, due to the effects of fatigue (time awake), can be measured by comparing mental performance at two points separated by 24 hr (see "X," at 08:00 hr, in Figure 2A). Effects of time awake due to other intervals after having woken up can also be estimated, and this becomes a key component in some models of mental performance (see below).

A variant of the constant routine protocol (Blatter & Cajochen, 2007; Buysse, Monk, Begley, Houck, & Seltman, 2000) attempts to remove effects due to the progressive rise in fatigue associated with remaining awake. The principle is illustrated in Figure 2B. The basic constant routine protocol is retained, but the subjects are allowed to take a 1-hr nap every 3 hr rather than to stay awake all the time. In this way, the accumulation of fatigue is minimized. The rhythm of mental performance is retained but it shows far less marked falls due to fatigue; after passing through a minimum during the night, the rhythm returns 24 hr later to its starting point (compare Figures 2A and 2B). The results from this protocol stress even more the general parallelism between mental performance and body temperature.

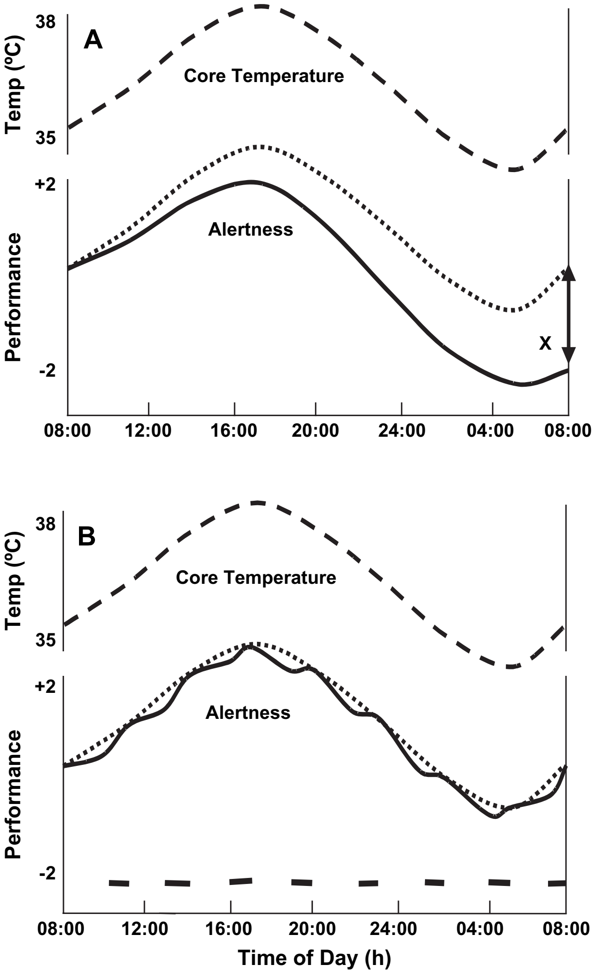

Fig. 2. (A) Diagrammatic illustration of the diurnal rhythms of, top, core temperature (dashed line) and, bottom, alertness during a constant routine (full line). The dotted line shows the time course of alertness in the absence of effects due to fatigue. (B) Diagrammatic illustration of the diurnal rhythms of, top, core temperature (dashed line) and, bottom, alertness during a constant routine interspersed with regular 1-hr naps (full line); the naps are shown as black bars below this curve. The dotted line shows the time course of alertness in the absence of effects due to fatigue. In both A and B, performance is expressed as the deviation from the daily mean (represented by 0) in terms of the standard deviation (calculated from all values obtained over the course of the 24 hr). The size of the standard deviation and the absolute value of the zero depend upon the particular task.

