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Sleep Environment Recommendations for Future Spaceflight Vehicles

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EXECUTIVE SUMMARY

Current evidence demonstrates that astronauts experience sleep loss and circadian desynchronization during spaceflight. Ground-based evidence demonstrates that these conditions lead to reduced performance, increased risk of injuries and accidents, and short and long-term health consequences. Many of the factors contributing to these conditions relate to the habitability of the sleep environment. Noise, inadequate temperature and airflow, and inappropriate lighting and light pollution have each been associated with sleep loss and circadian misalignment during spaceflight operations and on Earth. As NASA prepares to send astronauts on long-duration, deep space missions, it is critical that the habitability of the sleep environment provide adequate mitigations for potential sleep disruptors.

We conducted a comprehensive literature review summarizing optimal sleep hygiene parameters for lighting, temperature, airflow, humidity, comfort, intermittent and erratic sounds, and 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. Finally, we conducted structured interviews with individuals experienced sleeping in non-traditional spaces including oilrig workers, Navy personnel, astronauts, and expeditioners. We also interviewed the engineers responsible for the design of the sleeping quarters presently deployed on the International Space Station.

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. A summary of specific recommendations and supporting references is presented in Table 1.

TABLE 1. RECOMMENDATION SUMMARY

	Recommendation	Supporting Evidence
Sleep Station Location	<ul style="list-style-type: none"> • Sleep stations should be located away from common areas such as the galley. • Sleep stations in near proximity to lavatories, but should be separated by a distance sufficient to minimize noise from the waste management systems. • If watch schedules are used, then crew sleep stations should be situated away from the command center in order to minimize noise from communication with Mission Control and equipment. 	<p>Hoffman 2002; Astronaut SME 3 interview; Aviator SME interview; Navy SMEs interview; Oilrig SMEs interview; MSFC Skylab Structures 1974; Yan and England 2001; IFALPA 2013; Astronaut SME 3 interview; Aviator SME interview; Navy SMEs interview Hacker and Grimwood 1977; Caldwell et al. 2000; Watt 2009; IFALPA 2013; Green 2015; Astronaut SME 2 interview; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview</p>
Privacy	<ul style="list-style-type: none"> • Crewmembers should be provided with private crew quarters for optimal sleep health during deep space missions and for spending time away from other crewmembers. • Space for storing personal items should be accommodated in sleep stations. • Customization of the sleep environment should be allowed. • Hot bunking is associated with poor sleep quality, negative mood, and poor health and hygiene and should be avoided. 	<p>Johnston 1973; Willshire 1984; Stuster 1986; Koros et al. 1993; Carrere and Evans 1994; Vander Ark et al. 1994; MacCallum and Poynter 1995; Rosekind et al. 2000; Hendrickx, 2002; Hoffman 2002; Weiss et al. 2007; Green 2015; Astronaut SME 3 interview; Oilrig SMEs interview; Psychologist SME interview Yan and England 2001; Astronaut SME 1 interview; Astronaut SME 3 interview; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview Gillespie and Kelly 1974; Yan and England 2001; Astronaut SME 1 interview; ISS engineer SMEs interview; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview Stuster 1986; Caldwell et al. 2000; Navy SMEs interview; Oilrig SMEs interview; Sleeping Bag SMEs interview</p>
Habitable Volume	<ul style="list-style-type: none"> • The habitable volume of the sleep chambers for deep spaceflight should be a minimum of 2.1 m³. Larger chambers may be required for taller crewmembers. • Based on previous missions, the habitable volume for a planetary excursion should have minimum individual crew quarters of 2.8 m² in order to account for the reduction in usable space and to accommodate a bed, personal workspace and personal storage space. However, crew quarters of 5.4 m³ are recommended as there will be an increase need for privacy in response to the unprecedented nature of future planetary missions. • The minimum habitable volume for extended duration missions (i.e. longer than one year) was determined to be 25 m³ (883 ft³) per person. 	<p>Bluth and Helppie 1986; Broyan Jr. et al. 2008; Allen and Denham 2011; Astronaut SME 1 interview; ISS engineer SMEs interview Yan and England 2001; Hoffman 2002; ESA 2010; Whitmire et al. 2015; Oilrig SMEs interview Whitmire et al. 2015</p>

Sleep Environment Lighting	<ul style="list-style-type: none"> • Complete darkness is optimal for sleep. Sleeping quarters should be able to be darkened completely. • Light pollution from other areas should be eliminated. • Indicator lights should be used only when necessary and should be dim and red. • Eye masks should be available to crewmembers. • Mimicking sunrise/sunset with some proportion of the common area lights may be desirable. 	<p>Bierman et al. 2011; Figueiro and Rea 2012; Grandner et al. 2013; Figueiro et al. 2014; Thompson et al. 2014; Zeitzer 2014 NASA 1971; Potter et al. 1998; Caldwell et al. 2000; Dijk et al. 2003; Green 2015; Astronaut SME 3 interview NASA 1971; Hacker and Grimwood 1977; Mien et al. 2014 DOA 2009; Legler and Bennett, 2011; Astronaut SME 2 interview; Astronaut SME 3 interview; Aviator SME interview; Oilrig SMEs interview; Kleitman 1965; Halberg et al. 1970; Siffre 1988; Miller and Nguyen 2003; Duplessis et al. 2007; Arendt 2012; Basner et al. 2013; Young et al. 2015; Navy SMEs interview; Oilrig SMEs interview</p>
Noise	<ul style="list-style-type: none"> • All forms of noise should be below 35 dB in sleeping quarters. • Familiar noise, such as human voices, is disruptive to sleep at lower decibels, so noise mitigations to protect against noise pollution from common areas is important. • Intermittent noise is more disruptive to sleep than continuous noise and should not vary by more than 5 dB from background noise. • Continuous white noise of < 25 dB may be useful to protect sleep by buffering other noises, but its use should be controlled by the crewmember. • Earplugs and noise canceling headphones should be made available to crewmembers. • The depth of sleep and individual differences predict arousal from auditory alarms. Multi-sensory alarms may be desirable. 	<p>Kawada et al. 1998; Marks and Griefahn 2007; Basner et al. 2008; World Health Organization 2009; Basner et al. 2011 Oswald et al. 1960; Kuwano et al. 1998; Kuwano et al. 2002; Hendrickx 2002; Navy SMEs interview; Astronaut SME 2 interview; Astronaut SME 3 interview; Aviator SME interview; Oilrig SMEs interview NASA 1971; Johnston 1973; Hacker and Grimwood 1977; Watt 2009; Flynn-Evans 2010; Fyhri and Aasyang 2010; IFALPA 2013; Schmidt et al. 2013; Astronaut SME 1 interview; Navy SMEs interview; Oilrig SMEs interview Waye et al. 2003; Namba et al. 2004; Stanchina et al. 2005; Astronaut SME 3 interview; Aviator SME interview; Psychologist SME interview DOA 2009; Legler and Bennett 2011; Astronaut SME 3 interview; Aviator SME interview; Oilrig SMEs interview; Rechtschaffen 1966; Kawada and Suzuki 1999; Muzet 2007; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview</p>
Temperature	<ul style="list-style-type: none"> • Ambient temperature should be maintained between 18.3-22°C (65-72°F) during sleep (assuming adequate bedding is available, cooler is better. When no insulation is available, hotter temperatures are required). • Crewmembers should have control of ambient temperature within the normal range in order to account for individual preferences. • Humidity should be between 40-60% relative to ambient temperature. 	<p>NASA 1971; Hacker and Grimwood 1977; Ritchie and Small 1987; Weiland 1994; Okamoto-Mizuno et al. 2009; Flynn-Evans 2010; Kingma et al. 2014; ISS engineer SMEs interview Haskell et al. 1981; Okamoto et al. 1998; Okamoto-Mizuno et al. 2004; Lan et al. 2014; Aviator SME interview Johnston 1973; Okamoto-Mizuno et al. 2005; Okamoto et al. 1998; Okamoto-Mizuno et al. 2003; Astronaut SME 3 interview Haskell et al. 1981; Lin and Deng, 2008a; Häuplik-Meusburger 2011; Astronaut SME 2 interview; Astronaut SME 3 interview; Navy SMEs interview; Sleeping Bag SMEs interview Johnston 1973; Bluth and Helppie 1986; Kräuchi et al. 1999; Raymann et al. 2005; Raymann et al.</p>

