Risk of Performance Errors due to Sleep Loss, Circadian Desynchronization, Fatigue, and Work Overload

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Fatigue occurs during spaceflight and will jeopardize health and performance. This risk may be influenced by artificial and transmitted light exposure, individual vulnerability to sleep loss and circadian dynamics, and work/sleep schedules. Efforts are needed to improve sleep hygiene, and to identify and improve conditions that interfere with sleep quality. Research areas may include: development of a self-assessment tool for cognitive function and fatigue, light therapy for phase shifting, alertness and mood disorders, and other means to improve sleep quality and reduce fatigue. – *Human Research Program Requirements Document*, HRP-47052, Rev. C, dated Jan 2009.

Sleep accommodations on short-duration space shuttle flights were Spartan (as shown here), but sleep stations on board the International Space Station strive to provide a stable, comfortable, dark, and quiet environment to encourage the quality and quantity of sleep essential to optimize crew performance and health.

Executive Summary

Data that have been collected during space flight missions consistently indicate that sleep loss, circadian desynchronization, fatigue, and work overload occur, to varying degrees, for some individuals. Few studies of performance have been conducted in flight, however, and the findings that have been generated remain unclear as to how a crew member's performance during space flight is directly impacted by sleep loss. Extensive ground-based scientific literature, including controlled laboratory studies and data that have been gathered from industries, demonstrates that the degree of sleep and circadian disturbances that are often experienced by astronauts result in performance errors and may also impact long-term health.

Space flight evidence regarding sleep loss primarily includes data that were collected through controlled studies (Category II[15]) as well as through self-report (Category III). These evaluations, which have focused on short-duration (fewer than 30-day) missions, have provided data from astronauts' daily sleep logs, polysomnography, and actigraphy. These data have characterized sleep in space, overall, as shorter, less restful, and more interrupted than sleep on Earth. Circadian rhythms may also be misaligned due to scheduling constraints, with the result that fatigue (physical and mental) from work overload has been reported (Scheuring et al., 2007).

Questions, however, remain regarding the nature of sleep and circadian rhythms on long-duration space flight missions. Despite the fact that ISS construction has been under way for 9 years, systematic data collection to address this issue has only been undertaken recently. In light of ground-based evidence on sleep-loss-related performance effects, it is critical to understand the various factors that exist in the space flight and long-duration mission environment, and to identify ways in which sleep and circadian rhythms can be protected for crews who are flying on ISS and shuttle missions. NASA ground support personnel, as well as space flight crews, experience sleep loss, fatigue, circadian misalignment, and work overload. Ground teams that support robotic missions to Mars, as evidenced during the Mars Pathfinder, Spirit, Opportunity, and Phoenix missions, similarly face issues of sleep loss and circadian desynchronization.

As human space flight transitions from LEO (e.g., shuttle, ISS) to Exploration missions to the moon and Mars, and as NASA continues to support robotic missions to Mars and beyond, it becomes more important to characterize human risk factors accurately and adequately and to identify the ways in which to mitigate this performance risk safely and effectively. The first short-duration lunar missions, which will be similar to the shuttle missions, will seem to be fast-paced sprints as compared to the marathon-like races of later, longer lunar outpost missions (and ISS increments). Docking will require shifting of schedules for those in flight and for their support teams on the ground; the hurried schedule will likely include heavy workloads. Longer lunar missions will pose additional challenges to crews, including perpetual non-terrestrial day-night cues, environmental constraints, and extended periods of high-intensity workload. As the evidence reveals, crews on short- and long-duration lunar missions will need to be well-equipped and prepared for the potential performance and long-term health effects of sleep loss and circadian shifting.

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[15] To help characterize the kind of evidence that is provided in each of the risk reports in this book, the authors were encouraged to label the evidence that they provided according to the "NASA Categories of Evidence."

- Category I data are based on at least one randomized controlled trial.
- Category II data are based on at least one controlled study without randomization, including cohort, case-controlled or subject operating as own control.
- Category III data are non-experimental observations or comparative, correlation and case, or case-series studies.
- Category IV data are expert committee reports or opinions of respected authorities that are based on clinical experiences, bench research, or "first principles."

Introduction

Sleep disorders plague a staggering number of individuals. The authors of the 2007 Institute of Medicine (IOM) report *Sleep Disorders and Sleep Deprivation: An Unmet Public Health Problem* state that as many as "60 to 70 million individuals chronically suffer from a disorder of sleep and wakefulness, hindering daily functioning and adversely affecting health and longevity… a wide range of deleterious long-term health consequences are associated with chronic, or cumulative, sleep loss. These consequences include: hypertension, diabetes, obesity, heart attack, stroke, and psychiatric disorders such as depression or severe anxiety."

In addition to the negative health outcomes that are cited above, another risk that can result from sleep loss is an increase in performance errors. Evidence shows that 24 hours without sleep, or less severe but more chronic sleep loss, can lead to daytime feelings of fatigue and increase performance errors on a variety of tasks that require attention, memory, cognitive and psychomotor speed, and executive functioning (Harrison and Horne, 1998; Durmer and Dinges, 2006; Banks and Dinges, 2007). Research indicates that astronauts, on average, sleep fewer than 6 hours per day (Dijk et al., 2001; Barger and Czeisler, 2008). Several authors of Earth-based sleep-dose-response studies reveal that sleeping 6 hours or fewer per day results in cumulative cognitive performance deficits (Belenky et al., 2003; Van Dongen et al., 2003; Dinges et al., 2005; Mollicone et al., 2008). Moreover, there is a disconnect between subjective and objective measures of sleep loss under these conditions; e.g., individuals who are suffering from sleep deprivation or fatigue may not be able to accurately gauge their degree of impairment, and, therefore, will not take appropriate countermeasures to mitigate the impacts that can arise from these conditions.

Crews who are on orbit and the ground teams who support them face not only the likelihood of recurrent sleep loss but also the risk of circadian desynchronization. Circadian rhythms regulate subjective alertness, cognitive functions, and sleep propensity as well as core body temperature, hormone secretion (including melatonin), and the nocturnal secretion of growth hormone. A misalignment of circadian rhythms results in disturbed sleep and impaired performance and alertness (Ball and Evans, 2001, p.144; Van Dongen and Dinges, 2005). On Earth, shift workers often experience circadian misalignment, especially when they are working over night or rotating shifts; shift work schedules are associated with increased risk of accidents and injuries (Dinges, 1995; Czeisler et al., 2005; Barger et al., 2006). Recent evidence suggests that shift work, which includes exposure to light at night, suppresses the normal nocturnal production of melatonin by the pineal gland; this suppression over time may increase the risk of developing cancer among individuals who are working shifts (Blask et al., 2002; Glickman et al., 2002, Blask et al., 2005; Stevens et al., 2007).

Work overload also poses a risk to the behavioral health of space flight crews. NASA management currently sets limits, which are known as "Fitness for Duty Standards," for the planned number of hours in which astronauts are to complete tasks and events. The planned nominal number of work hours for space crews is 6.5 hours per day; it is recommended that crew members not exceed a 48-hour total work week. NASA researchers have found that maintaining nominal work hours and workload is especially important during critical operations. The NASA definition of a critical overload workload for a space flight crew is 10-hour work days that are undertaken for more than 3 days per week, or more than 60 hours per week (NASA STD-3001, Vol. 1). Not only is the duration of the workday important, but so, too, is the intensity of the workloads for space flight crews. Astronauts who have taken part in high-tempo missions, from the historic Apollo to the current space shuttle missions, have accomplished complex tasks in the most dangerous surroundings while enduring hours of intense concentration. Anecdotal reports from veteran astronauts (Scheuring et al., 2007) indicate that at times of high intensity, workload can result in mental and physical fatigue. Field studies from the medical and aviation industries show that increased and intense workloads, particularly in conjunction with disturbed sleep and fatigue, can lead to significant health issues and performance errors, which, in turn, can cause increased incidents of injuries, accidents, or death (Barger et al., 2006; Goode, 2003).

In light of the negative health and performance consequences that are associated with sleep, fatigue, circadian, and workload issues, the duration and quality of sleep among astronauts and ground crews is of concern to the designers of current NASA operations and the NASA Constellation Program. The consequences of human system risks for Constellation missions include loss of mission objectives as well as increased health risk during the mission or post-flight. Research addressing sleep quality and the circadian system endeavors to minimize these risks.

The NASA HRP BHP Element (http://humanresearch.jsc.nasa.gov/about.asp) aims to further characterize the risk of performance errors due to sleep loss, fatigue, circadian desynchronization, and work overload in preparation for Exploration missions to the moon and Mars. Operationally relevant monitoring technologies that detect sleep quantity and quality, and individualized countermeasures that prevent or mitigate the risk in long-duration isolated environments, will equip crews for optimal behavioral health and performance. Focused laboratory and ground analog studies as well as space flight studies will provide valuable insights into developing these technologies and countermeasures.