In the forced desynchronization protocol (based on Kleitman, 1939), subjects are required to live on "days" of abnormal length, equal to 21, 27, or 28 solar hours, for example. With a 28-hr day, the subjects' times of retiring, rising, and eating meals, as well as all their daily activities and the imposed light–dark cycle, become 4 hr later each day. The body clock cannot adjust to such imposed periods; under these circumstances, therefore, measured rhythms show two components—an exogenous component due to the imposed day and an endogenous, circadian component due to the free-running body clock. Data are collected at regular intervals during the waking periods throughout such a study and, by suitable mathematical treatment of them, it is possible to investigate each of these components separately. Thus, if the results are expressed in terms of the imposed day length, the circadian component is canceled out and the effects of time awake can be shown; if the results are expressed in terms of the circadian phase, the exogenous component is canceled out and the circadian component becomes manifest.

This method has been used to investigate several rhythms of self-rated subjective feelings and mental performance (Boivin et al., 1997; Harrison, Jones, & Waterhouse, 2007; Wright, Hull, & Czeisler, 2002). These variables have been found to decrease with time awake, in accord with the interpretation of data obtained diurnally and during constant routine protocols (Figures 1 and 2). Also, a circadian component in phase with the rhythm of body temperature is found. Further analysis (Wright et al., 2002) has indicated that core temperature affects mental performance independently of circadian rhythmicity, a conclusion that has been drawn also from studies using the constant routine (Monk & Carrier, 1998).

In summary, current evidence indicates that different types of mental performance show both circadian rhythms and effects due to time awake and that core temperature exerts an effect independent of its circadian rhythm.

Modeling Self-Rated Subjective Feelings and Mental Performance

There have been several attempts to construct mathematical models that would predict mental performance and alertness under a variety of circumstances, including night work and after sleep loss. A recent workshop compared their effectiveness in a variety of scenarios that might be expected in field conditions (Van Dongen, 2004). It was concluded that such models, though of value, needed further development to become fully comprehensive and to be flexible enough to describe the whole gamut of circumstances found in the field.

Several models have been based upon the concept that subjective feelings and mental performance are determined by the summed effects of circadian and homeostatic factors. The circadian factor is in phase with the rhythm of core temperature, and the homeostatic one reflects the fall associated with the accumulating drive to sleep when awake and its dissipation during sleep. Other models also incorporate effects due to prior sleep loss and sleep inertia.

One model that has a firmer rationale and more experimental evidence in support of it than some others is the "three-process model of alertness regulation." It is based on the two-process model of sleep regulation (Borbely, 1982). Subjective alertness data collected from a number of altered sleep–wake patterns indicated that alertness could be predicted from a combination of circadian and homeostatic components, together with a component for sleep inertia. The output of the model has been validated against subjective and objective ratings of performance and sleepiness (lack of alertness) in the laboratory and field. The model predicts sleep length and latency, and the risk of falling asleep, in addition to alertness (Åkerstedt, 1995, 2007; Åkerstedt & Folkard, 1995; Beersma & Gordijn, 2007; Folkard & Åkerstedt, 1991).

Predictions from a version of the above model that excluded the effect of sleep inertia were compared with results from field studies (Åkerstedt, 1998). Even though prediction and field observations were generally in agreement, it was concluded that field data were insufficient in quantity and quality. This raises again the earlier point that obtaining field data can be extremely difficult. It must also be remembered that a model is only a simplification of, and therefore an approximation to, real circumstances. The way forward is for the collection of field data and the predictive power of a model to be refined hand in hand.

EFFECTS OF SLEEP LOSS AND THE ROLE OF NAPS

Field and laboratory data indicate that sleep loss leads to a decline in mental performance (Åkerstedt, 2007; Angus, Pigeon, & Heslegrave, 1992; Bohnen & Gaillard, 1994; Koslowsky & Babkoff, 1992; Krueger, 1989). In general:

- Sleep loss of as little as 2 hr can produce decrements, the speed of performance tending to be affected more than the accuracy.
- Complex and vigilance-requiring tasks are affected most by sleep loss, and the situation is exacerbated by declines of self-rated subjective feelings due to fatigue and the resultant loss of motivation.
- The effects of sleep loss are worse if the task involves continuous testing and there is no opportunity to recover.