	<ul style="list-style-type: none"> • Sufficient bedding should be provided to allow crewmembers to achieve a microclimate 25-35°C (77-95°F). • Bedding should be modifiable, so that crewmembers can add or remove insulation based on individual preferences. • Providing socks or local heating sources to allow for the warming of proximal and distal skin temperature during sleep may facilitate sleep onset. 	<p>2008; Astronaut SME 1 interview; Astronaut SME 2 interview; Sleeping Bag SMEs interview</p>
Air quality	<ul style="list-style-type: none"> • 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). • The optimal air pressure during sleep is equivalent to the pressure on the Earth at sea level. • In depressurized environments, such as at elevation on Earth, supplemental oxygen can reduce headaches, periodic breathing and can improve sleep outcomes. • Adequate ventilation should be provided for the reduction of CO₂ and for the reduction of intrusive odors. • Air velocity should be between 12-36 meters/minute. • Air filters should be used to remove contamination from particulates and dust, particularly that emanating from a planetary excursion. 	<p>Robin et al. 1958; Reite et al. 1975; Gothe et al. 1981; Schiffman et al. 1983; Selvamurthy et al. 1986; Stuster 1986; MacCallum and Poynter 1995; Salvaggio et al. 1998; Lo et al. 2006; Daues 2006; Szymczak et al. 2009; Strøm-Tejsen et al. 2015 Miller and Horvath 1977; Mizuno et al. 1993; Aviator SME interview Luks et al. 1998; Barash et al. 2001 Hacker and Grimwood 1977; Bluth and Helppie 1986; FAA 2011; Strøm-Tejsen et al. 2015; ISS engineer SMEs interview; Navy SMEs interview NASA 1971; Bluth and Helppie 1986; IFALPA 2013; Zhu et al. 2013; Astronaut SME 1 interview NASA 1971; Bluth and Helppie, 1986; Craig et al. 1998; Altun et al. 2012</p>
Comfort	<p>Microgravity</p> <ul style="list-style-type: none"> • The bedding provided during spaceflight should: <ul style="list-style-type: none"> ○ allow for crewmembers to strap themselves to the inside of a sleep station if desired. ○ be easily cleaned. <p>Planetary excursion</p> <ul style="list-style-type: none"> • The bedding provided for a planetary excursion should: <ul style="list-style-type: none"> ○ allow for horizontal positioning on a flat surface. ○ be sized to accommodate movement during sleep and changes in body position. ○ provide natural fiber bedding for breathability. ○ provide a medium-firm mattress, blankets and pillows selected by the crewmember. 	<p>Astronaut SME 1 interview; Astronaut SME 3 interview; Psychologist SME interview; Sleeping Bag SMEs interview Astronaut SME 3 interview; Aviator SME interview; ISS engineer SMEs interview; Sleeping Bag SMEs interview Nicholson and Stone 1987; Spencer and Robertson, 2000; SAE International 2006; Shen et al. 2012; Bluth and Helppie 1986; Verhaert et al. 2011; Astronaut SME 3 interview; Aviator SME interview; Sleeping Bag SMEs interview Yao et al. 2007; Aviator SME interview Persson and Moritz 1998; Rosekind et al. 2000; Jacobson et al. 2007; Jacobson et al. 2008; Jacobson et al. 2009; Gordon and Grimmer-Somers 2011; Verhaert et al. 2011; Jeon et al. 2014; Aviator SME interview; Navy SMEs interview; Oilrig SMEs interview</p>

Turbulence	<ul style="list-style-type: none"> • Vehicle movement should be minimized in order to facilitate sleep. When vehicle movement occurs, the sleep opportunity should be lengthened to allow for adequate sleep. 	Mantsangas et al. 2015; Aviator SME interview; Navy SMEs interview
Safety	<ul style="list-style-type: none"> • Uncertainty about safety can induce anxiety, leading to sleep disruption. Clear and accurate information about safety hazards should be provided to crewmembers in order to alleviate stress due to false alarms regarding safety. 	NASA 1970; NASA 1971; Shephard Jr 1972; Aviator SME interview; Psychologist SME interview
Backup Systems	<ul style="list-style-type: none"> • Given the importance of sleep quality, there should be an emergency deployable sleep station and thermal blankets in the event that a sleep station is damaged. 	Astronaut SME 1 interview; Psychologist SME interview

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 (Akerstedt and Gillberg 1979; Klerman et al. 2002; Wilkinson 1969). Quantification of this dependency has demonstrated that proper alignment of scheduled sleep episodes to the circadian pacemaker is important for sleep consolidation and sleep structure (Dijk and Czeisler 1994; Dijk and Czeisler 1995). 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 (Dijk and Czeisler 1994; Dijk and Czeisler 1995). Sleep onsets before or after this time result in significantly lower sleep efficiencies, either due to increased wake during the sleep episode or shorter sleep episode durations. 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.

METHODS

We conducted a comprehensive literature review summarizing optimal sleep hygiene parameters for lighting, temperature, airflow, humidity, comfort, intermittent and erratic sounds, and 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. Finally, we conducted structured interviews with individuals experienced in sleeping in non-traditional spaces including oilrig workers, Navy personnel, astronauts, and expeditioners. We also interviewed the engineers responsible for the design of the sleeping quarters presently deployed on the International Space Station.

SLEEP HYGIENE

Even when sleep is timed to provide for an optimal sleep opportunity, an inappropriate sleep environment can lead to disrupted sleep and reduced sleep quality. Environmental factors such as light and noise pollution, inappropriate ambient temperature, air quality and humidity, altitude, and comfort each have the potential to interfere with the quality and quantity of sleep.

Light

Light leads to sleep disruption due to two primary factors; first, light resets the circadian pacemaker, leading to a shift in the timing of phase relative to the scheduled sleep episode and second, light is an environmental stimulus that can cause sleep disruption and night waking.

Light is the primary synchronizer of the human circadian rhythm. The circadian pacemaker is the internal biological clock, located in the suprachiasmatic nucleus (SCN) of the hypothalamus. The circadian rhythm is reset by exposure to light through the eyes, which is transmitted down the retinohypothalamic tract to the SCN (Czeisler and Dijk 1995; Czeisler and Gooley 2007). The SCN is the master pacemaker that coordinates the rhythms of a variety of measurable output rhythms including sleep propensity, alertness, performance, hormone production (e.g. melatonin, cortisol) and the body temperature (Klerman et al. 1999).

Regular timing of light exposure on Earth leads to entrainment to the 24-hour day. In the absence of photic cues, the circadian pacemaker will revert to its endogenous period, as is the case for totally blind individuals (Flynn-Evans et al. 2014). For circadian resetting, the intensity, spectra, duration, and timing of light determine the magnitude and direction of phase shifting and potency of acute alerting (Lockley 2005). Under carefully controlled lighting conditions, the circadian rhythm is capable of being reset to a non-24-hour period. When an imposed light-dark cycle is too rapid or too long for circadian entrainment, circadian desynchronization occurs, such that the internal biological function, including the drive for sleep is misaligned relative to the imposed schedule (Czeisler and Gooley 2007).