The NASA HRP BHP Element is tasked with managing three risks. These are the risk of: (1) performance errors due to sleep loss, circadian desynchronization, fatigue, and work overload; (2) performance errors due to poor team cohesion and performance, inadequate selection/team composition, inadequate training, and poor psychosocial adaptation; and (3) behavioral and psychiatric conditions. As each of these risks is addressed in a separate evidence report chapter, they should not be construed to exist independently of one another but, rather, should be evaluated in conjunction with the other. Furthermore, the BHP risks overlap with the risks in other HRP Elements and, as such, must also be considered in conjunction with these other risks (see figure 3-1 for an example of these possible overlaps).

The relationships of BHP with the other Elements are further outlined in the HRP IRP, which can be found at http://humanresearch.jsc.nasa.gov/about.asp. The nature of the IRP implies that BHP is continually reviewing and updating integration points with other Elements. Current research efforts are under way through collaborative efforts with the Exploration Medical Capabilities (ExMC) Element, Human Health and Countermeasures (HHC) Element, as well as the SHFH Element. While current research is designed to address identified gaps, it will be necessary to update and revise each of the BHP Evidence Reports as the Element gaps are closed and new gaps emerge. Such information will also inform the human system risk mitigation and assessment strategy of the NASA JSC Space Life Sciences Directorate.

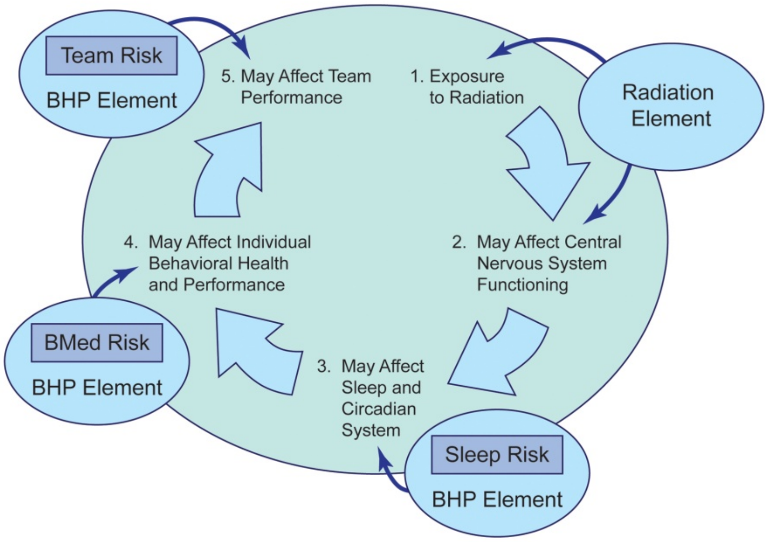

Figure 3-1. ***Sample integration within the BHP Element, and with other HRP Elements.***

Evidence

Ground-based evidence

Studies, which include laboratory investigations (Category I) and field evaluations (Category II and Category III) of population groups that are analogous to astronauts (e.g., medical and aviation personnel), provide compelling evidence that working long shifts for extended periods of time contributes to sleep deprivation and can cause performance decrements, health problems, and other detrimental consequences, including accidents, that affect both the worker and others.

Performance Errors Relative to Sleep Loss and Extended Wakefulness

A meta-analysis (Category I) that was conducted by Pilcher and Huffcutt (1996) examined data that were drawn from 19 research studies to characterize the effects of sleep deprivation on specific types of human performance. Motor skills, cognitive skills, and mood were assessed in terms of: partial sleep deprivation (also known as sleep restriction), which is defined as fewer than 5 hours of sleep in a 24-hour period for 1 or more days; short-term total sleep deprivation (no sleep attained for fewer than 45 hours); and long-term sleep deprivation (no sleep attained for a period in excess of 45 hours). These researchers found that sleep-deprived subjects performed considerably worse on motor tasks, cognitive tasks, and measures of mood than did non-sleep-deprived subjects. The greatest impact on cognitive performance was seen from multiple days of partial sleep deprivation, although short- and long-term sleep deprivation also showed an effect. Meta-analyses of sleep deprivation effects in medical residents found deficits in both laboratory tasks and clinical tasks (Philibert, 2005).

The magnitude of the chronic partial sleep loss that has been experienced by astronauts in flight (Barger and Czeisler, 2008; Monk et al., 1998; Dijk et al., 2001; Kelly et al., 2005; Gundel et al., 1997; Santy et al., 1988; Frost et al., 1976) has been reported to negatively impact cognitive performance in multiple Category I, Category II, and Category III laboratory and field studies (Dinges et al., 1997; Lockley et al., 2004; Landrigan et al., 2004; Ayas et al., 2006; Barger et al., 2006). Performance can be affected whether sleep loss is in the form of a night of substantially reduced sleep, a night of total sleep deprivation, or a series of less drastic, but more chronic, restricted sleep hours. A 1997 study by Dinges et al. revealed that when sleep is restricted to the level that is commonly experienced by astronauts (i.e., 4 to 6 hours per day), a "sleep debt" accrues and, in less than 1 week, performance deficits during waking hours reach levels of serious impairment.

Chronic reduction of sleep can impact performance in a manner that is similar to that of total sleep deprivation. A study by Van Dongen et al. (2003), which used 48 subjects, evaluated the specific performance effects of chronic sleep restriction in comparison to the effects of 3 nights of total sleep deprivation. Sleep restriction conditions included 14 consecutive nights of 8, 6, or 4 hours of sleep opportunity, with actual sleep quantity validated by polysomnography recordings. Subjects who were subjected to sleep restriction conditions underwent neurobehavioral assessments every 2 hours during their scheduled wakefulness, while subjects who were subjected to the sleep deprivation condition were tested every 2 hours throughout their total 88 hours of sleep deprivation.

The neurobehavioral assessment battery that was used in the Van Dongen et al. (2003) study included the psychomotor vigilance task (PVT). The PVT – which determines alertness and the effects of fatigue on cognitive performance (as determined by lapses in response time and accuracy of responses) by measuring the speed with which subjects respond to a visual or an auditory stimulus (by pressing a response button) – has become a standard laboratory tool for the assessment of sustained performance in a variety of experimental conditions (Dorrian et al., 2005). The PVT detects changes in basic neurobehavioral performance that involve vigilant attention, response speed, and impulsivity; and it has been extensively validated in ground-based laboratory studies to detect cognitive deficits that are caused by a variety of factors (e.g., restricted sleep, sleep/wake shifts, motion sickness, residual sedation from sleep medications) (Dinges and Powell (1985), Van Dongen et al. (2003), Drummond et al. (2005)). The PVT is an optimal tool for repeated use, in contrast to some other cognitive measures, as studies have shown no minimal learning effects and aptitude differences when using the PVT (Van Dongen et al., 2003; Balkin et al., 2004; Dorian et al., 2003).

Results from these laboratory studies indicate that multiple consecutive sleep episodes of 4 or 6 hours significantly erode performance on the PVT and on measures of working memory, and that performance under these two conditions (i.e., 4 or 6 hours) was comparable to the performance that is found under conditions of 1 to 2 days of total sleep deprivation. Surprisingly, by the end of the 14 days of sleep restriction, subjects in the 4- and 6-hour sleep period conditions reported feeling only slightly sleepy. As these reports were taken when performance was at its lowest level, this indicates that the subjects may no longer have been aware of their performance deficits because of inadequate recovery sleep (Van Dongen et al., 2003) (figure 3-2).

Subjects who spent 4 hours in bed reached levels of impairment at 6 days and of severe impairment at 11 days. Subjects who spent 6 hours in bed reached levels of impairment at 7 days. Interestingly, it appears that subjects who spent 8 hours in bed approached levels of impairment. Figure 3-3, which is from Belenky et al. (2003), however, demonstrates that subjects who spent 9 hours in bed did not approach these levels of impairment, indicating that 9 hours in bed may be needed to alleviate the risk of performance errors.

Similar performance effects resulting from chronically restricted sleep can also be seen in the Category I study by Belenky et al. (2003) and in figure 3-3. This study involved 66 subjects who were observed in four conditions (i.e., 3, 5, 7, and 9 hours in bed) for 7 days. PVT testing showed severe impairments in reaction time under the 3-hour condition, with lapses in responses increasing steadily across the 7 days of sleep restriction. Subjects who spent 3 hours in bed reached levels of *severe* impairment at 5 days, while subjects who spent 5 hours in bed reached levels of impairment at 4 days.