The most obvious way to reduce these decrements is by taking short sleeps or naps. It is not unusual for adults, particularly elderly ones, to nap during the daytime, but the frequency or ability to take naps does not seem to have been investigated in schoolchildren. Naps lasting as little as 1 hr can counteract the effects of performance decrement in adults who have lost at least one night's sleep or who are working at night (Rogers, Spencer, Stone, & Nicholson, 1989; Stampi, Broughton, Mullington, Rivers, & Campos, 1990). However, it is not known if such naps would improve mental performance in children whose nocturnal sleep was not long enough due to retiring too late or rising too early. In addition, the rates of decrement in performance, as well as the recuperative role of a nap, depend upon the type of mental task (Åkerstedt, 2007), and investigations aimed specifically at learning in school have not been performed. Even so, current evidence suggests that the recuperative role of a nap is the same as that of a sleep, when differences in length have been taken into account.

In general, naps and full sleeps are most easily taken in the middle of the night, when core temperature is low, and most difficult to take in the daytime when core temperature is high. The exception to this generalization is a window of increased opportunity to nap in the early afternoon (Borbely, Ackermann, Trachsel, & Tobler, 1989), which coincides with the time of the postlunch dip in performance (see above).

When sleep and naps are being considered, the phenomenon of sleep inertia needs to be borne in mind (Campbell, 1992; Dinges, 1992; Naitoh, Kelly, & Babkoff, 1993). Immediately after waking from a nap, particularly one during the night, performance falls for some minutes after being woken. The effect is more marked if the subject wakes from slow-wave sleep and/or is in a quiet rather than a noisy environment (Stampi et al., 1990). Because, with short naps, slow-wave sleep is rarely achieved, this aspect of sleep inertia would not be expected.

Much of the effect of sleep inertia has worn off about 10 min after waking up, but, in practice, the benefits of a nap are not apparent immediately after waking from it. There is a longer lasting component of sleep inertia that can take at least 1 hr to disappear completely.

COGNITIVE PROCESSES UNDERLYING MENTAL PERFORMANCE

As mentioned above, mental performance can be assessed using many tasks, such as subjective measures, reaction time, memory tasks, reading comprehension, arithmetical operations, time estimation, or logical reasoning. All these tasks are the output of basic cognitive processes that are the building blocks of higher cerebral functions and human behavior. To understand fully and to generalize laboratory data on mental performance to efficiency at work and learning at school, it is necessary to analyze the cognitive processes underlying performance.

There are three basic cognitive processes that may be the bases of mental performance: attention, working memory, and executive functions (Cajochen, Blatter, & Wallach, 2004). A disorder in any of these processes produces alterations in many tasks. To consider these processes in more detail:

- Attention is the capacity to interact efficiently with the environment. It has several components: tonic alertness, phasic alertness, selective attention, and sustained attention (vigilance) (Cohen, 1993; Posner & Rafal, 1987). Tonic alertness is the capacity to respond to events in the environment; it reflects the arousal level, general alertness, or activation of the organism at any time, and it is also the more primitive component of attention. The level of tonic alertness determines the capacity for, and speed in, processing information. Phasic alertness is the capacity to respond to an event after a warning signal—it is crucial to be ready and respond to a change in the environment. Selective attention is the capacity to produce a specific response to a specific stimulus and a different response to another stimulus; it involves filtering out irrelevant information from the environment. Sustained attention (vigilance) refers to the capacity to continue responding efficiently for some time (minutes to hours). Tonic alertness depends on the reticular activating system, whereas the other components require the participation of the cerebral cortex (mainly the parietal and frontal lobes). There are circadian variations in tonic alertness, phasic alertness, and selective attention. The lowest levels of these components of attention processes occur from 04:00 to 07:00 hr (Valdez et al., 2005). Sleep deprivation impairs tonic alertness and selective attention (Thomas et al., 2000), and fatigue produces a reduction in sustained attention (Gillberg & Åkerstedt, 1998).
- Working memory is the capacity to store, retrieve, and use information for a very limited period (seconds). There are two storage components of working memory: phonological and visuospatial. Phonological storage is crucial for verbal comprehension, speech production, and reading and writing; whereas visuospatial storage is relevant for image and spatial processing, as well as for drawing and mathematical ability (Baddeley & Logie, 1999). The phonological storage component depends on the activity of the temporal lobe of the left hemisphere, whereas the visuospatial storage component depends on that of the occipital lobe of the right hemisphere (Burton, Locasto, Krebs-Noble, & Gullapalli, 2005). Circadian rhythms have been documented in both storage components of working memory, with the lowest levels occurring from 04:00 to 07:00 hr (Ramírez et al., 2006). Sleep deprivation also produces a reduction in the capacities of these components of working memory (Weaver, 2001).
- Executive functions include initiative, planning, action, monitoring ongoing activity, and adjustment of behavior according to current conditions. Executive functions are crucial for decision making, self-control, and problem solving. Components of executive functions are initiation or “go” responses, inhibition, planning, flexibility, and self-monitoring (Godefroy, 2003; Stuss & Levine, 2002). All cognitive processes are modulated by some components of executive functions; for this reason, a central executive component is included in analyses of attention (Berger &