Under normal conditions (and in the absence of countermeasures), when a person is exposed to regularly timed light during the day and darkness at night, biological function will be synchronized with poorest performance, lowest alertness, melatonin production and the primary drive to sleep occurring during the night and peak performance and alertness occurring during the day. The fluctuation in the circadian rhythm may also be revealed when conditions including light exposure are held constant over a 24-hour period of time, such as during an experimental constant routine (CR) protocol (Minors and Waterhouse 1984) or in extended-duty work shifts (Lockley et al. 2004). When light exposure is not regularly timed, circadian misalignment can result, where the drive to sleep, and alertness and performance are not optimally timed relative to scheduled wake and sleep.

Light also has a direct effect on the hormone melatonin and on alertness. Under normal light-dark conditions, melatonin (N-acetyl-5-methoxytryptamine) is produced during darkness by the pineal gland upon receiving input from the SCN (Kneisley et al. 1978; Zeitzer et al. 2000). Melatonin production is acutely suppressed following exposure to light during the biological night. Similarly, exposure to light suppresses sleep and promotes alertness (Rahman et al. 2014), therefore it is important to eliminate light pollution during scheduled sleep episodes.

Although the majority of light exposure occurs during waking, inappropriately timed light exposure is capable of inhibiting sleep onset and leading to shifts in circadian phase that can impact sleep on subsequent nights. Evening light exposure as low as 65 lux is capable of shifting circadian phase and sleep by one hour compared to evening light exposure of 3 lux (Burgess and Molina 2014). In addition, pre-bedtime light exposure from illuminated e-readers and computers leads to circadian phase shifts of an hour or more relative to exposure to typical dim ambient lighting (Chang et al. 2015).

The potency of the light stimulus on human physiology depends on the wavelength of light in addition to the intensity of the light. The human circadian pacemaker is most sensitive to short-wavelength light in the 460-480 nm range (Brainard et al. 2008; Lockley et al. 2006; Rahman et al. 2014). This response follows a dose response with higher irradiances of blue light eliciting greater suppression (West et al. 2011). Although blue light is the most powerful

circadian time cue and alertness-promoting wavelength, other wavelengths of light also have an effect on circadian timing and alertness. The human visual system has peak sensitivity to green light of approximately 555 nm (Gooley et al. 2012; Zaidi et al. 2007). Gooley and colleagues demonstrated that both blue and green wavelength light are capable of eliciting melatonin suppression, but the effect of green light is temporary, while blue light elicits sustained suppression (Gooley et al. 2010). In contrast, exposure to low intensity red light does not suppress melatonin (Brainard et al. 2001), but is capable of eliciting phase shifts, when timed near the circadian nadir (Mien et al. 2014).

Given that the light signal must be transmitted through the eyes in order to reach the circadian pacemaker, most researchers have examined the impact of light on sleep and circadian phase in awake individuals with their eyes open. Recent evidence suggests that the eyes do not need to be open in order for light to induce a circadian phase shift. Five studies have demonstrated that light can be transmitted through the eyelids. Bierman and colleagues showed that light between the 450-650 nm wavelengths could be transmitted through the eyelid at about 9% (Bierman et al. 2011). Of note, the authors did not find that skin pigmentation was significant in modulating the amount of light that was transmitted. The same group demonstrated in two separate studies that light exposure through the eyelids was capable of suppressing melatonin and shifting circadian phase when administered during the biological night, during conditions of sleep or wake (Figueiro et al. 2014; Figueiro and Rea 2012). Another group examined the impact of dawn simulation on the dissipation of sleep inertia and found increased melatonin suppression and improved subjective sleep quality following a dawn simulation, however, the researchers did not verify that the participants were sleeping with eyes closed throughout the exposure (Thompson et al. 2014). A similar study by Grandner and colleagues demonstrated that a light mask timed to deliver light through closed eyelids, approximately two hours prior to habitual wake time, was sufficient to cause a phase advance in circadian phase, although they also did not verify objectively that the participants' eyes were closed throughout the light exposure sessions (Grandner et al. 2013). Zeitzer and colleagues conducted the most rigorous study examining the impact of light during polysomnographically confirmed sleep (Zeitzer et al. 2014). For this study, researchers evaluated the effect of millisecond flashes of light on circadian phase shifting and sleep architecture. They found that light flashes of 2 milliseconds given every 30 seconds for one hour during sleep was sufficient to cause a phase shift of approximately 30 minutes. The authors did not find that the light caused any significant difference in sleep stage or power density, but they did find that the brain waves registered an extra-retinal potential timed with each light flash, supporting the notion that extremely brief light flashes are capable of being registered by the brain and have an impact on circadian timing.

Although Zeitzer and colleagues found no change in sleep quality or stage following millisecond pulses of light exposure during sleep, other evidence suggests sleeping with a light on all night is associated with reduced sleep quality. Cho and colleagues examined the impact of constant light exposure on human sleep quality and duration (Cho et al. 2013). They conducted a randomized within-subjects experiment comparing polysomnography defined sleep on a night in darkness to sleep on a night with a 40-lux light source on all night. They found that study participants had reduced slow wave sleep, increased arousals and increased presence of stage 1 sleep in the light condition compared to the dark condition, with no difference in total sleep time between the two nights. These findings suggest that continuous illumination from a dim light source is sufficient to lead to sleep disruption and altered sleep architecture.

Noise

Exposure to noise can disrupt sleep quality and quantity. The magnitude of sleep disruption conferred by noise depends on the decibel level (dB), the frequency and pitch, duration (i.e. continuous, intermittent, or impulsive) and whether the noise is meaningful (e.g. a familiar voice). The frequency range for hearing in humans is between 20 hertz (Hz) and 20,000 Hz (Rosen and Howell 2011). Reference values for different types of noise exposure are presented in Table 2. The Occupational Safety and Health Administration standards limit workplace noise exposure to 90 dBA for eight hours of work (Occupational Safety & Health Administration). Exposure to eight hours of noise (74-76 dB) has been shown to increase hearing thresholds by 4-5 dB for low frequencies and 5-10 dB for high frequencies (i.e. a higher volume than previously is needed to be perceived (Chernigovskiy 1969). The World Health Organization working group report on noise determined that there is a causal relationship between nighttime noise exposure and self-reported sleep disturbances, use of pharmaceuticals, self-reported health problems, and insomnia-like symptoms (World Health Organization 2009). The same group issued guidelines for noise exposure during sleep, setting the maximum noise during sleep at 35 dB, citing that higher levels of noise in the sleep environment leads to changes in the duration of sleep stages and increase sleep fragmentation. A summary of noise levels that have been shown to disrupt sleep are presented in Table 3.

TABLE 2. NOISE REFERENCES

Reference Event	Noise (dB)
Threshold of hearing (1000 Hz)	0
Silent study room	20
North rim of Grand Canyon	30
Soft whisper (5 ft away)	40
Urban Residence	50
Conversation (3 ft away)	60
Classroom chatter	70
Freight train (100 ft away)	80
Boiler room	90
Construction site	100
Night club (with music)	110
Operating heavy equipment	120
Jet taking off (200 ft away)	130
Threshold of pain	140

Note: Adapted from Occupational Safety & Health Administration (Occupational Safety & Health Administration).