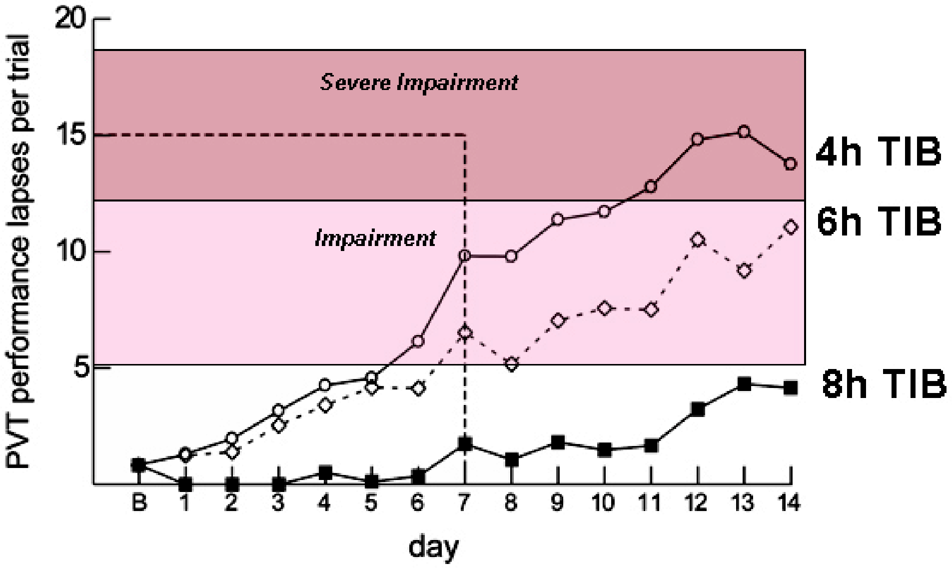

Figure 3-2. ***Performance lapses for time in bed (TIB) over 14 days of sleep restriction (Van Dongen et al., 2003).***

These Category I laboratory studies by Van Dongen et al. (2003) and Belenky et al. (2003) clearly show that subjects suffered performance impairments resulting from total sleep deprivation and/or chronic sleep restriction.

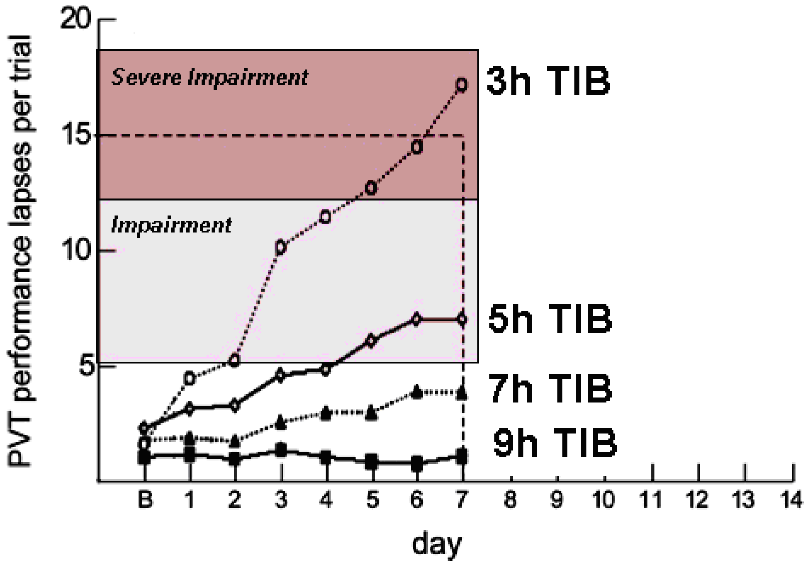

Figure 3-3. ***PVT performance lapses for TIB over 7 days sleep restriction (Belenky et al, 2002).***

Cognitive impairments are present even after an individual has been awake for approximately 17 hours; in fact, recent studies have shown that these decrements are similar to those that result from an elevated blood alcohol level. A compelling Category I laboratory study from Williamson and Feyer (2000) used a cross-over randomized control design to observe cognitive and motor performance after minor sleep deprivation to performance after alcohol consumption. All subjects participated in both alcohol consumption and sleep deprivation, and the order of testing was counterbalanced so that half of the subjects participated in the alcohol consumption part first while the other half participated in the sleep deprivation part first. To avoid carry-over effects from one condition to the next, subjects were provided with a night of rest in a motel between each condition.

Results indicate that, on average, performance with a blood alcohol level of 0.05% remained equivalent to performance after being awake for 16.9 to 18.6 hours. Performance with a blood alcohol level of 0.1% was equivalent to performance after being awake for 17.7 to 19.7 hours, or to restricted sleep of 4 to 5 hours per night for 1 week (Czeisler, 2006). Similar studies that compare performance after a time of sleep deprivation to performance with elevated blood alcohol levels have confirmed these results (Dawson and Reid, 1997; Arnedt et al., 2001). These findings are compelling as the duration of wakefulness (17 hours), which results in decrements that are similar to those that are induced by a 0.05% blood alcohol level, is considered by many to be within the range of a "normal" waking "day"; many individuals can recall an incident in which they had to waken early in the morning and work all day and into the night. Astronauts, who sleep an average of 6 hours per night (Santy et al., 1988; Gundel et al., 1997; Monk et al., 1998; Kelly et al., 2005), may be performing critical tasks 17 hours or more after wakening.

■ Performance Errors Relative to Sleep Desynchronization and Work Overload

Research suggests that circadian desynchronization and work overload may also impair performance. Specifically, a controlled laboratory study by Wright et al. (2002) evaluated the relationship between circadian rhythms and performance by assessing body temperature, which is regulated by the circadian mechanisms of the body. Body temperature is at its highest near the circadian peak and lowest near the circadian minimum (this is when the body is driven to sleep). It has long been recognized that a positive relationship exists between daily rhythms of body temperature and neurobehavioral performance and alertness in humans (Wright et al., 2002).

The study protocol (Wright et al., 2002) forced circadian desynchronization for 12 consecutive 28-hour days; participants were allowed 9.3 hours of scheduled time in bed and 18.7 hours of scheduled wakefulness. Performance on validated measures was evaluated every 2 hours, beginning 2 hours after the scheduled wake time. The protocol, therefore, assessed performance when the body is normally driven to sleep (which is related to the point at which body temperature at its lowest) relative to performance during normal waking hours, and allowed for assessment of the effects of body temperature independent of (and associated with) sleep hours and time of day. During the circadian peak (when body temperature is high), performance and alertness are high; conversely, near the circadian phase of low body temperature, performance and alertness are low. These results have been replicated in other forced desynchrony and extended wakefulness laboratory protocols (Wyatt et al., 1999).

Results from these laboratory protocols can be extrapolated to field conditions. Studies in the medical industry, where highly educated and trained individuals (e.g., physicians) are subject to circadian shifting and extended work shifts in addition to sleep loss, further demonstrate serious performance errors with populations that are analogous to astronauts. In a two-session, within-subject, Category II experiment that was conducted by Arnedt et al. (2005), the performance of 34 medical interns was observed under four conditions:

after 4 weeks of a light rotation (averaging 44 hours of rotations/week); after 4 weeks of a heavy rotation (averaging 80 hours of rotations/week); after 4 weeks of a heavy rotation with a 0.05% blood alcohol level; and after 4 weeks of a light rotation with a 0.05% blood alcohol level.

Performance measures included the PVT and a simulated driving task. Findings of the Arnedt et al. (2005) experiment indicate that performance impairment after a heavy-call rotation is comparable to the impairment that is associated with a combined 0.04% to 0.05% blood alcohol level and a light-call rotation. Results of this experiment demonstrate that decrements that are created by extended work shifts are similar to the decrements that are created by elevated blood alcohol levels.

Work hours and sleep loss were shown to impact performance in a Category III evaluation by Rogers et al. (2004). A total of 393 registered nurses logged scheduled hours worked, actual hours worked, time of day worked, overtime, days off, and sleep/wake patterns. Questions concerning errors and near-errors were also included. Analysis showed that work duration, overtime, and number of hours worked per week significantly affected the number of errors. The likelihood of making an error increased with longer work hours, and was three times higher when the nurses worked shifts lasting 12.5 hours or more. Working overtime increased the odds of making at least one error, regardless of the originally scheduled length of the shift. Working more than 40 and more than 50 hours per week significantly increased the risk of making an error.

Similar findings were attained in a subsequent Category III evaluation of 2,737 medical interns (Barger et al., 2006). A Web-based survey was conducted across the U.S. in which interns completed 17,003 confidential monthly reports. These 60-item reports contained information concerning work hours, sleep, and activities during the month, number of days off, and the number of extended-duration work shifts (defined as at least 24 hours of continuous work). These interns were also asked to report whether they had made significant fatigue-related or non-fatigue-related medical errors. Other questions assessed how often they had nodded off or fallen asleep during patient care or educational activities.

Analysis revealed a significant relationship between the number of extended-duration work shifts and the reported rates of fatigue-related noteworthy medical errors. Specifically, the number of reported fatigue-related medical errors increased as the number of extended-duration shifts per month increased. At least one fatigue-related significant medical error was reported in 3.8% of months with no extended-duration work shifts; and at least one fatigue-related significant medical error was reported in 9.8% of months that had between one and four extended-duration work shifts and in 16% of months that had five or more extended-duration work shifts (Barger et al., 2006). Furthermore, the frequency of attentional failures was strongly associated with the frequency of extended-duration work shifts. Evidence from this study further corroborates the negative impact that extended-duration work shifts may have on performance, as well as increased accidents and injuries (Barger et al., 2006; Ayas et al., 2006).