Posner, 2000) and of working memory (Baddeley, 1996). Executive functions exert an influence also on complex cognitive processes, such as language, learning, and problem solving. Executive functions depend on the activity of the frontal cortex, specifically, the prefrontal areas (Miller & Cohen, 2001). Circadian variations and sleep deprivation effects have been documented in some components of executive functions (Harrison et al., 2007; Killgore, Balkin, & Wesensten, 2006; Nilsson et al., 2005), but there are problems when assessing these functions in laboratory conditions. Tests designed to measure executive functions require procedures that incorporate decision making, planning, and solving new problems (Alexander & Stuss, 2006; Jones & Harrison, 2001); they must also be "ecologically valid," that is, directly related to the capacity to solve problems in the real world (Harrison & Horne, 2000).

Why do so many components of these basic cognitive processes (attention, working memory, and executive functions) change with time of day, sleep deprivation, and fatigue? A possible explanation is that tonic alertness (arousal, general alertness), the more primitive process, is affected first and produces interference with other basic cognitive processes, so resulting in some errors. In this condition, the goal-setting component of executive functions keeps the person working on the task. Therefore, as somnolence and fatigue increase, other components of attention, working memory, and executive functions are affected, producing more frequent and more serious errors that may compromise decision making, learning, and problem solving. More research is needed to analyze further changes in these cognitive processes with time of day, sleep loss, and fatigue.

SUMMARY—ADVICE ON IMPROVING MENTAL PERFORMANCE

Some of the factors that influence mental performance are summarized in Figure 3. This knowledge can form the basis for advice designed to improve self-rated subjective feelings and mental performance:

1. *Optimize the conditions in which study is taking place.* Good mental performance and positive subjective feelings require a quiet environment conducive to study and suitable levels of lighting. The level of lighting depends upon whether a video display unit is being used (in which case the screen should not be illuminated too brightly and the screen itself should be neither too dim nor bright) or paper is being written on (in which case the lighting should be bright enough to allow fine detail to be seen with ease).
2. *Length of time on a single task.* Particularly if the task is complex (arithmetic or comprehension, for example), then time spent at it should not be too long due to the effects of fatigue. If possible, alternate between tasks.

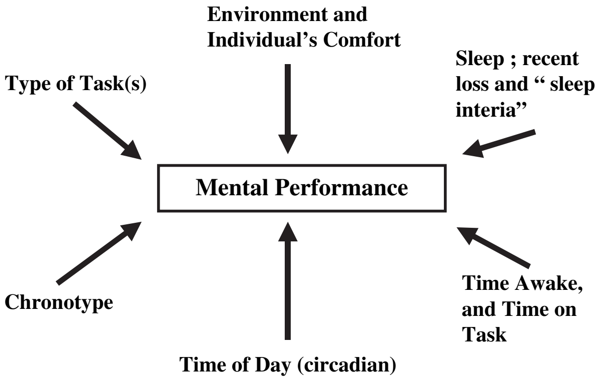

Fig. 3. Some factors affecting mental performance.