Intermittent noise is generally perceived as more disruptive to sleep than continuous noise. A majority of research investigating the impact of intermittent noise on sleep has come from investigations of the impact of noise emanating from trains, aircraft flyovers, and automobiles. In order to investigate the impact of traffic noise on sleep, Kawada and colleagues exposed 15 participants to controlled noise simulating a passing truck amplified to 45 dBA, 50 dBA, 55 dBA, 60 dBA or a quiet control night (Kawada et al. 1998). They found that exposure to all levels of truck noise resulted in an immediate transition to lighter sleep when a participant was in stage 2, stage 3 or REM sleep. Similarly, Basner and colleagues conducted a laboratory study where they exposed individuals to different combinations of intermittent aircraft (39.7 dB),

rail (39.7 dB) or traffic (36.9 dB) noise during sleep episodes over 11 nights (Basner et al. 2011). They characterized the noise sources and found that rail noise contained the highest low frequency noise (peak mean at 31.5 Hz), while air and road noise peaked at the 63 Hz frequency. Compared with a baseline quiet night, they found that exposure to any type or combination of noise was associated with a reduction in slow wave (deep) sleep, an increased frequency of arousals, and increased frequency of sleep stage transitions. Participants also reported feeling unrested following exposure to any of the noise conditions relative to baseline. In a separate study, Schmidt and colleagues exposed 75 participants to two different noise exposure nights of 30 or 60 aircraft flyovers of 60 dBA and a quiet control night (Schmidt et al. 2013). They found that both 30 and 60 pulses of 60 dBA noise resulted in sleep disruption compared to the control night. In a similar experiment, Basner and colleagues found that the number of awakenings and transitions to stage 1 sleep due to aircraft noise were increased in response to noise at 65 dBA compared to a quiet control night (Basner et al. 2008). In the same study, they reported that the odds of experiencing sleep stage changes, and arousals from sleep were significantly increased following exposure to both 45 dBA and 65 dBA noise. These findings highlight the notion that intermittent noise can disrupt sleep by altering sleep architecture in addition to increasing night waking.

Heavy road traffic noise, such as that coming from a highway, and exposure to wind turbines can be considered environmental sources of continuous noise. Wind turbines have also been identified as a source of continuous environmental noise that disrupts sleep. Nissenbaum and colleagues found that individuals living within 1.5 km from a wind turbine, where noise levels were estimated to range between 40-52 dBA, reported poorer sleep with higher Pittsburgh Sleep Quality Index and Epworth Sleepiness Scores compared to those living 3-7 km from the wind turbine (Nissenbaum et al. 2012). Although highway road traffic may produce continuous noise during sleep, variations in pitch within traffic distinguish such noise from noise generated from wind turbines and other sources of continuous noise. Fyhri and Aasvang conducted a study in Oslo, Norway evaluating subjective sleep quality in response to different levels of traffic noise among 2,786 participants (Fyhri and Aasvang 2010). They found that only 35% had nighttime noise levels that were below 40 dB and 10% experienced levels above 55 dB. Reported annoyance to nighttime noise was strongly related to sleep problems and such noise-related sleep disruption was particularly apparent in individuals with cardiovascular problems, who reported poorer quality of sleep, being awoken more frequently in the morning, and higher levels of daytime tiredness. This may also relate to the fact that exposure to environmental traffic noise during sleep results in more arousals in men compared to women (Roosli et al. 2014). Additionally, Fyhri and Aasvang also found gender to be a predictor of cardiovascular problems, with men to be more likely to develop cardiovascular problems, though no relationship between noise and cardiovascular problems was found (Fyhri and Aasvang 2010).

Several laboratory studies have been conducted to evaluate the impact of exposure to continuous simulated environmental noise on sleep. In a laboratory study designed to evaluate the impact of air, road and rail noise, Marks and Griefahn exposed 24 participants over 13 nights to randomized conditions of 39 dBA, 44 dBA, 50 dBA, and a pink noise control night (i.e. noise with equal contribution from each frequency) of 32 dB (Marks and Griefahn 2007). They found that the noise conditions were associated with more arousals, shorter total sleep duration, poorer sleep efficiency, more time in stage 1 sleep, and suppressed slow wave and REM sleep, however, they did not report whether there were differences between the noise exposure conditions. In support of those findings, Scott reported that exposure to 93 dB of white noise every night for

eight nights, resulted in decreased REM sleep and increased stage 1 and 2 sleep relative to sleep in a quiet environment (Scott 1972). In contrast, Popp and colleagues conducted a laboratory study examining the impact of road noise on truckers sleeping in truck berths and found that exposure to recorded traffic, averaging 44 dBA, resulted in no significant difference in sleep duration, sleep efficiency, arousals or sleep stage transitions compared to a silent control night (Popp et al. 2015). Of note, that group did not study a control group in a quiet bedroom setting, so it is difficult to determine how much sleeping in the truck berth contributed to sleep disruption in both conditions.

Although exposure to high levels of continuous noise can be disruptive to sleep, continuous noise can protect sleep by dampening the influence of exposure to other intermittent noises. A study of 20 individuals conducted by Namba and colleagues demonstrated that exposure to continuous noise of 30-35 dBA, similar to that generated by an air conditioner, had no effect on sleep relative to a baseline night of silence (Namba et al. 2004). However, exposure to continuous noise over 35 dBA resulted in sleep disruption. Similarly, Waye and colleagues conducted a within-subject study of 12 males and found that compared to a reference night with a background of 25 dBA, exposure to low frequency noise of 31.5 to 125 Hz at 40 dBA led to a longer sleep latency (~40 minutes vs. 20 minutes for the reference night; Waye et al. 2003). Stanchina and colleagues found that exposure to white noise reduced the number of arousals from sleep due to recorded ICU noise. These findings suggest that the addition of low decibel white noise can increase the arousal threshold in an environment where intermittent noises are likely (Stanchina et al. 2005). These studies suggest that continuous noise can be useful in protecting against intermittent noise intrusion, but should be kept below 35 dBA for preservation of sleep.

TABLE 3. NOISE LEVELS THAT HAVE BEEN SHOWN TO DISRUPT SLEEP.

Source of Disruption	Noise Level	Type of Noise	Source
Recommended night noise level limit	40 dBAL _{night, outside}	Not specified	WHO (2009)
Air conditioner-like noise	35 dBA	Continuous	Namba et al. (2004)
Sleep disruption can be detected by EEG	35 dBL _{Amax, inside}	Not specified	WHO (2009)
Aircraft noise caused reduced sleep quality	37-40 dBA	Intermittent	Basner et al. (2011)
Transportation noise exposure lead to poor sleep quality	39-50 dBA	Continuous	Marks & Griefahn (2007)
Low frequency noise (31.5 - 125 Hz) lead to fatigue in morning	40 dBA	Intermittent	Waye et al. (2003)
Reported lower subjective sleep quality in response to wind turbine noise exposure	40-52 dBA	Continuous	Nissenbaum et al. (2012)
Intermittent & premature waking can occur	42 dBL _{Amax, inside}	Not specified	WHO (2009)
Traffic noise caused sleep disruption	45-60 dBA	Intermittent	Kawada et al. (1998)
Aircraft noise caused sleep disruption	60 dBA	Intermittent	Schmidt et al. (2013)
Aircraft noise caused poorer sleep quality	60 dBA	Intermittent	Basner et al. (2008)
White noise exposure caused decrease REM and S1/S2 sleep.	93 dBA	Continuous	Scott (1972)

Note: dBA denotes A-weighted decibels (where low frequencies are reduced); dBAL_{Amax, inside} denotes maximum levels per event inside a bedroom; dBAL_{Amax, outside} denotes maximum level per event outside a bedroom; dBAL_{night, outside} is defined as the 1 year LAeq (A-weighted equivalent sound pressure level) exposure over 8 h outside at the most exposed façade.

