Sleep Environment Recommendations for Future Spaceflight Vehicles

Zachary A. Caddick[1], Kevin Gregory[1], and Erin E. Flynn-Evans[2]

[1]San Jose State University Research Foundation, San Jose CA, USA and
[2]NASA Ames Research Center, Moffett Field CA, USA {erin.e.flynn-evans@nasa.gov}

Abstract. Evidence from spaceflight and ground-based missions demonstrate that sleep loss and circadian desynchronization occur among astronauts, leading to reduced performance and, increased risk of injuries and accidents. We conducted a comprehensive literature review to determine the optimal sleep environment for lighting, temperature, airflow, humidity, comfort, intermittent and erratic sounds, privacy and security in the sleep environment. We reviewed the design and use of sleep environments in a wide range of cohorts including among aquanauts, expeditioners, pilots, military personnel, and ship operators. We also reviewed the specifications and sleep quality data arising from every NASA spaceflight mission, beginning with Gemini. We found that the optimal sleep environment is cool, dark, quiet, and is perceived as safe and private. There are wide individual differences in the preferred sleep environment; therefore modifiable sleeping compartments are necessary to ensure all crewmembers are able to select personalized configurations for optimal sleep.

Keywords: Extreme Environments · Habitability · Human Factors · Sleep

1 Introduction

Sleep quality -- including the ability to fall asleep and remain asleep -- and sleep duration are dependent upon circadian phase, length of prior wake duration, and time within the sleep episode [1-3]. Proper alignment of scheduled sleep episodes to the circadian pacemaker is important for sleep consolidation and sleep structure [4-5]. High sleep efficiency is best maintained for eight hours when sleep is initiated approximately six hours before the endogenous circadian minimum of core body temperature [4-5]. This phase relationship between the rest-activity cycle and the endogenous circadian timing system implies that even small circadian phase delays of the sleep propensity rhythm with respect to the rest-activity schedule can result in sleep onset insomnia or substantial wake after sleep onset.

In order to quantify the impact of a sub-optimal sleep environment on sleep quality and duration, it is important to measure sleep outcomes when sleep is appropriately timed relative to the circadian and homeostatic drives for sleep. It is possible for an individual to experience sleep disruption in an optimal sleep environment due to the imposed sleep schedule. Similarly, it is possible for an individual to experience high sleep efficiency in a sub-optimal sleep environment when accumulated sleep debt is present, which dampens the arousal threshold. Our aim was to compile the evidence associated with sleep disruption due to controllable, environmental stimuli in order to aid NASA engineers and operational personnel in the optimal design of crew sleep accommodations for deep spaceflight.

2 Methods

We conducted a comprehensive literature review summarizing optimal sleep hygiene parameters for lighting, temperature, airflow, humidity, comfort, intermittent and erratic sounds, privacy and security in the sleep environment. We reviewed the design and use of sleep environments in a wide range of cohorts including among aquanauts, expeditioners, pilots, military personnel and ship operators. We also reviewed the specifications and sleep quality data arising from every NASA spaceflight mission, beginning with Gemini.

3 Recommendations

The sleep environment required for long duration missions will differ from the sleep accommodations that NASA has developed in the past. Our review revealed several modifications that will be important to make in order to ensure that deep space crews have sleep environments that will provide them with quality sleep.

3.1 Sleep Chamber Location

The location of the sleep station within the vehicle is key to reducing noise and light pollution. Noise emanating from common areas has been shown to be disruptive to sleep [6-7]. Given that there are individual differences in sleep timing preference, it is likely that some crew will chose to be awake, while others are asleep [8-9]. In order to ensure that morning-types and evening-types are both afforded adequate rest, it is desirable to position crew quarters away from the galley area and exercise machinery. We also found that individuals living in a variety isolated and confined environments reported experiencing sleep disruption due to other crewmembers using the waste management system during sleep episodes [9-11]. Therefore, the waste management system should be located far enough away from sleeping quarters that noise is buffered, but close enough that crewmembers are able to quickly access the facility and return to sleep without having to travel too far. It may be appropriate to locate waste management facilities in a module adjacent to the sleep stations.

It is likely that watch schedules will be necessary during deep space missions. We found that in the early history of human spaceflight, watch schedules were very disruptive to sleeping crewmembers due to the close proximity of the sleeping crewmember to the "on watch" crewmember [12]. According to studies of military personnel and pilots, locating the sleep chambers for off-duty crewmembers away from the command and communication area is desirable [11, 13-15]. However, the sleep chambers should be positioned near enough to the vehicle command center that crewmembers may quickly respond in an emergency situation [11].