3. *Time of day for particular type of task.* Because mental performance deteriorates with time awake, it is, in principle, best in the morning and first part of the day; from the late afternoon onward, increasing time awake will compromise performance. In the latter part of the school day, therefore, physical activities (Reilly, Atkinson, & Waterhouse, 1997) and artistic pursuits are more appropriate. In addition, there are two times of day when performance might be compromised for other reasons. First, early in the morning, performance might be poorer due to the combined effects of body temperature (not having risen far enough above its nocturnal minimum) and sleep inertia. Second, immediately after lunch, performance is prone to show a postlunch dip.
4. *Preparations for work.* Performance will be worse if individuals are suffering from sleep loss due to retiring too late, rising too early, or being disturbed during the night, by any babies in the household, for example. In extreme cases, it might be that sleep loss can be compensated for by a nap, the best time for which is immediately after lunch. Because glucose intake guards against the negative effects of possible hypoglycemia due to overnight fasting, having breakfast before starting work is recommended.
5. *Interindividual differences.* If the individual has an intermediate or morning chronotype, performance will be best early in the school day; in the case of evening types, subjective feelings and mental performance during the early part of the school day are likely to be submaximal.

REFERENCES

Adan, A. (1993). Circadian variations in psychological measures: A new classification. *Chronobiologia*, *20*, 145–162.

Åkerstedt, T. (1995). Work hours, sleepiness and the underlying mechanisms. *Journal of Sleep Research*, *4*(Suppl. 2), 15–22.

Åkerstedt, T. (1998). Is there an optimum sleep-wake pattern in shiftwork? *Scandinavian Journal of Work, Environment and Health*, *24*(Suppl. 3), 18–27.

Åkerstedt, T. (2007). Altered sleep/wake patterns and mental performance. *Physiology and Behavior*, *90*, 209–218.

Åkerstedt, T., & Folkard, S. (1995). Validation of the S and C components of the three-process model of alertness regulation. *Sleep*, *18*, 1–6.

Alexander, M., & Stuss, D. T. (2006). Frontal injury: Impairments of fundamental processes lead to functional consequences. *Journal of the International Neuropsychological Society*, *12*, 192–193.

Angus, R., Pigeon, R., & Heslegrave, R. (1992). Sustained operations studies: From the field to the laboratory. In C. Stampi (Ed.), *Why we nap* (pp. 217–241). Boston: Birkhauser.

Armstrong, S. (1980). A chronometric approach to the study of feeding behaviour. *Neuroscience and Behavioural Physiology*, *4*, 27–53.

Baddeley, A. (1996). The fractionation of working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *93*, 13468–13472.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (1st ed., pp. 28–61). New York: Cambridge University Press.

Beersma, D., & Gordijn, M. (2007). Circadian control of the sleep-wake cycle. *Physiology and Behavior*, *90*, 190–195.

Berger, A., & Posner, M. I. (2000). Pathologies of brain attentional networks. *Neuroscience and Biobehavioral Reviews*, *24*, 3–5.

Blatter, K., & Cajochen, C. (2007). Circadian rhythms in cognitive performance: Methodological constraints, protocols, theoretical underpinnings. *Physiology and Behavior*, *90*, 196–208.

Bohnen, H., & Gaillard, A. (1994). The effects of sleep loss in a combined tracking and time estimation task. *Ergonomics*, *37*, 1021–1030.

Boivin, D., Czeisler, C., Dijk, D. J., Duffy, C., Folkard, S., Minors, D., et al. (1997). Complex interaction of the sleep-wake cycle and circadian phase modulates self-rated subjective feelings in healthy subjects. *Archives of General Psychiatry*, *54*, 145–152.

Borbely, A. (1982). Sleep regulation: Circadian rhythm and homeostasis. In D. Ganten & D. Pfaff (Eds.), *Sleep. Clinical and experimental aspects* (pp. 83–104). Berlin, Germany: Springer Verlag.