Working extended hours or overnight shifts also poses the added difficulty of requiring performance from an individual at a time when the body is driven to sleep by the circadian system. Sleep, alertness, and cognitive functioning are determined by the interaction of two processes: the endogenous circadian pacemaker and the homeostatic drive for sleep (Czeisler et al., 2001). The endogenous circadian pacemaker generates the 24-hour circadian rhythm that regulates subjective alertness and sleep propensity as well as core body temperature, cognitive functions, and melatonin secretion, as described above (Czeisler, 2006). It is also highly sensitive to light, which is its primary synchronizer. Misalignment of the circadian rhythm results in disturbed sleep, impaired performance alertness, waking-hour melatonin secretion, and reduced levels of nocturnal secretion of growth hormone (Ball and Evans, 2001). The outcome, therefore, can range from performance errors to long-term health decrements.

Individuals who work at night and attempt to sleep during the day suffer because the timing of their sleep/wake schedule remains out of phase with the timing of the environmental light. Night workers are particularly prone to vehicle accidents, and their decreased alertness, performance, and vigilance are likely to blame for a higher rate of industrial accidents and quality control errors on the job, injuries, and a general decline in work productivity rate (Czeisler et al., 2001). Recent information also suggests that as the body normally releases melatonin when it is dark, working under artificial light at night suppresses the release of melatonin, which may increase the risk of developing cancer (Blask et al., 2002; Glickman et al., 2002, Blask et al., 2005; Stevens et al., 2007).

In summation, ground-based evidence demonstrates that sleep loss, circadian desynchronization, and extended work shifts lead to increased performance errors and accidents. The extent to which these risk factors are also present in the space flight environment is therefore an important consideration.

Space flight evidence

Occurrence of Sleep Loss and Fatigue in Space Flight

Space flight research indicates that, overall, sleep quantity and quality in astronauts are markedly reduced in comparison to terrestrial sleep quantity. Seven Category II and Category III studies, which used polysomnographic measurements, actigraphy, or other measures, have consistently shown that astronauts sleep, on average, fewer than 6 hours per day (Table 3-1). This amount of sleep is between 1.5 to 2 hours fewer than the 8 hours that are recommended for astronauts per NASA-STD-3001, Vol. 1.

Table 3-1. ***Space Flight Sleep Studies Summary and Category of Evidence***

Source	Average Hours of Sleep	Missions	Subjects (N)	Measurement Tool	Category of Evidence
Barger and Czeisler, preliminary unpublished data	5.9	STS-104, -109, -111, -112, -113, -114, -115, -116, -118, -120, -121, -122, -123, -124	23 analyzed to date	Actigraphy	II
Dijk et al., 2001	6.5	STS-90, -95	5	Polysomnogram, actigraphy	II
Kelly et al., 2005	6.0	STS-89	4	Sleep logs	III
Monk et al., 1998	6.1	STS-78	4	Sleep physiology	II
Gundel et al., 1997	6.1	*Mir*	4	Sleep physiology	II
Santy et al., 1988	6.0	Space shuttle	58	Post-flight debriefing	III
Frost et al., 1976	5.8	Skylab	3	Physiology	II

A post-flight debriefing survey that was conducted in 1988 (Category III) found that 58 crew members from nine space shuttle missions (ranging in duration from 4 to 9 days) reported sleeping on average 6 hours per day while in space compared to 7.9 hours terrestrially (Santy et al., 1988). Sleep was most reduced during the first and last days of a mission (total 5.6 and 5.7 hours, respectively). Many crew members reported fewer than 5 hours sleep on some nights, and some crew members slept 2 hours or less (Santy et al., 1988, p. 1096). While NASA flight surgeons recommend 8 hours of sleep per day in space, studies on 101 astronauts have found that, in space, they sleep an average of approximately 6 hours per day.

Note that, in the table, the categories of evidence are limited to Category II and Category III. This limitation is due to the nature of space flight, which requires that researchers evaluate a small number of subjects, rendering it practically impossible to truly replicate a Category I when astronauts are on orbit.

Actigraphy and self-reporting are currently measuring to what degree space flight results in disruption of sleep during both short-duration (shuttle) and long-duration (ISS) missions (Barger and Czeisler, 2008). This study will be the largest and most rigorous of its type. To date, 36 subjects on shuttle missions and six subjects on ISS missions have completed the protocol; a total of 20 subjects from ISS missions are planned to take part in the study, and shuttle data collection will continue until the ISS goal is achieved and/or the shuttle is retired. Data are collected at 90 days before launch for 2 weeks (to establish a baseline), from 11 days before launch until launch, in flight (as soon as possible on orbit until the last flight day), and, after landing, for 7 more days. Preliminary analysis, using 23 subjects over nine shuttle missions, estimated that the average total nightly sleep duration (estimated with actigraphy) was 5.9 hours in flight and 6.9 ± 1.0 hours in the first week after flight. Of the 279 nights in flight that were recorded with actigraphy, 52 (18.6%) included fewer than 6 hours of sleep. These findings confirm previous studies that show an incidence of reduced sleep quantity in space.

Further preliminary analysis shows that sleep quantity may be reduced even more prior to undergoing critical mission operations. Evaluations of nine crew members who were performing between one and three EVAs each, across five missions, estimate that the average total amount of sleep that the crew members had the night before the EVAs was 5.6 ± 1.1 hours. As previously discussed, ground-based studies have consistently reported performance impairments under conditions of acute or chronic reduced sleep.

Objective feedback on sleep quantity is important information to provide to flight surgeons and astronauts who are preparing to engage in critical mission activities; this will be particularly true for the more autonomous Exploration missions. Currently, actigraphy data for some missions are being shared among the researcher, the flight surgeon, and the crew member; the flight surgeons and astronauts, who have commented on the benefit of having this information available, support transitioning the Actiwatch (figure 3-4) protocol to an operational tool (flight surgeons G Beven and S Johnston, personal communication, 2008).

A compelling testimony of sleep disturbances in flight is the degree to which sleep medications are used. A 1999 Category III study reviewed records from 79 space shuttle missions: of the 219 records that were obtained (each record representing one person on one flight), 94% indicated medication use during flight; and of the records that indicated medication use, 45% of them indicated that the medications were taken for sleep disturbances and that these were taken consistently for 9 flight days (Putcha et al., 1999). Two examples of astronaut sleep facilities on the ISS are provided in figure 3-5 and 3-6.

Figure 3-4. ***Image of an Actiwatch activity monitor that is shown next to a ruler to demonstrate the size of the Actiwatch.***

Figure 3-5. ***With most of his body tucked away in a sleeping bag, astronaut Daniel Tani, Expedition 16 flight engineer, poses for a photograph near two extravehicular mobility unit spacesuits in the Quest Airlock of the ISS.***

Figure 3-6. ***Cosmonaut Vladimir Dezhurov of Rosaviakosmos, Expedition 3 flight engineer, works on a laptop computer in the temporary sleep station in the U.S. Laboratory.***

Recent unpublished data from shuttle missions (Barger and Czeisler, 2008) also show a trend of regular use of medication to promote sleep. Of the first 32 crew members studied during 11 missions, 26 (81%) reported taking a sleep-promoting medication in flight. Crew members who used sleep medications reported taking them on approximately half the nights that data were collected aboard the space shuttle; two doses of sleep medication were taken on 7% of the nights when medication was used. The frequent use of sleep medication in flight serves as a strong indication that sleep is disturbed for some crew members.

Sleep structure (i.e., sleep quality) may also be altered in space. A 1997 study (Gundel et al.), which used polysomnography (Category II) to evaluate sleep content, found that latency to the first rapid eye movement (REM) episode was shorter, and slow wave sleep (SWS) was redistributed from the first to the second sleep cycle. Dijk et al. (2001), who also used polysomnography, found a reduction of SWS during the final third of in-flight sleep episodes and post-flight (evaluated at 2, 4, and 5 days post-landing), with an increase in sleep duration and the amount of restorative sleep.

Subjective sleep quality diminished in flight in both the Gundel et al. (1997) and Dijk et al. (2001) studies. Studies by Gundel et al. (1997) and Monk et al. (1998) also revealed decreases in SWS and electroencephalogram (EEG) slow wave activity (SWA), reflecting the decrements in the putative restorative component of sleep that are known as Process S (Borbély and Achermann, 1999). In contrast, ground-based studies of sleep restriction have revealed a rapid increase in EEG SWS and SWA (Brunner et al., 1990). This discrepancy suggests that not only is sleep quantity reduced during space flight, but also that the restorative component of sleep may be disrupted in space, which may further increase the likelihood that waking neurobehavioral performance deficits will occur (Bonnet et al., 2005).

Individual, Physiological, and Environmental Factors that Contribute to Sleep Loss and Fatigue During Space Flight

Various factors influence the extent to which individuals experience sleep loss and fatigue in space. Differences exist among subjects when experiencing the deleterious effects resulting from inadequate sleep. Some may need less sleep and/or be more resistant to the effects of sleep loss on brain functions. Laboratory and field studies have found this to be the case for 10% to 30% of individuals when sleep loss is mild to moderate (Van Dongen et al., 2004, 2005b; Caldwell et al., 2005). For the majority of astronauts, however, sleep loss and fatigue remain a relevant issue, and self-report of alertness has been shown to be inaccurate under conditions of sleep loss (see above), even in motivated and trained individuals.