The auditory arousal threshold that causes a transition from sleep to wake has significant implications both for development of countermeasure strategies to protect against noise-related sleep disruption and for the design of alarms sufficient to cause awakenings during emergency situations. Rechtschaffen and colleagues used repeated 5-second exposures to fixed tones of various intensities to evaluate the auditory arousal threshold among seven individuals over nine nights (Rechtschaffen et al. 1966). They found that the average auditory arousal threshold was 65 dB, however, they observed wide individual differences in noise sensitivity, ranging from 15 dB to 100 dB. In the same study, the investigators determined individual arousal thresholds to quantify the difference in arousal threshold by sleep stage. Using the same decibel-level sound, they found that participants woke at approximately the same rate from stage 2 and REM sleep, but only 19% of the time during slow wave sleep, highlighting the differences in arousal threshold by sleep stage. These findings were confirmed in subsequent experiments, demonstrating that awakening due to noise exposure is more likely in shallow stages of sleep (i.e. stages 1 & 2), in contrast to deeper stages of sleep (i.e. stages 3 & 4; Kawada and Suzuki 1999; Muzet 2007). It is notable that the arousal threshold in REM sleep is not easily determined due to the influence of dreaming. In a pilot experiment (described in Rechtschaffen 1966), the investigators attempted to determine the auditory threshold using a gradually increasing stimulus, but found that the arousal threshold in REM sleep was inconsistent, with some individuals never waking in response to a tone, but instead incorporating the auditory stimulus into dream content. This finding highlights a challenge that may arise with the development of alarms designed to quickly wake an individual from sleep.

The awareness of sleeping individuals to their surroundings can also contribute to increased awakenings. For example, speaking a sleeper's name can be more arousing than a louder, but more neutral noise (Oswald et al. 1960). Similarly, exposure to talking at 25 dBA is reportedly more disruptive to sleep compared to other ambient sounds, such as traffic and air conditioning (Kuwano et al. 2002; Kuwano et al. 1998). Such noise disruption may not be limited to meaningful noise, but may also result from other local and familiar noise sources, such as noises emanating from a bed partner, household noises and neighborhood noise, which have been shown to be more disruptive than noises emanating from distant sources, such as aircraft and traffic noise (Sasazawa et al. 2006). These findings highlight the importance of separating sleep spaces from community spaces, where quiet conversation may occur.

Although the low decibel sound of human voices results in sleep disruption, there is some evidence to suggest that sleeping in an unfamiliar environment exacerbates sleep disruption due to noise. Stevenson and Mckellar (1989) found that individuals were about 10 dB more sensitive in laboratory settings than they were in familiar, at-home settings (Stevenson and McKellar 1989). Additionally, Öhrström and Skånberg found that participants were more likely to wake in response to noise in laboratory settings in comparison to more familiar settings (Öhrström and Skånberg 2004). This finding is supported by Horne et al. who found that there was no relationship between sound levels of 82 dBA (measured outside a residence) and sleep disturbances for those sleeping in a familiar environment (Horne et al. 1994).

Although individuals may report that they have habituated to local noise, there is evidence to suggest that sleep disruption still occurs. In a community setting, individuals who reported being the least annoyed with traffic noise experienced the most sleep disruption compared to those who reported being very annoyed by traffic noise. However, those who lived in the noisiest environments also had the poorest sleep outcomes (Fyhri and Aasvang 2010).

These findings were confirmed by Kuroiwa and colleagues, who exposed individuals to 49.6 dBA for 10 nights and found that habituation was apparent in subjective ratings from participants, but polysomnographically determined sleep showed continued evidence of sleep disruption (Kuroiwa et al. 2002). Similarly, autonomic arousals in response to noise during sleep have been observed in the absence of complete waking from sleep (Griefahn and Robens 2010). These findings suggest that although the perceived disruption from habituated noise may be reduced, sleep disruption is still evident in physiological measures.

Ambient Temperature

The relationship between endogenous core body temperature, skin temperature, ambient thermal temperature, airflow and humidity, clothing, and insulation of bedding must all be taken into account when evaluating the impact of temperature on sleep (Figure 1). Under normal conditions, the circadian rhythm of core body temperature declines just prior to the time of optimal sleep onset and continues to decline throughout the sleep episode, reaching a nadir at approximately six hours after sleep onset (Dijk and Lockley 2002; Krauchi and Wirz-Justice 1994). During a circadian entrained sleep episode, the morning waking occurs on the rising phase of core body temperature rhythm. This change in core temperature arises from a drop in heat production due to a reduction in the metabolic rate (Senses et al. 2013) and heat loss due to inactivity (Krauchi and Wirz-Justice 1994). In contrast, proximal and distal skin temperatures rise during sleep, relative to active waking (van Marken Lichtenbelt et al. 2006). A sleep environment that facilitates nighttime skin warming is typically self-selected by individuals through the use of bedding and clothing to create a microclimate within the ambient environment.

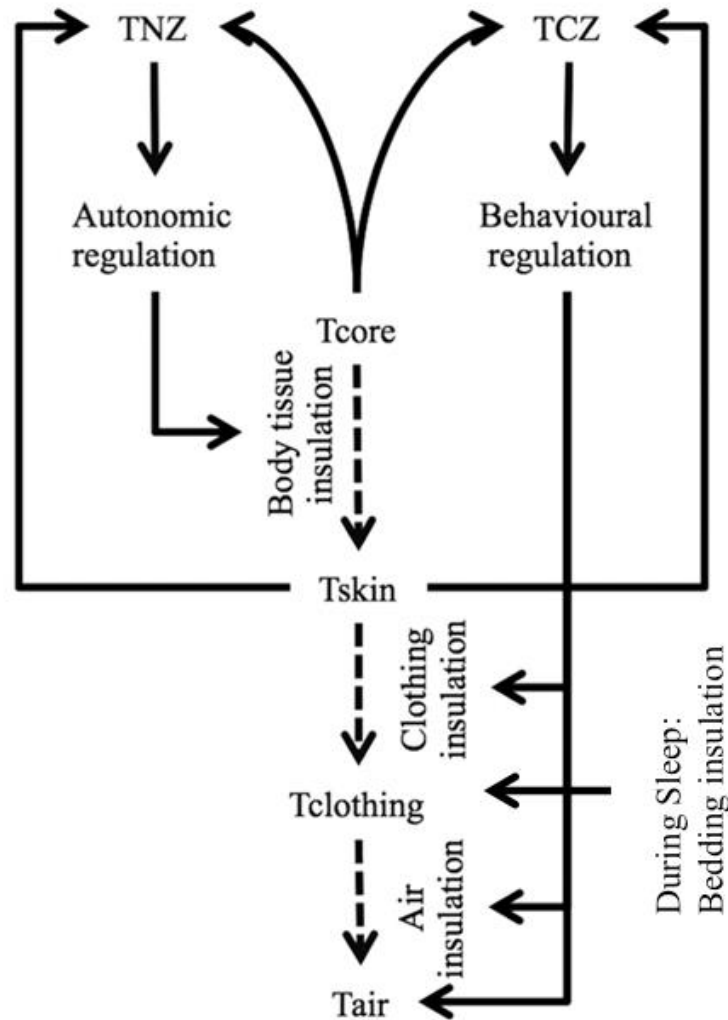


Figure 1. Schematic overview of autonomic and behavioral control of thermal insulation. Solid arrows denote relation and/or control and dashed arrows denote heat flow. Adapted from Kingma et al 2014. TNZ = thermal neutral zone, TCZ = thermal comfort zone, Tcore = core body temperature, Tskin = skin temperature, Tclothing = clothing insulation, Tair = ambient temperature and airflow.

During wake and sleep, the core and skin temperature interact to maintain a balance between heat loss and heat production. Ambient thermoneutrality, the point at which ambient air temperature allows for optimal maintenance of core (36-38°C, 96.8-100.4°F) and skin temperature (32°C, 89.6°F) in the absence of clothing and bedding ranges from 27.9-28.5°C (~82-83°F; Kingma et al. 2014). Ambient temperatures above this range induce sweating, while temperatures below this range induce shivering. The addition of insulation, such as clothing or bedding allows for a substantial reduction in ambient temperature required to preserve thermoneutrality, with typical clothing allowing for an optimal ambient temperature range between 14.8-24.5°C (58-76°F; (Kingma et al. 2014). Table 4 summarizes what ambient temperature is required to maintain thermoneutrality with varying insulation.