Borbely, A., Ackermann, P., Trachsel, L., & Tobler, I. (1989). Sleep initiation and initial sleep intensity: Interaction of homeostatic and circadian mechanisms. *Journal of Biological Rhythms*, *4*, 149–160.

Burton, M. W., Locasto, P. C., Krebs-Noble, D., & Gullapalli, R. P. (2005). A systematic investigation of the functional neuroanatomy of auditory and visual phonological processing. *Neuroimage*, *26*, 647–661.

Buysse, D., Monk, T., Begley, A., Houck, P., & Seltman, H. (2000). Circadian and homeostatic influences on sleep during a 90-minute day paradigm. *Sleep*, *23*, A45.

Cajochen, C., Blatter, K., & Wallach, D. (2004). Circadian and sleep-wake dependent impact on neurobehavioral function. *Psychologica Belgica*, *44*, 59–80.

Campbell, S. (1992). The timing and structure of spontaneous naps. In C. Stampi (Ed.), *Why we nap* (pp. 71–81). Boston: Birkhauser.

Carrier, J., & Monk, T. (2000). Circadian rhythms of performance: New trends. *Chronobiology International*, *17*, 719–732.

Craig, A., Baer, K., & Diekmann, A. (1981). The effects of lunch on sensory- perceptual functioning in man. *International Archives of occupational and Environmental Health*, *49*, 105–114.

Cohen, R. A. (1993). *The neuropsychology of attention*. New York: Plenum Press.

Dinges, D. (1992). Adult napping and its effect on ability to function. In C. Stampi (Ed.), *Why we nap* (pp. 118–134). Boston: Birkhauser.

Dinges, D. (1995). An overview of sleepiness and accidents. *Journal of Sleep Research*, *4*(Suppl. 2), 4–14.

Dye, L., Lluch, A., & Blundell, J. (2000). Macronutrients and mental performance. *Nutrition*, *16*, 1021–1034.

Folkard, S. (1990). Circadian performance rhythms: some practical and theoretical implications. *Philosophical Transactions of the Royal Society of London B*, *327*, 543–553.

Folkard, S., & Åkerstedt, T. (1991). A three process model of the regulation of alertness and sleepiness. In R. Ogilvie & R. Broughton (Eds.), *Sleep, arousal and performance: Problems and promises* (pp. 11–16). Boston: Birkhduser.

Folkard, S., & Monk, T. H. (1985). Circadian performance rhythms. In S. Folkard & T. H. Monk (Eds.), *Hours of work. Temporal factors in work scheduling* (pp. 37–52). Chichester, England: Wiley.

Ganong, W. (1999). *Review of medical physiology* (19th ed.). Stamford, CT: Appleton and Lange.

Gillberg, M., & Åkerstedt, T. (1998). Sleep loss and performance: no "safe" duration of a monotonous task. *Physiology and Behavior*, *64*, 599–604.

Gillooly, P., Smolensky, M., Albright, D., Hsi, B., & Thorne, D. (1990). Circadian variation in human performance evaluated by the Walter Reed performance assessment battery. *Chronobiology International*, *7*, 143–153.

Godefroy, O. (2003). Frontal syndrome and disorders of executive functions. *Journal of Neurology*, *250*, 1–6.

Hamelin, P. (1987). Lorry drivers' time habits in work and their involvement in traffic accidents. *Ergonomics*, *30*, 1323–1333.

Harrison, Y., & Horne, J. A. (2000). The impact of sleep deprivation on decision making: A review. *Journal of Experimental Psychology Applied*, 6, 236–249.

Harrison, Y., Jones, K., & Waterhouse, J. (2007). The influence of time awake and circadian rhythm upon performance on a frontal lobe task. *Neuropsychobiologia*, *45*, 1966–1972.