The space flight environment affects this risk as well. For instance, recent data indicate that noise levels on the ISS, even during sleep periods, can average more than 70 dB, and that the recordings have “maxed out” at over 90 dB during scheduled sleep episodes (Goodman, 2003). For comparison, a circular saw creates noise levels from 91 to 99 dB. The degree to which noise and environmental disturbances impact sleep during space flight missions remains to be determined.

Recent Category III unpublished data (Barger and Czeisler, 2008) confirm the findings of previous assessments of sleep quantity and quality on orbit. In particular, these findings suggest that the amount and quality of in-flight sleep is reduced in comparison to terrestrial sleep behavior for multiple reasons. Data from 23 astronauts who completed 274 sleep logs on nine shuttle flights indicate that in 163 (59%) of these logs, sleep was recorded as having been disturbed on the previous night. The most frequent causes of sleep disturbance were voids; noise; physical discomfort; other crew member disturbances; and temperature. These physiological and environmental factors may interfere with achieving good sleep quality on either the shuttle or the ISS, thereby depriving crews of the full restoration afforded by sleep. An evidence-gathering effort is under way by BHP researchers to evaluate the impact of these individual, physiological, and environmental factors on sleep and fatigue, and to address several BHP gaps concerning the effects of work-rest schedules, environmental conditions, and flight rules and requirements on sleep, fatigue, and performance.

Occurrence of Circadian Desynchronization in Space Flight

A recent summary of findings from several short-duration evaluations shows that circadian desynchronization can and does affect at least some crew members in space, largely as a result of lighting conditions, scheduling constraints, or other aspects of the space flight environment (Mallis and DeRoshia, 2005).

Limited research is available on circadian rhythms in space. From the studies that have been conducted, there are inconsistencies as to the degree of circadian desynchronization experienced in flight (Mallis and DeRoshia, 2005). As an example, Gundel et al. (1997) assessed the circadian rhythms (using body temperature) of four astronauts over a period of 6 to 8 days during their stay on the Russian space station *Mir*. In comparison to baseline measures, these astronauts displayed a phase delay of more than 2 hours. The phase delay was attributed to the alterations of external cues (i.e., reduced light/dark modulation) and possibly delayed bedtimes, as well as the fact that the intrinsic period of the circadian pacemaker is longer than 24 hours (Gundel et al., 1997). Monk et al. (1998), however, analyzed the circadian rhythms of four astronauts (using body temperature) prior to, during, and following a 17-day shuttle mission. From this study, the authors determined that circadian rhythms in orbit appear to be very similar in phase and amplitude to those on the ground.

Far fewer analyses have been conducted on circadian rhythms over long-duration missions. A case study involving an astronaut on a mission to *Mir* (Monk et al., 2001), revealed that a 24-hour circadian rhythm was maintained for about the first 3 months, with disruptions in sleep and a reduced circadian amplitude occurring during the last 12 days (Mallis et al., 2004).

Another case study that was conducted over a 438-day *Mir* mission revealed delays in circadian rhythms (Mallis and DeRoshia, 2005). This and other circadian delays are attributed to a variety of factors including: the alterations of external cues, i.e., reduced light/dark modulation (Mallis and DeRoshia, 1995); possibly delayed bedtimes; as well as the fact that the intrinsic period of the circadian pacemaker is longer than 24 hours (Gundel et al., 1997. These inconsistencies in circadian desynchronization may also be due to individual differences, as some individuals (as previously mentioned) are more susceptible to sleep loss or the debilitating effects of shifted work-rest cycles (Dinges, 2004; Mallis and DeRoshia, 2005).

Factors that Contribute to Circadian Desynchronization During Space Flight

Lighting remains the most significant external cue for altering the phase of the circadian rhythm. Lighting is so effective, in fact, that numerous Category I and Category II ground-based laboratory studies have shown that timed exposure to specific types of bright light and blue-enriched (short-wavelength) light serves as an effective countermeasure for circadian phase-shift and performance deficits due to sleep deprivation (Czeisler et al., 1986; Brainard et al., 1988; Czeisler et al., 1989; Brainard et al., 2001; Czeisler et al., 1995; Lockley et al., 2003; Brainard and Hanifin, 2005; Cajochen et al., 2005; Gronfier et al., 2007; Lockley, 2007).

Any natural lighting to which crews are exposed on a spacecraft may impact their circadian adaptation. Note that the ISS and docked shuttle orbit the Earth every 1.5 hours, resulting in 16 sunrises and sunsets every 24 hours, causing the natural lighting cues surrounding the ISS to vary greatly from the terrestrial 24-hour day and night cycle. Indeed, astronauts on shuttle and ISS are no longer exposed to the natural 24-hour day and night cycle of the Earth but, rather, rely on cues from artificial lighting in addition to those from any of the sunrises/sunsets. Thus, the astronauts' circadian rhythms may be altered by these changes in light exposure.

Less-than-optimal artificial lighting conditions have been reported on the ISS (Category IV). Station lighting is provided by both incandescent and fluorescent light sources. Over time, this lighting has degraded due to lamp burnout and the difficulty in supplying replacement lamps on orbit. Over the 9 years of ISS construction, lamps were resupplied piecemeal, with one or two lamps being shipped up by the Soyuz. The resultant decline in on-board lighting eventually was addressed by the first major resupply by STS-114 in July 2005. As soon as the lamps were delivered to the ISS, however, the re-lamping duty was officially given a relatively low priority. Crew members raised this priority significantly, however, because of their desire to improve the illumination on board the station (see Appendix 1 for additional details). This was not only to avoid eyestrain but because, as artificial lighting can impact circadian rhythms and acute alertness, inadequate lighting contributes to circadian desynchronization and fatigue.

Slam shifting, which is an acute shift in the sleep/wake schedule to accommodate a docking or critical task in flight (Leveton et al., 2006), is another risk factor for circadian desynchronization in the current space flight environment. Slam shifting can result in sleep loss and fatigue for astronauts (Category III). Recent data from the JSC Missions Operations Directorate (MOD) (Korth et al., 2006) reveal that critical operations often require slam shifting. In 2,043 days of ISS operations (2000–2006), slam shifts occurred on 13% of these days, typically before and during critical operations (e.g., dockings/undockings, taxi spacecraft relocations, EVAs). Such schedule changes force critical mission operations to occur against the body's natural circadian rhythm and after sleep deprivation.

Slam shifting also affects the ground teams that are supporting the ISS during critical operations when these NASA teams often are working overnight. As described previously, people whose employment requires that they work overnight shifts must try to remain awake and alert to function well at times when their circadian rhythm and homeostatic drive are promoting sleep. Category IV evidence that is derived from flight surgeons indicates that crew members have said that "the shifting (circadian) was tougher on them than they thought it was going to be" (flight surgeon S Johnston, personal communication, 2007).

Occurrence of Work Overload During Space Flight

Category III evidence reveals work overload occurring during some space flight missions, including those of the Skylab and Apollo Programs. The workload during the second Skylab mission steadily increased over 8 weeks, while crew members of the third Skylab mission reported that they quickly ran into difficulty due to work overload. The fast-paced schedule and workload of the mission had initially caused these crew members to consistently "feel" behind on tasks as well as demoralized. At the start of the 45th day of their 59-day mission, the crew members of Skylab 3 elected to have a sit-down, during which they refused to perform scheduled tasks. Mission Control personnel later acknowledged that the schedule had been such that it had not given the crew members adequate time in which to adjust to their environment (Cooper Jr., 1996). Category III evidence from the Apollo Program also reveals that some of the Apollo crews reported serious mental fatigue while they were performing lunar EVAs (Scheuring et al., 2007). Current shuttle missions to ISS are recognized for their high-tempo nature as crews perform complex, critical tasks. Of the 22 EVAs that were conducted during 2007, nine of these dangerous, and critical, endeavors lasted 7 or more hours.

Space Flight Performance Errors Due to Sleep Loss, Fatigue, Circadian Desynchronization, and Work Overload

While evidence indicates that sleep loss, fatigue, circadian desynchronization, and work overload have occurred during space flight, it remains unclear whether these factors directly affect the performance of a crew in space flight. A limited number of space flight studies have evaluated performance for sleep and fatigue effects, and, of those studies, many of them have very few subjects. In the limited studies in which performance was shown to be affected, questions remain regarding whether sleep loss and fatigue were the root cause. It is also difficult to ascertain causality and relevance to future long-duration missions, when the data from these studies are largely derived from short-duration space flight studies (Table 3-2).

One of the first studies to evaluate cognitive in-flight performance was conducted by Benke et al. in 1993. This Category II evaluation assessed the performance of one cosmonaut in several cognitive tasks at three intervals during a 6-day mission on *Mir*. These tasks evaluated response time and accuracy. In-flight performance on the tasks was compared with pre- and post-flight performance. No significant decrements resulting from a short stay in space were found in this case study.