3.2 Privacy

It is imperative that each crewmember is provided with a private sleep chamber for the duration of the mission. We found that shared sleep spaces and common bunkrooms are associated with frequent sleep disruption due to other crewmembers [13]. The practice of "hot bunking" has been virtually eliminated from all occupations that we evaluated due to hygiene concerns and the impact that hot bunking has on psychological mood and health [13, 16]. We found that individuals view their sleep location not just as a place for sleep, but also as a space for privacy [7, 14, 16-25]. Access to a private space is viewed as critical to the psychological well-being of individuals living in isolated and confined environments [26]. Similarly, provision for storage of personal items within the sleep chamber was viewed as highly desirable [9, 27]. The sleep chambers for deep space vehicles should also allow crewmembers to customize the space with personal items and reconfiguration of stowage compartments [9].

There have been situations where crewmembers have been displaced from private quarters during spaceflight missions [28]. In these situations it is very difficult for the displaced individuals to obtain adequate sleep [29-31]. Given that the loss of a sleep chamber would likely also be associated with a breach of the spaceflight vehicle, the resulting anxiety may further reduce crewmember sleep quality and quantity. As a result, it is possible that the loss of a sleep chamber could greatly impact the physical and psychological health of crewmembers at a time when successful performance of duties is essential. Given the importance of sleep in conferring fitness for duty, future crew vehicles should include back up, deployable sleep chambers in order to ensure that individuals have access to a private sleep environment throughout the mission.

3.3 Habitable Volume

The crew quarters that are presently on ISS appear to provide enough habitable volume for crewmembers to move as desired during sleep [32-33]. We found one case where a crewmember was too large to fit in the assigned sleep chamber during spaceflight [34]. Although it may be necessary to design all sleep chambers and sleeping bags to the same standard, it is important to consider that larger crewmembers will have less habitable volume relative to smaller crewmembers. As such, it is important to ensure that the crewmembers selected for a deep space mission are able to evaluate the size of the sleep stations in advance of the mission. It may also be desirable to design two sizes for the sleep stations to accommodate larger and smaller crewmembers.

The optimal sleep environment for a planetary excursion will be necessarily different from the optimal sleep environment for spaceflight. During a long duration planetary excursion, larger crew quarters are necessary due to the comparatively reduced habitable space available in a partial gravity environment. We found that individuals living in isolated and confined environments on Earth use their sleep rooms as a place for privacy and to work in addition to sleep [7, 27, 35]. As a result, the crew rooms on a planetary excursion should include space for a bed (placed horizontally on the floor), a desk and storage of personal belongings. The use of bunkrooms or shared sleep spaces is only appropriate for a short-duration planetary excursion. In these cases, bunks or cots may be used to accommodate crewmembers [7]; however, even during such short excursions private crew quarters would be preferable [27].

3.4 Light

Sleep chambers in spaceflight and on the ground must include features that protect individuals from being awoken by external forces such as light, noise, inadequate temperature and poor air quality. Light is the primary resetting cue for the human circadian pacemaker [36]. Exposure to light at inappropriate times leads to circadian misalignment, which causes sleep disruption [37]. Similarly, exposure to light is alerting and suppresses the drive to sleep [38]. The intensity, spectra, duration, and timing of light determine the magnitude and direction of phase shifting and potency of acute alerting [39]. All wavelengths of light have a negative impact on sleep, but blue light elicits the strongest effect due to the stimulation of intrinsically photosensitive retinal ganglion cells [38]. Exposure to green light is capable of enhancing alertness and suppressing sleep [38], while exposure to red light has the weakest effect on alertness and circadian phase shifting [40]. Evidence from the laboratory, field and subject matter experts support the notion that exposure to light during sleep episodes is disruptive to sleep quality and quantity [12-14, 29, 41-49]. Based on this evidence, all light should be eliminated from the sleep environment. If indicator lights are necessary for identifying egress points, then they should be dim and red [40].

There is strong evidence to suggest that individuals living in isolated and confined environments away from typical solar light dark cues are prone to circadian desynchrony due to self-selecting inappropriate patterns of light exposure [8, 50-54]. This circadian misalignment leads to individuals experiencing a drive to sleep during scheduled wake and an inability to sleep during scheduled sleep opportunities. In order to preserve a stable 24-hour pattern of work and sleep among the crewmembers, it may be desirable to provide a strong cycling of light and darkness in common spaces to mimic the solar light dark cycle and help crewmembers maintain a regular sleep-wake schedule and circadian entrainment [55-56]. However, if such a strategy is utilized, it is important that crewmembers maintain some autonomy in controlling dimmer, personal lighting as would be the case at home on Earth. Similarly, crewmembers scheduled to be on night watch may benefit from supplemental lighting in the vehicle command center in order to enhance alertness and performance [57].