Hildebrandt, G., Rohmert, W., & Rutenfranz, J. (1975). The influence of fatigue and rest period on the circadian variation of error frequency in shift workers (engine drivers). In P. Colquhoun, S. Folkard, P. Knauth, & J. Rutenfranz (Eds.), *Experimental studies on shiftwork* (pp. 177–187). Opladen, Germany: Westdeutschen Verlag.

Horne, J., & Reyner, L. (1995). Driver sleepiness. *Journal of Sleep Research*, *4*(Suppl. 2), 23–29.

Horne, J. A., & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness in human circadian rhythms. *International Journal of Chronobiology*, *4*, 97–110.

Jarrett, R. (1979). Rhythms in insulin and glucose. In D. Krieger (Ed.), *Endocrine rhythms* (pp. 247–258). New York: Raven Press.

Johnson, M., Duffy, J., Dijk, D., Ronda, J., Dyal, C., & Czeisler, C. (1992). Short-term memory, alertness and performance: A reappraisal of their relationship to body temperature. *Journal of Sleep Research*, *1*, 24–29.

Jones, K., & Harrison, Y. (2001). Frontal lobe function, sleep loss and fragmented sleep. *Sleep Medicine Reviews*, *5*, 463–475.

Kennedy, R., Bittner, A., Harbeson, M., & Jones, B. (1982). Television computer games: A new look, in performance testing. *Aviation, Space and Environmental Medicine*, *53*, 49–53.

Kerkhof, G. (1985). Inter-individual differences in the human circadian system: A review. *Biological Psychology*, *20*, 83–112.

Killgore, W. D., Balkin, T. J., & Wesensten, N. J. (2006). Impaired decision making following 49 h of sleep deprivation. *Journal of Sleep Research*, *15*, 7–13.

Kleitman, N. (1939). *Sleep and wakefulness*. Chicago: University of Chicago.

Koslowsky, M., & Babkoff, H. (1992). Meta-analysis of the relationship between total sleep deprivation and performance. *Chronobiology International*, *9*, 132–136.

Krueger, G. (1989). Sustained work, fatigue, sleep loss and performance: A review of the issues. *Work and Stress*, *3*, 129–141.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

Mills, J., Minors, D., & Waterhouse, J. (1978). Adaptation to abrupt time shifts of the oscillator(s) controlling human circadian rhythms. *Journal of Physiology*, *285*, 455–470.

Minors, D., & Waterhouse, J. (1981). *Circadian rhythms and the human.* Bristol, UK: Wright PSG.

Monk, T., Buysse, D., Reynolds, C., Berga, S., Jarrett, D., Begley, A., et al. (1997). Circadian rhythms in human performance and self-rated subjective feelings under constant conditions. *Journal of Sleep Research*, *6*, 9–18.

Monk, T., Buysse, D., Reynolds, H., & Kupfer, D. (1996). Circadian determinants of the post lunch dip in performance. *Chronobiology International*, *13*, 123–133.

Monk, T., & Carrier, J. (1998). A parallelism between human body temperature and performance independent of the endogenous circadian pacemaker. *Journal of Biological Rhythms*, *13*, 113–122.

Naitoh, P., Kelly, T., & Babkoff, H. (1993). Sleep inertia: Best time not to wake up? *Chronobiology International*, *10*, 109–118.

Nilsson, J. P., Soderstrom, M., Karlsson, A. U., Lekander, M., Akerstedt, T., Lindroth, N. E., et al. (2005). Less effective executive functioning after one night's sleep deprivation. *Journal of Sleep Research*, *14*, 1–6.

Nouguier-Soule, J., Nouguier, J., Bicakova-Rocher, A., Gorceix, A., & Reinberg, A. (1999). Utilization of a self-contained psychometry-oriented device, for study of affective and cognitive functions of a subject. *Encephale—Revue de Psychiatrie Clinique Biologique et Therapeutique*, *25*, 110–117.

Pokorny, M., Blom, D., & Van Leeuwen, P. (1987). Shifts, duration of work and accident risk of bus drivers. *Ergonomics*, *30*, 61–88.