Table 3-2. ***Space Flight Cognitive Performance Studies***

Study	Year	Mission	No.	Measurement type	Effect	Type of Effect	Mission Days
Manzey and Lorenz	1998	*Mir*	1	Accuracy and response time: four tasks from AGARD-STRES (GRT, MST, UTT); mood and workload assessments	Yes	Pre-launch decrements associated with lowered mood scores; decrements in tracking performance varied in flight, associated w/adaptation (i.e., to space, and back to Earth)	438
Manzey et al.	1998	*Mir*	1	Accuracy and response time: four tasks from AGARD-STRES (GRT, MS, UTT, DT)	Yes	Fine manual control decrements (UTT) due to adaptation; potential decrement in tracking/ memory-search during DT	8
Newman and Lathan	1999	STS-42	4	Memory recall task	No		4
Schiflett et al.	1996	STS-65, STS-78	7	PAWS (battery of performance tests); subjective assessments of cumulative fatigue	Yes	Decrements in memory-search performance, correlated with self-assessment fatigue	14 (STS-65) 15 (STS-78)
Dijk et al.	2001	STS-90, STS-95	5 (STS-90) 1 (STS-95)	PVT (calculation, recall memory, VAS, KSS)	PVT-not sig.	Most lapses in flight; least lapses post-flight	16 (STS-90) 10 (STS-95)
Dijk et al.	2001	STS-90, STS-95	5 (STS-90) 1 (STS-95)	Self-assessment of fatigue	Yes	Fatigue levels worst in flight; best post-flight	16 (STS-90) 10 (STS-95)

Note: AGARD=Advisory Group for Aerospace Research and Development (NATO). STRES=simulated training requirements effectiveness report. GRT=grammatical reasoning task. MST=Memory Search Task. UTT=Unstable Tracking Task. PAWS=Performance Assessment Workstation. VAS=Visual Analog Scale. KSS=Karolinska Sleepiness Scale. DT=dual task.

Manzey et al. (1998) conducted a similar study over an 8-day mission to *Mir*; this again was a short-duration evaluation using one subject. The study involved administering six pre-flight and six post-flight assessments to one subject, with 13 in-flight assessments occurring during the Soyuz approach to *Mir* (high stress) and also during the stay on board *Mir*. Four tasks were administered: grammatical reasoning, MST, UTT, and a DT that consisted of unstable tracking with concurrent memory search. These tasks probe information-processing functions that are known to react sensitively to the adverse effects of environmental stressors or that might become impaired by the direct effects of microgravity on sensory motor processes (Kanas and Manzey, 2000). The speed and accuracy of short-term memory retrieval and logical reasoning were found to be unimpaired under space flight conditions. Decrements, however, were found in fine manual control movements during the UTT. DT interference effects on the tracking task and the memory search were also reflected, increasing from the beginning to the end of the mission.

During the experiment, researchers administered questionnaires to evaluate the crew members' mood, fatigue levels, and assessment of workload. Correlations between reported fatigue and decrements that were observed during the tasks were revealed. As a result, the investigators proposed that the decrements may have been caused in part by the effects of accumulated fatigue.

Newman and Lathan (1999) conducted a Category II experiment on cosmonauts during space flight and did not find impairments in a memory-search performance task, although tracking disruptions were apparent. A performance monitoring study by Schiflett et al. (1996) included daily assessments of the different mental functions of three astronauts during a 13-day shuttle mission. Impairments and decrements were found in tracking performance, time-sharing efficiency, and memory-search performance in space. The researchers hypothesized that the impairment in memory-search performance in two of the three astronauts was not related to microgravity but, rather, was a side effect of decreased alertness and fatigue.

To further investigate the relationship between sleep and performance on orbit, Dijk et al. (2001) conducted an evaluation of the sleep, circadian rhythms, neurobehavioral performance, and light-dark cycles of five astronauts during two space shuttle flights, STS-90 (Neurolab) and STS-95. The researchers assessed neurobehavioral function and performance by administering several different tests, including the 10-minute PVT; a 4-minute, two-digit addition task; and a memory task. Subjective assessments of performance and effort were also recorded.

Analysis of variance revealed that across performance and mood variables, there was a consistent trend toward worse performance in flight than was noted before or after flight (Dijk et al. 2001). A detailed analysis of the time course of changes involving neurobehavioral measures, which was based on two measures that were derived from the PVT and the probed recall memory test, suggested that most of the study subjects exhibited a decline in performance during the last week before launch, a further decline in flight, and a slow recovery post-flight. While the effect for the number of lapses in attention on the PVT and for the median reaction time was not significant, this lack of effect could be due to the small sample size.

Although findings were not significant, this continuously declining performance appearing in short-duration flight, and the trend of improvement in subjects post-flight correlated with the amount of REM sleep. On return to Earth, subjects experienced a marked increase in REM sleep, and their subjective sleep quality and neurobehavioral performance recovered.

In summation, performance data from space flight thus far reveal some effects on accuracy, response time, and recall tasks; however, the quality of the evidence for performance decrements occurring as a result of fatigue and sleep loss during space flight remains uncertain. To date, no systematic attempt has been made to measure the performance effects of fatigue, sleep loss, circadian desynchronization, and work overload during space flight, and it is unknown whether the effect of these factors on performance significantly impacts the completion of mission objectives. More evaluation is therefore needed to accurately characterize this risk in space, and to understand how sleep loss, fatigue, circadian desynchronization, and work overload in flight translate into performance decrements. Other questions of interest include: Even if performance decrements exist on cognitive assessments, do these indeed translate into potential operational errors? And are decrements, when they exist, related to sleep, fatigue, circadian, and workload issues, or are they instead related to other aspects of the space flight environment? Undoubtedly, thorough evaluation is needed to accurately characterize this risk in space. Testing with the 3-minute PVT, which will be conducted on ISS starting in 2009, will include a larger number of subjects and test sessions to evaluate cognitive performance over the course of long-duration missions.

As noted previously, ground evidence strongly indicates that sleep loss, fatigue, circadian desynchronization, and work overload lead to performance decrements for some individuals. Evidence from space flight clearly demonstrates the occurrence of sleep loss, fatigue, and circadian desynchronization on orbit. One could therefore conclude that, based on the ground evidence, astronauts do indeed face a realistic risk of performance errors.

It is essential, however, to accurately characterize the performance effects arising from sleep loss, fatigue, circadian desynchronization, and work overload more fully in the space flight environment so that individualized countermeasures can be implemented to prevent or reduce the risk. BHP research activities aim to determine the best measures and tools to assess cognitive performance in space and to characterize the effects of sleep loss, fatigue, extended work shifts, circadian desynchronization, and work overload on cognitive performance in this environment.

Computer-based Simulation Information

As detailed above, astronauts and ground personnel are exposed to many factors that may force their schedules away from the normal 24-hour routine: shift work, extended work hours, timeline changes, slam shifting, prolonged light of a lunar day, a Mars sol on Earth, a Mars sol on Mars, and abnormal environmental cues (e.g., inadequate or inappropriate light exposure). In addition, their quantity of sleep, particularly during critical mission operations, tends to be reduced due to a variety of operational, environmental, and individual factors. Extensive ground-based evidence demonstrates that reduced sleep increases the risk of performance errors, injuries, and accidents. As a result, a validated biomathematical model that instantiates the biological dynamics of sleep need and circadian timing could predict astronaut performance relative to fatigue and circadian desynchronization (Dinges, 2004). Such models could also provide a means by which to optimally schedule targeted countermeasures for maintaining astronaut performance. Various biomathematical models that seek to achieve these goals are under development (Mallis et al., 2004; Dean et al., 2007; Kronauer et al., 2007).

Two biomathematical models are discussed here: the Astronaut Scheduling Assistant, and the Circadian, Neurobehavioral Performance, and Subjective Alertness Model. Both of these models are based on extensive evidence that shows that the temporal dynamics and level of cognitive performance during wakefulness are the result of the interaction of sleep homeostatic drive and circadian timing (e.g., Borbély and Achermann, 1999). Both models incorporate predictions that are based on countermeasures. These predictions allow for the evaluation of the risk and safety of sleep/wake and work schedules during both the planning and the execution of space missions. Prospective studies on the accuracy of these model predictions remain to be done on Earth in conditions that simulate many of the sleep loss and circadian provocations that occur in space flight. Such studies are essential and may indicate the need for additional model parameters and changes in model structure.

The Astronaut Scheduling Assistant software tool, which was developed in 2007 by David Dinges and Hans Van Dongen, is based on a validated biomathematical model that relates cognitive performance to the neurobiology of sleep and wakefulness and to the biological clock. As previously discussed, studies in recent years have documented that the detrimental effects on cognitive performance of chronic sleep loss accumulate linearly across consecutive days of sleep restriction below 7 hours per day (Belenky et al., 2003; Van Dongen et al., 2003; Molicone et al., 2007; Mollicone et al., 2008). This model therefore takes into account cumulative sleep loss and more accurately predicts performance than traditional models (Avinash et al., 2005). For more information, refer to Appendix 2 of this report.