TABLE 4. SUMMARY OF FINDINGS FOR PRESERVATION OF AMBIENT THERMONEUTRALITY

Finding	Ambient Temperature	Source
Ambient thermoneutrality with insulation present (e.g. clothing/bedding)	14.8-24.5°C 58-76°F	Kingma et al. (2014)
Ambient thermoneutrality (clothed)	20-22.2°C 68-72°F	Lin & Deng (2008a)
Ambient thermoneutrality for maintaining skin temperature in absence of clothing and bedding	27.9-28.5°C 82.2-83.3°F	Kingma et al. (2014)
Ambient thermoneutrality (semi-nude)	28-32°C 82.4-89.6°F	Lin & Deng (2008a)
Ambient thermoneutrality (semi-nude)	29°C 84.2°F	Okamoto-Mizuno & Mizuno (2012)

Ambient temperature and humidity are intimately linked. The optimal humidity for human comfort ranges between 40-60%. As humidity levels rise above this range, the ambient temperature feels hotter than the measured dry bulb temperature and as they fall below this range, the ambient temperature feels colder (Steadman 1979). Exposure to very low humidity levels, such as during a cold winter, leads to increased prevalence of nosebleeds (Rijal et al. 2012), itching, and dry eyes (Sunwoo et al. 2006). Conversely, exposure to high humidity is associated with poorer air quality and increased air concentration of mites, airborne fungal spores, bacteria and viruses and airborne contaminants (Baughman and Arens 1996).

When humidity levels are outside this range sleep is also negatively affected. Okamoto-Mizuno and colleagues compared sleep under 26°C (78.8°F) with 50% relative humidity to sleep under 32°C (89.6°F) with 80% relative humidity and found that the high humidity condition was associated with more sleep disruption (Okamoto-Mizuno et al. 2005). In addition, the introduction of humidity in continuous positive airway pressure (CPAP) treatment for sleep apnea is associated with reduced dry nose and mouth (Mador et al. 2005; Ruhle et al. 2011). Similarly, humidity delivered through a heated breathing tube, combined with low ambient temperature has been shown to decrease daytime sleepiness, improve sleep efficiency, and increase total sleep time in sleep apnea patients (Nilius et al. 2008). Conversely, damp environments have been shown to be associated with sleep disruption including difficulty with sleep initiation, sleep fragmentation and early morning waking (Janson et al. 2005), highlighting the need for moderation of the humidity in the environment.

During sleep, the ambient temperature required for thermoregulation also varies depending on clothing. The insulation of clothing is measured in Clo, where naked is equal to 0 Clo, 1 Clo is approximately equal to wearing comfortable clothing in an ambient temperature of 21°C (70°F) and 4 Clo is approximately equal to the insulation required for being outside in arctic conditions (Stellman 1998). When individuals sleep semi-nude (Clo 0.04), ambient temperatures ranging between 28-32°C (82-90°F) are required to maintain thermoneutrality (Lin and Deng 2008a). In contrast, temperatures ranging from 20-22.2°C (68-72°F) are sufficient for individuals when sleeping naked covered in bedding (Lin and Deng 2008a). In an evaluation of different combinations of bedding and pajamas on a standard manikin exposed to an ambient temperature of 22°C (71.6°F), Lin and Deng found that Clo ranged between 0.90 and 4.89 depending on the use of sleeping materials (Lin and Deng 2008b). These differences in Clo

illustrate the wide range in possible combinations of sleep insulation that are chosen by individuals.

Heat and cold affect sleep in different ways depending on the interaction between ambient temperature and insulation. When individuals sleep with minimal clothing and no blankets, ambient temperatures both above and below the thermoneutral range cause sleep disruption. In these cases, temperatures below the thermoneutral zone increase night waking, while temperatures above the thermoneutral zone both increase night waking and alter sleep architecture. In a study of six young semi-nude adult males, Haskell and colleagues studied the impact of ambient temperatures of 21, 24, 29, 34 and 37°C (69.8, 75.2, 84.2, 93.2, and 98.6°F, respectively) on sleep (Haskell et al. 1981). They found that compared to the thermoneutral condition of 29°C (84.2°F), sleeping in 21°C (69.8°F) elicited the greatest sleep disruption, which resulted in reduced time in REM and increased waking and stage 1 sleep, a finding likely due to the cold ambient temperature amplifying the cold sensation experienced during the drop in core body temperature, which immediately precedes REM-rich sleep cycles (Czeisler et al. 1980). The authors also observed wide inter-individual differences in tolerance to cold temperatures. In the same sample, warmer temperatures of 34-37°C (93.2-98.6°F) also disrupted sleep, but not as dramatically.

Ambient temperatures at or above the thermoneutral zone have been shown to suppress slow wave sleep, while temperatures at or below thermoneutrality have been shown to enhance or restore slow wave sleep. Togo and colleagues found that partially nude individuals sleeping in 29.5°C (85°F) experienced more slow wave sleep when the ambient temperature was slowly reduced to 27.5°C (81°F) over the second to fourth hour of a sleep episode, relative to sleep in a continuous ambient temperature of 29.5°C (85.1°F; (Togo et al. 2007). Similarly, another group found that sleeping in a hot ambient environment of 35°C (95°F) during sleep restriction of four hours suppressed slow wave sleep relative to sleep in 20°C (68°F; (Bach et al. 1994).

When insulation, such as clothing and a blanket are used, hotter ambient temperatures are more disruptive to sleep compared to colder temperatures, likely due to the fact that access to insulating material allows for individuals to modify the sleep environment during a sleep episode (i.e. through the addition or removal of blankets). In a study measuring the impact of wearing lightweight pajamas and a light blanket (Clo 1.64) under ambient temperatures of 23°C, 26°C and 30°C (73.4°F, 78.8°F, & 86°F), Lan and colleagues found 23°C (73.4°F) and 30°C (86°F) were both associated with a longer sleep latency compared to 26°C (78.8°F; Lan et al. 2014). They also found that slow wave sleep and subjective sleep quality was reduced in both the 23°C (73.4°F) and 30°C (86°F) conditions compared to the 26°C (78.8°F) condition. A similar finding has been reported in older men (mean age 69.2 ± 1.35 years), who reportedly sleep better in lightweight pajamas with a light blanket at 26°C (78.8°F) compared to 32°C (89.6°F; Okamoto-Mizuno et al. 2004). Under typical circumstances, individuals tend to self-select a bedding microclimate of between 33-35°C (91-95°F), until the rising phase of the core temperature rhythm (Okamoto et al. 1998; *for review, see* Van Someren et al. 2002), when individuals tend to remove covering and reduce the bedding microclimate to approximately between 25-30°C (77-86°F; Okamoto-Mizuno et al. 2003). When individuals sleep with bedding insulation sufficient to maintain a bedding microclimate within the typical range, sleep quality and quantity is reportedly unaffected even at extremely low ambient temperatures of 3-17°C (37-62°F; Okamoto-Mizuno et al. 2009). A recent study evaluating sleep among hunter-gatherer tribes in South America and Africa showed that proximal skin temperature was maintained throughout a

night of sleep, despite a drop in temperature overnight from approximately 20°C to 10°C (68°F to 50°F), presumably due to the maintenance of a bedding microclimate (Yetish et al. 2015).