Posner, M. I., & Rafal, R. D. (1987). Cognitive theories of attention and the rehabilitation of attentional deficits. In M. Meier, A. Benton, & L. Diller (Eds.), *Neuropsychological rehabilitation* (pp. 182–201). New York: Guilford Press.

Ramírez, C., Talamantes, J., García, A., Morales, M., Valdez, P., & Menna-Barreto, L. (2006). Circadian rhythms in phonological and visuospatial storage components of working memory. *Biological Rhythm Research*, *37*, 433–441.

Reilly, T., Atkinson, G., & Waterhouse, J. (1997). *Biological rhythms and exercise*. Oxford, UK: Oxford University Press.

Rogers, A., Spencer, M., Stone, B., & Nicholson, A. (1989). The influence of a 1 h nap on performance overnight. *Ergonomics*, *32*, 1193–1205.

Ryu, K., & Myung, R. (2005). Evaluation of mental workload with a combined measure based on physiological indices during a dual task of tracking and mental arithmetic. *International Journal of Industrial Ergonomics*, *35*, 991–1009.

Smith, A., & Miles, C. (1986). The effects of lunch on cognitive vigilance tasks. *Ergonomics*, *29*, 1251–1261.

Stampi, C., Broughton, R., Mullington, J. Rivers, M., & Campos, J. (1990). Ultrashort sleep strategies during sustained operations: The recuperative value of multiple 80-, SO- and 20-min naps. In G. Costa, G. Cesana, K. Kogi, & A. Wedderburn (Eds.), *Shiftwork: Health, sleep and performance* (pp. 623–628). Frankfurt, Germany: Peter Lang.

Stuss, D. T., & Levine, B. (2002). Adult clinical neuropsychology: Lessons from studies of the frontal lobes. *Annual Review of Psychology*, *53*, 401–433.

Szlyk, J., Myers, L., Zhang, Y., Wetzel, L., & Shapiro, R. (2002). Development and assessment of a neuropsychological battery to aid in predicting driving performance. *Journal of Rehabilitation Research and Development*, *39*, 483–495.

Thomas, M., Sing, H., Belenky, G., Holcomb, H., Mayberg, H., Dannals, R., et al. (2000). Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. *Journal of Sleep Research*, *9*, 335–352.

Valdez, P., Ramírez, C., García, A., Talamantes, J., Armijo, P., & Borrani, J. (2005). Circadian rhythms in components of attention. *Biological Rhythm Research*, *36*, 57–65.

Van Dongen, H. (2004). Comparison of mathematical model predictions to experimental data of fatigue and performance. *Aviation, Space, Environmental Medicine*, *75*(Suppl.), A15–A36.

Vidacek, S., Kaliterna, L., Radosevic-Vidacek, B., & Folkard, S. (1988). Personality differences in the phase of circadian rhythms: A comparison of morningness and extraversion. *Ergonomics*, *31*, 873–888.

Waterhouse, J., Minors, D., Åkerstedt, T., Reilly, T., & Atkinson, G. (2001). Rhythms of human performance. In J. Takahashi, F. Turek, & R. Moore (Eds.), *Handbook of behavioral neurobiology: Circadian clocks* (pp. 571–601). New York: Kluwer Academic/Plenum.

Weaver, T. E. (2001). Outcome measurement in sleep medicine practice and research. Part 2: Assessment of neurobehavioral performance and mood. *Sleep Medicine Reviews*, *5*, 223–236.

Wojtczak-Jaroszowa, J., & Jarosz, D. (1987). Chronohygienic and chronosocial aspects of industrial accidents. In J. E. Pauly & L. E. Scheving (Eds.), *Advances in chronobiology B* (pp. 415–426). New York: Alan R Liss.

Wright, K., Hull, J., & Czeisler, C. (2002). Relationship between alertness, performance, and body temperature in humans. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *283*, R1370–R1377.

Young, M., & Stanton, N. (2007). What's skill got to do with it? Vehicle automation and driver mental workload. *Ergonomics*, *50*, 1324–1339.