Differential vulnerability to the effects of sleep loss (Van Dongen et al., 2004) and night work (Czeisler et al., 2005) on performance must also be addressed by biomathematical models of astronaut performance because recent studies have documented large stable (trait-like) differences among individuals in the degree of cognitive deficits that are experienced during sleep loss (Van Dongen et al., 2004; Klerman and Dijk, 2005). Preliminary validation of these techniques indicates that as the number of past data points increases, the model increases the accuracy with which the trait parameters are estimated, resulting in significant improvements in performance prediction accuracy over population average models (figure 3-7) (Van Dongen et al., 2007).

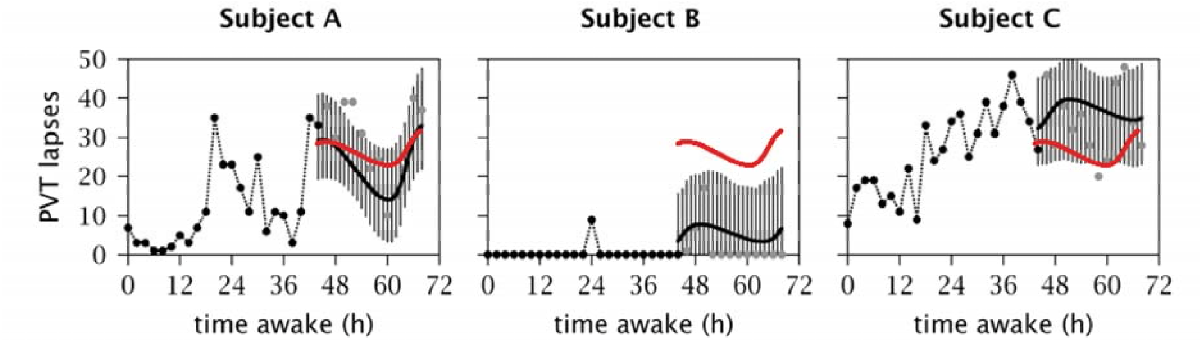

Figure 3-7. ***Future performance of three individuals, measured with the 10-minute PVT, during total sleep deprivation condition is predicted starting from t = 44h of wakefulness, with mean (thick black line) and 95% confidence interval (vertical bars). Individual predictions are based on traits that are identified from prior performance measurements up to t = 44h (block dots). The individualized predictions more accurately forecast the actual future performance of each individual (gray dots) than does the population average prediction (red line).***

The second model that was mentioned previously – the Circadian, Neurobehavioral Performance, and Subjective Alertness Model – predicts the effects of different light/dark and sleep/wake patterns on the circadian biological clock, performance, and alertness. Astronaut performance or alertness for an entire schedule or for a mission-critical time can thus be predicted. The model has been validated with data from shifted sleep-wake (e.g., jetlag or night work), low-light conditions, intermittent bright-light exposure data, and non-24-hour schedules (e.g., Mars), all of which apply to NASA operations. This model has also been used successfully to design a pre-flight light exposure regimen that is associated with the early-morning launch times that are often necessary for shuttle flights.

These methods can be used to design a variety of schedules that are relevant to NASA operations, including shifting sleep/wake (slam shifting) and non-24-hour schedules. Critically, these methods will be able to satisfy the variety of schedules that will be encountered during a Mars mission, where a day is 24 hours and 39 minutes.

Current work includes quantifying individual differences in response to circadian and sleep/wake factors, and incorporating non-light stimuli (e.g., posture and social cues) and information concerning the various wavelengths of light into the model, since the circadian system is responsive to specific wavelengths of light and the wavelength distribution that is found in space differs from that found on Earth (both indoors or outdoors).

This work allows for mathematical simulations that assess the impact of circadian alignment and sleep disruption on performance and alertness.

Risk in Context of Exploration Mission Operational Scenarios

As previously detailed in this report, space flight evidence shows that astronauts lose sleep during flight, and ground-based evidence shows that sleep loss, fatigue, extended work shifts, circadian desynchronization, and work overload lead to performance errors, injuries, and accidents.

A possible qualitative likelihood scale for performance errors during certain mission operational scenarios is

- Level 1 – will most likely not occur
- Level 2 – could occur
- Level 3 – will most likely occur

Using this scale, **the risk of performance errors due to sleep loss, fatigue, circadian desynchronization, and work overload is considered a Level 2 risk for ISS, lunar sortie, lunar long, and Mars missions.** As this section addresses risk in the context of Exploration mission operational scenarios, the Level 2 risk for ISS will not be addressed.

Lunar sortie

Early, short-duration lunar missions will be fast-paced “sprints” that are similar in nature to current shuttle missions. Representatives from MOD anticipate that crew rotations and schedule shifting will still be required during lunar sortie missions, particularly at the beginning and end of a mission when rendezvous between vehicles (the crew exploration vehicle and the lunar lander) will need to occur (S Curtis, personal communication). While shifting should not be prevalent for the duration of the lunar sortie stay, crews will be required to shift while they are conducting critical mission tasks (S Gibson, personal communication, 2008).

In addition, the day-night cues on the surface of the moon will be different than the day-night cues on Earth. The elevated portions on the rim of Shackleton crater, which is a proposed landing site that is near the South Pole of the moon, may be exposed to light as much as 90% of the time (flight surgeon R Scheuring, personal communication, 2007). Anecdotal reports of individuals conducting 2- to 3-week exploration missions in the Arctic, where light exposure is, as it is on the moon, close to continuous, indicates that exposure to constant light may result in an individual being unable to detect a need for sleep and/or rest (flight surgeon R Scheuring, personal communication, 2007). If daily EVAs are conducted on the lunar surface, this level of sunlight exposure may stimulate the same physiological response as are experienced during Arctic expeditions. The high-tempo operations of multiple EVAs on the lunar surface could lead to work overload, extended wake durations, cumulative sleep loss, and excessive fatigue.

If the landing site is not at the lunar poles, however, but is at more equatorial locations, the day-night cycle on the moon involves 2 weeks of light exposure and 2 weeks of darkness. Either way, the natural lighting conditions will not be the same as those experienced on Earth due to the 24-hour clock. This means that astronauts will not be able to depend on natural lighting cues to help with their circadian rhythms.

Additional factors that are associated with sleep and circadian issues in the current space flight environment – e.g., high-tempo workloads and adaptation to the space flight environment – will remain risk factors on lunar sortie missions. Subsequently, performance errors remain a plausible risk during the short-duration missions to the moon and could occur during the lunar sortie mission scenario.

Lunar long

Long-duration lunar missions will be marathon-like events that are similar in nature to the current ISS increments. During these missions, both ground and flight crews will experience high-tempo operations and shift work. As was noted above, unfamiliar day-night cues could affect the circadian system and the subjective need to sleep. As a result, for long-duration lunar missions, it is estimated that human performance errors due to sleep loss, fatigue, extended work shifts, circadian desynchronization, and work overload could occur.

Mars

For a Mars mission, this risk remains relevant and important, although certain aspects of the risk may vary for the different mission phases. The initial transit to Mars is anticipated to be similar to the ISS long-duration experience with regard to sleep loss, extended work durations, and workload. It is anticipated that this transit will exclude the slam shifting and high-tempo schedules that are similar to the dockings and critical mission activities that were experienced during the building of the ISS.

On the surface of Mars, work activities may consume a large part of crew time; the slam shifting that can lead to circadian desynchronization should be absent from a Mars scenario as the crews will, of necessity, manage their own timelines. It is suspected, however, that daylight is not bright on the surface Mars; the sunlight on Mars is about one-half of the brightness of that seen on Earth, and the martian sky does not appear blue but pink due to suspended dust, which means that the surface of Mars is, in fact, darker than what is experienced on Earth (Murphy, 1997). The spectrum of light wavelengths is also different on Mars than on Earth. This difference in light exposure may complicate the entrainment of circadian rhythms, since the circadian system is most sensitive to blue wavelengths (Brainard et al., 2001), which are less prevalent on Mars than on Earth (Murphy, 1997).

Additionally, Mars has a day-night cycle (lasting 24 hours 39 minutes) that differs from that on Earth, which, as evidenced by recent ground studies, may pose challenges to performance. Sleep disruption and subjective decrements in alertness and performance were reported to be very burdensome to the scientists and engineers at the NASA Jet Propulsion Laboratory who lived on a Mars sol schedule while working on the Mars exploration rovers (MERs) (Bass et al., 2004; Czeisler et al., 2001). A study by DeRoshia et al. (2007) on self-report findings from MER operations personnel showed increased fatigue levels among 82% of the participants, as well as increased levels of sleepiness and irritability. Reduced levels of concentration and energy were also reported by most of the participants. The degree to which the physiological challenge of living on the Mars sol can threaten the success of a mission is described further in the appendix of the DeRoshia et al. report.

Subjects who were living on a laboratory-simulated Mars sol schedule experienced sleep disruption and decrements in alertness and performance (Wright et al., 2006; 2001). Most humans cannot adapt to this non-24-hour day without adequate countermeasures (Gronfier et al., 2007). Performance and circadian entrainment data have just been collected from the Mars Phoenix scout lander (MPSL) mission (May 25 – Sep 1, 2008) ground crew who were living on a Mars sol (L Barger, unpublished results, 2008). From these previous studies and a preliminary review of the MPSL data, it is expected that future crews who are traveling to Mars and the ground crews who will support the Mars missions will experience similar decrements in sleep, circadian alignment, performance, and alertness. As a result, for Mars missions, it is estimated that human performance errors that are due to sleep loss, fatigue, extended work shifts, circadian desynchronization, and work overload could occur.