The high temperature of the bedding microclimate may promote skin warming and thereby facilitate the initiation and maintenance of sleep. Skin temperature is elevated during sleep relative to active wake (van Marken Lichtenbelt et al. 2006) and mechanisms that increase vasodilation have been shown to result in faster sleep onset. The endogenous distal-proximal skin temperature gradient transition to warm distal and cool proximal skin temperature has been shown to be associated with rapid sleep onset in a bed-rest protocol (Kräuchi et al. 1999), suggesting that warm feet and hands precede optimal sleep initiation. In a laboratory study where individuals were not confined to bed rest between sleep opportunities, Raymann has shown that using a thermosuit to warm proximal, rather than distal skin regions is associated with improved sleep latency, even when sleep opportunities occurred during the biological day (Raymann et al. 2005). In this randomized, within subjects study, individuals were exposed to warm and cold manipulation of the proximal skin, distal skin and core body temperature via a thermosuit and ingestion of hot and cold beverages. The thermosuit was warmed to 33°C (91.4°F) in the cool condition and 37°C (98.6°F) in the warm condition capturing the impact of sleeping in temperatures just under and just above the high and low range of the typical sleeping microclimate. This manipulation of temperature resulted in a skin temperature difference of 0.78°C (33.4°F) in the proximal warming condition, and resulted in a significantly faster sleep onset relative to the cool condition, suggesting that modest skin warming is sufficient to accelerate sleep onset. In a similar study by the same group, when skin temperature was warmed to at or above approximately 33.5°C (92°F) young and older individuals experienced fewer night awakenings and increased deep sleep compared to sleep when skin temperature was below that threshold (Raymann et al. 2008). Together these findings support the notion that a sleep environment sufficient to warm skin temperatures to at least 33.5°C (92.3°F) is necessary for optimal sleep.

There appear to be sex differences in how temperature impacts sleep. Baker and colleagues found that women taking contraceptives had significantly less REM sleep in an environment featuring a warm quilted blanket than on their baseline night with a lighter blanket, in contrast with men, who exhibited no detectable difference in sleep outcomes (Baker et al. 1998). Women taking contraceptives have also been shown to have higher body temperatures during sleep than naturally cycling women (Baker et al. 1998). Additionally, progesterone, used in many oral contraceptives, has hypnotic properties that has been shown to increase non-REM sleep in both men and women (Baker et al. 1998; Friess et al. 1997). These findings support the importance of having a flexible sleep environment that can be modified to meet the needs and preferences for both men and women.

Air Quality

The air mixture on Earth at sea level is comprised of 78% nitrogen, 21% oxygen, and 1% various other gases (Encyclopædia Britannica). Deviations from this typical gas mixture and altitude lead to a wide range of consequences depending on the relative changes in the gas composition and atmospheric pressure. The presence of oxygen in the air mixture is required to sustain human life. The OSHA guidelines state that the minimum acceptable breathing air should contain 19.5-23.5% oxygen (Occupational Safety & Health Administration), citing that hypoxia occurs below that level as evidenced by rapid breathing, increased heart rate and cognitive decline. Although it is possible for a human to survive in air mixtures that include

higher levels of oxygen, toxicity can occur following prolonged exposure. Exposure to 100% oxygen for as little as 10 minutes leads to changes in ventilation and respiratory rate (Crowley et al. 2012).

Exposure to elevated levels of carbon dioxide (CO₂) can be lethal to humans. The OSHA Permissible Exposure Limit (PEL) for carbon dioxide is 5,000 particles per million (ppm), or 0.5% of the air mixture (Occupational Safety & Health Administration). Exposure to lower levels of carbon dioxide has an influence on human cognition and breathing. For example, exposure to carbon dioxide levels of 1,000 ppm for 2.5 hours is associated with moderately impaired decision-making, while exposure to 2,500 ppm is associated with large reductions in decision-making performance (Satish 2014). Exposure to higher levels of CO₂ leads to hyperventilation, hypercapnia and unconsciousness. There have been several aviation accidents where passengers and crew aboard aircraft have been exposed to high levels of carbon dioxide (estimated exposures ranged from 4-38%) due to failures of fire extinguishers or dry ice (solid CO₂), leading to near misses and fatalities (Rice 2014).

When barometric pressure is decreased, as occurs at altitude, the partial pressure of oxygen is reduced, which causes a reduction in the oxygen received with inspiration (Dietz 2001). Humans compensate for the reduced oxygen received at altitude by hyperventilating. Periodic breathing, when respiration cycles between apnea (no breathing) and accelerated breathing, occurs at altitude due to the lack of oxygen. It is possible for humans to acclimatize to living at high altitude through frequent exposure to hypoxia (Muza et al. 2004).

At sea level, respiratory function follows a diurnal rhythm, with a peak in respiratory outcomes occurring during the day and a nadir occurring at night (Kerr 1973). Some aspects of respiratory function, such as the hypercapnic ventilator response (HCVR) and end-tidal pCO₂ follow a circadian rhythm, with a minima occurring 6-8 hours prior to the minimum of the core body temperature minimum (Spengler et al. 2000). There is a direct effect of non-REM sleep on respiratory function, including a sleep-induced increase in PaCO₂, a decrease in HCVR slope and an increase in mechanical impedance between wakefulness and NREM sleep (Skatrud et al. 1988).

Poor air quality or gaseous air mixtures that deviate from typical Earth-based sea level air mixtures are capable of causing sleep disruption and impaired breathing during sleep. Exposure to elevated levels of CO₂ can lead to sleep disruption. Ventilatory responses to hypercapnia have been shown to be lower during sleep than during wake (Robin et al. 1958); (Lo et al. 2006) and a mean value of 3.8% (range 2.3-6.5%) end-tidal CO₂ partial pressure has been shown to cause awakening from sleep (Gothe et al. 1981). Similarly, there is a decreased respiratory response to CO₂ exposure during sleep at both at 14,000 feet altitude and sea level compared to waking (Reed and Kellogg 1958). The ventilatory response to exposure to CO₂ is decreased following 24 hours of sleep deprivation (Schiffman et al. 1983), but the interaction between sleep deprivation and air mixture has not been systematically studied.

Exposure to CO₂ during sleep also influences daytime cognitive function. Strøm-Tejsen and colleagues found a reduction in sleep quality following exposure to modest levels of CO₂ (Strøm-Tejsen et al. 2015). They randomized student volunteers to sleep for a night in their dormitory with airflow and to a night in their dormitory with no airflow. They found that when individuals slept in bedrooms with airflow, the average CO₂ was 660 ppm and when they slept in the room with no airflow, CO₂ levels averaged 2,585 ppm. In this study, sleep quality, and sleep

efficiency was reduced in the closed environment. In addition, logical reasoning as measured by Baddeley's test of grammatical reasoning was reduced after sleeping in the higher CO₂ concentration. It is unclear whether these findings relate to the sleep disruption that participants experienced in the high CO₂ condition, or to a direct effect of CO₂.

Sleep disruption arising from variations in the ambient gas mixture is dependent on pressurization, as evidenced by studies simulating sleep and breathing at altitude. Mizuno and colleagues studied sleep and respiration in five males in a hyperbaric simulator at sea level, 1,500, 3,000, and 4,000 meters (Mizuno et al. 1993). They found that arterial oxygen saturation significantly decreased with the increasing of altitude. All participants experienced periodic breathing and developed apnea and/or hypopnea when sleeping at an altitude of 3,000 meters and above. Hypoxemia occurred during sleep at 4,000 leading to arousal from sleep. This change in sleep does not necessarily reflect disruption due to changes in the gas mixtures alone as individuals sleeping in hypobaric chambers with pressure equivalent to 3,500 m and CO₂ less than 1% also experience altered sleep stages and arousals from sleep (Miller and Horvath 1977).

There appears to be an interaction between sleep at altitude and daytime symptoms of mountain sickness and headaches. Miller and Horvath reported that sleep in a hyperbaric chamber resulted in severe headaches in some participants at 3,500 m of pressure (Miller and Horvath 1977). In this study, headache symptoms were so intense for three out of eight study participants that after two days the researchers had to reduce the pressure in the chamber. The authors hypothesize that this increase in headaches may relate to differences in periodic respiration that they observed between individuals during sleep.