3.5 Noise

Noise is ever-present on space vehicles. We found that noise has been a major cause of sleep disruption throughout the history of spaceflight [12, 19, 29, 58]. The current guidelines allow for exposure to continuous noise above the WHO recommended guidelines [33, 59]. In addition, the current NASA guidelines do not provide mitigations against impulsive or intermittent noise [33]. We found that exposure to intermittent noise is at least as disruptive to sleep as continuous noise exposure [11-12, 15, 19, 29, 58, 60-61]. Given this evidence, exposure to noise be limited to below 35 dB, because exposure to noise above this level is associated with a reduction in sleep quality and quantity, even when individuals do not wake fully [59]. In addition, intermittent noise should be minimized, so that it does not vary beyond 5 dB from background noise levels. There is some evidence to suggest that exposure to continuous white noise less than 25 dB is sufficient to mask intermittent noises [62], therefore it is desirable to allow crewmembers access to white noise in their sleep chamber if desired. Earplugs and/or noise canceling headphones should also be made available for crewmembers [63]. Due to crewmember concerns about missing alarms while wearing earplugs, it may be desirable to develop multi-sensory alarms that include auditory and visual stimulation [64-66].

3.6 Temperature and Humidity

The ambient temperature on early space vehicles varied widely. For optimal sleep, an individual needs to reach his or her thermoneutral equilibrium and should have sufficient bedding available to create a microclimate of between 25-35˚C (77-95˚F) [67-68]. Given that there are wide individual differences in the optimal temperature for sleep, the sleep environment on future space vehicles should be cool, but there should be sufficient insulation available for crewmembers to modify their environment to suit individual preferences [69-71]. This may mean providing crewmembers with sleeping bags of different thicknesses, or a mechanism for layering sleeping bags together. It is also desirable for sleeping bags to include vents to release heat, because the human core body temperature falls and rises during a typical sleep episode [72]. Warming of proximal and distal skin temperature has been associated with faster sleep onset [73-75] and crewmembers have reported having difficulty sleeping due to cold feet and hands [19, 34], therefore providing a way for crewmembers to warm their extremities prior to sleep may be desirable.

The level of humidity in the environment can also influence sleep quality and quantity. The optimal humidity range for human health is between 40-60% [19]. The presence of humidity in the environment changes the perceived temperature. Higher humidity, with high temperatures are disruptive to sleep [76]. Therefore, lower humidity of 50-60% is optimal for sleep, particularly when ambient temperature is increased.

3.7 Air Quality

The optimal ambient gas mixture for sleep is equivalent to the air experienced at sea level on Earth (78% nitrogen, 21% oxygen, 1% other gases) [16, 21, 77-86]. Similarly, the optimal air pressure during sleep is equivalent to the pressure on the Earth at sea level [87-88]. Air mixtures that deviate from these conditions, such as what mountaineers experience during expeditions, results in disrupted sleep and periodic breathing [80, 82, 84, 88-90]. In depressurized environments, such as at elevation on Earth, supplemental oxygen can reduce headaches, periodic breathing, and can improve sleep outcomes [91-92]. Airflow is also associated with positive sleep outcomes and aids in the reduction of O_2 [85, 93] and intrusive odors, such as body odor, food, and mechanical smells [12, 34, 85]. Although there is little information on the impact of air pollution and particulates on sleep quality and quantity, reports from lunar expeditions suggest that dust from planetary extra vehicular activities may build up in the habitable environment [29, 34]. As a result, the vents providing airflow to crew sleep chambers should include air filters to protect against crewmembers breathing particulate matter and dust during sleep.

3.8 Involuntary Movement

Involuntary movement due to turbulence is associated with sleep disruption [94]. Therefore, vehicle movement and vibration should be minimized as much as possible. Similarly, the microgravity environment results in the potential for crewmembers to free-float during sleep episodes. Although some crewmembers have reported that they enjoyed that experience, other crewmembers have reported that they prefer to be restrained while sleeping [95]. Given that some individuals may not use harnesses and other attachments, they should be designed, so that they can be removed or secured out of place when not in use. Similarly, separate attachments should be available to secure the sleeping bag to the wall of the sleep chamber if desired.

3.9 Summary

Although we present evidence to support the design of future space vehicles, it is possible that new information will be revealed in the future. NASA supports a great deal of studies in analog and spaceflight environments. As new information becomes available recommendations may evolve and change. Such information should help to further define the optimal sleep environment for deep space transit.

In summary, sleep is critical to crewmember health and performance. In order for crewmembers to achieve optimal sleep, they must be provided with a sleep environment that allows them to achieve quality sleep, free of external disruption. We found that the optimal sleep environment is cool, dark, quiet, and is perceived as safe and private. There are wide individual differences in the preferred sleep environment; therefore modifiable sleeping compartments are necessary to ensure all crewmembers are able to select personalized configurations for optimal sleep. A sub-optimal sleep environment is tolerable for only a limited time, therefore individual sleeping quarters should be designed for long duration missions. In a confined space, the sleep environment serves a dual purpose as a place to sleep, but also as a place for storing personal items and as a place for privacy during non-sleep times. This need for privacy during sleep and wake appears to be critically important to the psychological well being of crewmembers on long duration missions. Designing sleep chambers for optimal sleep health should produce benefits beyond simply improving sleep quality and quantity on long duration missions.

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