Implications for future space flight

The behavioral consequences of performance errors due to sleep loss, circadian desynchronization, extended work shifts, fatigue, and work overload on ISS are currently being evaluated. Cognitive decrements that are caused by fatigue, inadequate light exposure, circadian dynamics, and work-sleep schedules, will more profoundly affect crews who are on a long-term lunar or Mars mission, where fewer resources will be available to mitigate these factors. The risk factors may become compounded by the fact that lunar and Mars missions bring additional restrictions. For example, returning to Earth from a lunar mission is not a readily available option, and returning to Earth during a Mars mission is not an option at all.

Currently, NASA STD-3001, Vol. 1 provides standards regarding a normal, uninterrupted sleep period; standards for circadian shifting caused by schedule demands; and limits for the amount of work that can be performed within 1 day and 1 week. The current standards, however, do not provide specific limits for performance thresholds. BHP anticipates developing normative databases for space flight using tools and measures that have been initially tested and verified in laboratories and high-fidelity analogs such as NEEMO [NASA Extreme Environment Mission Operations] and, subsequently, space flight. In mission analogs, astronauts can establish individual and group baselines as well as normative data for an environment that can be compared with space flight.

Flight designers and flight surgeons are concerned that crew members, and especially ground control personnel, may not be obtaining the minimum recommended rest periods: actual work-sleep time is not the same as the time that is planned. Evidence shows that, overall, sleep is shorter and interrupted in flight. During critical mission phases, schedule shifting and workload demands are strenuous for both ground and flight teams. It is important to ensure that the current NASA STD-3001, Vol. 1 standards are enforced to protect work-rest schedules for both ground and flight crews, particularly during high-tempo operations. If crews are shifted or have to perform during this allotted sleep time, recovery time needs to be allowed and individualized countermeasures need to be readily available.

Conclusion

Ground evidence clearly demonstrates the risk of performance errors due to sleep loss, fatigue, circadian desynchronization, and work overload. Reviews in the aviation and medical industry have consistently attributed accidents, injuries, and even death to performance errors arising from sleep and circadian issues. Furthermore, long-term health consequences serve as another potential outcome. The WHO International Agency for Research on Cancer Monograph Working Group recently concluded that, on the basis of published evidence, “shift work that involves circadian rhythm disruption is probably carcinogenic to humans” (Straif et al., 2007).

Space flight evidence shows that astronauts are regularly subject to shifting their sleep/wake schedules, long work hours, complex tasks, and sleep loss. The ground teams that support flight crews and robotic missions endure similar issues. As NASA transitions from LEO to lunar and Mars missions, flight and ground crews will certainly continue to face the challenges that are associated with acquiring adequate sleep, circadian desynchronization, fatigue, extended work shifts, and workload demands.

As space flight performance data are limited, BHP research aims to further characterize performance in the space flight environment using validated tools that detect cognitive deficits that are related to fatigue. Evaluations of gross motor performance in space flight are also anticipated. BHP research efforts will further describe the nature of sleep in space over long-duration missions, and tasks are under way to determine which factors enhance or infringe on sleep and disrupt circadian rhythms in space. The space flight environment is reported to be noisy, poorly lit, and, for some, uncomfortable. Shifting schedules and heavy workloads, particularly for the shuttle astronauts, can pose additional challenges. Adequately assessing the environment and making recommendations to improve on it, as well as understanding individual vulnerabilities to sleep loss, is an essential part of preparing for future missions to the moon and Mars.

Astronauts have proven to be resourceful in mitigating sleep loss, circadian desynchronization, fatigue, extended work shifts, and work overload. Lighting, medication, good sleep hygiene, and improved scheduling serve as effective countermeasures for space flight crews. Much remains unknown concerning the best ways in which to implement these countermeasures, however, particularly over time. Some medications, for instance, are suspected to work differently in space than they do on Earth. Non-sleep medications may be required in flight, and the potential interactions between these and the sleep medications that are prescribed in space flight have yet to be determined. Similarly, additional research will aid in the use of artificial lighting as a countermeasure for increasing acute alertness as well as facilitating the alignment of circadian rhythms. The long-term safety and efficacy of light as a non-pharmaceutical aid for alertness, circadian shifting, and sleep will inform requirements for the lunar and Mars crew habitats as well as recommendations to the crews, flight controllers, and flight medical operations.

Continued research efforts are necessary to address the psychological and physiological health of individuals during and following space flight missions. The sleep and circadian systems affect immunology, hormone production, GI function, and cardiovascular health; sleep disruption can also serve as a contributing factor for the risk of behavioral conditions (Chapter 1) as well as for the risk that is related to poor team cohesion and psychosocial adaptation (Chapter 2). Similarly, countermeasures that are developed to aid the sleep and circadian system can also serve to enhance other aspects of health; as an example, research indicates that bright light can serve as an effective treatment for Seasonal Affective Disorder (Glickman et al., 1998). Addressing the sleep and circadian system thus further addresses other risks within BHP as well as enhances other discipline research areas that are related to the human system and health outcomes from living and working in the space flight environment.

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Appendix 1: International Space Station Lighting

The following information was provided by James Maida, Habitability and Human Factors Branch, NASA Johnson Space Center, and Charles Bowen, Ph.D., Human Factors Design Engineering Specialist from the Lockheed Martin Human Factors Design Team. This information illustrates the dim lighting that crew members experience on board the ISS.

The best-case average illumination on board Node 1 of the ISS with eight out of eight fluorescent lamps burning is 13.82 foot-candles (fc). In contrast, on Mar 31, 2005, Node 1 was down to only one lamp burning, with an illuminance of 0.55 fc. Since color vision fails at approximately 0.30 fc, that lighting level is unacceptable for most tasks. The dim illumination in Node 1 presented a safety issue that was addressed, initially, by moving lamps from another area. The problem was ultimately solved by a resupply of the ISS by STS-114, which flew in Jul 2005.

In other examples, when the U.S. Laboratory on ISS has all 12 lamps burning, the illumination is 57.79 fc. When only four of the 12 lamps are burning, illumination is reduced to 16.48 fc. Finally, in an airlock that has all four of its fluorescent lamps working, the illuminance is 17.55 fc. When the airlock is down to one lamp, the illuminance can be as low as 2.62 fc.

The above illuminances were determined by the radiance illuminance model of the Lawrence Berkeley National Laboratory, Berkeley, Calif., with modifications for space flight applications.

Required illuminances for various tasks include: maintenance, 25 fc; transcribing, 50 fc; repair, 30 fc; reading, 50 fc; and night lighting, 2 fc.

Foot-candles can be converted to the international unit of lux by multiplying by 10. Thus, 10 fc = 100 lux.

Appendix 2: Mathematical Models of Human Circadian Rhythms and Performance

NASA currently uses two different mathematical models of human circadian rhythms and performance: the Astronaut Scheduling Assistant, and the Circadian, Neurobehavioral Performance, and Subjective Alertness Model.

At the heart of the Astronaut Scheduling Assistant is a comprehensive set of mathematical equations, numerical strategies, and computer program routines that enables the prediction of changes in astronauts' neurobehavioral performance capability over time. The model core makes predictions of neurobehavioral performance capability that are based on sleep and sleep loss (acute and chronic), naps, circadian rhythms, and light exposure, which means that the model also incorporates predictions that are based on countermeasures. These predictions allow for the evaluation of risk and safety of sleep/wake/work schedules during both the planning and the execution of space missions. Prospective studies on the accuracy of these model predictions that simulate the conditions of many of the sleep loss and circadian provocations that occur in space flight remain to be done on Earth. Such studies are essential, and may indicate the need for additional model parameters and changes in model structure.

Future work involves modifying the Astronaut Scheduling Assistant by integrating adaptive Bayesian performance prediction methods that use the results of an individual's past performance to identify individual specific trait parameters (e.g., rate of homeostatic decay, magnitude of circadian fluctuation in performance, etc.) prior to predicting future performance with an individual-specific model.

The Circadian, Neurobehavioral Performance, and Subjective Alertness Model approach has been directed towards increasing the accuracy of predictions and adding operationally relevant features. For example, melatonin is now incorporated as a circadian marker rhythm to accurately predict the phase and amplitude of the circadian pacemaker. Incorporation of wavelength-specific inputs is in progress. This model has recently been amended to allow the determination of an optimal light countermeasure regime for a given shift in sleep/wake or work schedule to improve performance at a desired time; this includes a schedule/countermeasure design prototype program that allows a user to interactively design a schedule and automatically design a countermeasure regime.

A current BHP in-flight effort is collecting sleep-wake data through use of actigraphy. These data, which are accumulated from actual astronauts in flight, will be integrated into the Circadian, Neurobehavioral Performance, and Subjective Alertness Model.