Little research has been done on the impact exposure to other gas mixtures and air quality on sleep. Helium has been shown to decrease muscle activity in most individuals during sleep (Skatrud et al. 1988). Air pollution has not been shown to have a direct effect on sleep disruption in objective studies (Kerr 1973); however, a cross-sectional survey of university students demonstrated that poor air quality, cigarette smoke, and room scents were disruptive to sleep quality (Altun et al. 2012). Air pollution may affect sleep via secondary effects, such as by leading to an increase in asthma, which can then lead to sleep disruption due to a circadian peak in asthma symptoms during the biological night. Air pollution might also contain allergens, which are known to disrupt breathing and therefore sleep (Craig et al. 1998).

There is little research on the optimal velocity of airflow in the sleep environment. Zhu and colleagues surveyed 1,055 Chinese citizens and found that 90% used a fan during sleep (Zhu et al. 2014). They further found that individuals prefer constant to intermittent airflow and that their preferred airflow velocity while laying down is around 0.6 meters/second.

Comfort

Comfort is dependent on a large number of variables, including temperature, spinal alignment, and mattress and pillow quality. There are limited studies on how changes in each of these factors affects sleep quality and quantity.

The bedding system used has been shown to impact sleep quality. Jacobson and colleagues found that a medium-firm mattress increased subjective sleep quality for normal, pain-free sleepers compared to 28 days of baseline in the individual's own beds (Jacobson et al. 2008). In a follow up study of individuals with minor musculoskeletal sleep-related pain, the medium-firm mattress increased sleep quality and efficiency compared to a baseline period of 28

days in their own beds (average bed age = 9.5 years; Jacobson et al. 2009). In another study using the same protocol, the same group compared the impact that the medium-firm had on sleep quality among individuals scoring both high and low in back pain ($N = 59$; women = 30; Jacobson et al. 2007). Both groups reported improved sleep quality, lower levels of back pain, higher levels of sleep quality, and greater sleep efficiency compared to baseline sleep in their own beds.

There may be an interaction between the age of a mattress and body position on sleep quality. Verhaert and colleagues designed a counterbalanced study comparing participant's sleep quality in a personalized stiffness distribution bed to a bed that simulated a sagging mattress (Verhaert et al. 2011). When sleeping posture of participants was taken into account, two clusters of sleepers were found. One cluster was of individuals who slept primarily in the lateral or supine position and the other were those who primarily slept in the prone or lateral position. Those who primarily slept in the lateral and prone position spent less time in REM and were awake a greater percentage of the night when sleeping in the sagging mattress compared to the personalized one. However, no significant differences were found between the two mattresses for those who primarily slept in the lateral and supine position. Similarly, Shen and colleagues found that beds with poor stability were related to increased body movement (Shen et al. 2012). Additionally, the firmness of a mattress might affect the amount of body surface area in contact with the mattress, but the resultant variation in insulation is minimal among conventional mattresses (McCullough et al. 1987). These findings suggest highlight the importance of replacing bedding that has deteriorated or designing bedding with materials that will maintain a constant level of firmness suited to individual preferences.

In addition to the influence of mattress firmness on sleep quality, pillows have also been shown to play a role in maintaining spinal alignment. Jeon and colleagues evaluated the impact of pillow choice on comfort (Jeon et al. 2014). Participants ($N = 20$) laid in the supine position for 30 minutes with a feather, memory foam, and orthopedic pillow. The cervical curve was found to be significantly greater with the orthopedic pillow. The orthopedic pillow was more resistant to temperature increases than the feather and memory foam pillows. Additionally, the orthopedic pillow was found to be more comfortable when compared to the other pillows. Gordon and Grimmer had participants compare their normal sleeping pillow to five trial pillows for one week each (Gordon and Grimmer-Somers 2011). A relationship between reported poor sleep and uncomfortable pillows was found, as was the relationship between cervical stiffness and poor sleep. Interestingly, evidence suggests that many participants used a pillow at home that was not well suited for them. Feather pillows were associated with the lowest quality of sleep, while polyester and latex pillows were related to higher sleep quality. In a separate study, Persson and Moritz randomly assigned one of six pillows to participants every night for three weeks ($N = 55$; Persson and Moritz 1998). They found that the pillow that was firm and featured two supporting cores was the most preferred. In that study, 65% of the participants found that the pillows improved upon sleep quality and 64% felt that the pillows lessened neck pain.

The attire that individuals choose for sleep also affects sleep quality. Yao and colleagues explored the effect that fabric has on stratum corneum (i.e. outermost layer of skin) water content (SCWC; Yao et al. 2007). Participants wore either pajamas that were 95% polyester and 5% spandex or 95% cotton and 5% spandex for three weeks before switching to the other pajamas for three weeks. The sleep environment was maintained at 20°C ($\pm 1^{\circ}\text{C}$; 68°F , $\pm 1.8^{\circ}\text{F}$) and a relative humidity of 55% ($\pm 5\%$). A subjective questionnaire addressing comfort and the

Pittsburgh Sleep Quality Index were used. When participants wore the polyester pajamas they were more likely to feel cold at night, less likely to feel comfortable, and more likely to have elevated levels of SCWC. Sleep quality was positively related to reported coldness and comfort.

SPACEFLIGHT ANALOG ENVIRONMENTS

Spaceflight analog environments serve an important function in the goal of human exploration and spaceflight. These environments offer analogous insights into the hardships faced by astronauts in the harsh environment of space. Analog environments for spaceflight offer terrain and elements that cannot be survived without special equipment, suits, care, collaboration, and technical expertise. In a review conducted by Duke and Keaton, individuals isolated in analog spaceflight environments, reported symptoms often include boredom, restlessness, anxiety, sleep disturbances, somatic complaints, temporal and spatial disorientation, anger, and deficits in task performance over time (Duke and Keaton 1986).

Polar Expeditions

There are currently more than 100 research stations in the Polar Regions. Arctic and Antarctic expeditions involve living conditions that are similar to spaceflight. Both Polar Regions feature a harsh environment with extreme temperatures and dryness as well as varying amounts of sunlight throughout the year. The temperature and altitude experienced by those living in the Polar Regions varies depending on the time of year and geographic location. For example, the mean temperature at the Palmer Station, latitude 64°45'S, averages -7°C (19.4°F), in contrast to the South Pole Station, latitude 90°S, which is much colder, averaging -52°C (-61.6°F; Palinkas et al. 2000). Additionally, the altitude of stations varies widely from 5 to 3,350 meters (Palinkas et al. 2000). The differences between the stations are linked to how often individuals are able to conduct expeditions outside the research stations. Despite the large number of research stations in the Regions, there are few reports on the impact of the sleep environment on sleep quality, alertness and performance.

Polar stations typically accommodate a large number of individuals during the summer season, while fewer live at polar stations during the winter. The individuals who overwinter in Antarctic are confined to small living quarters with limited private space for sleeping and personal activities. On some bases, individuals may be assigned to sleep in a bunkroom until gaining enough seniority to be rewarded with a personal sleep space (Antarctic Support Associates).

Sleep disruption is a common problem during polar expeditions. In one analysis of overwintering expeditioners in Antarctica, Palinkas found that 64.1% of the individuals reported sleep problems (Palinkas 1992). In addition, during winter 62.1% felt depressed, 47.6% reported increased irritability, and 51.5% had trouble with concentration or memory (Palinkas 1992). In a seven month long overwinter study in Antarctica, self-reported hostility and anxiety increased linearly over the winter, and anxiety increased as a function of total working hours reported (Evans et al. 1988). Given the high prevalence of circadian desynchrony due to shiftwork operations and the polar light-dark cycle (Arendt 2012), it is difficult to distinguish what proportion of sleep disturbance relates to the habitability of the physical environment.

In a sample of overwintering expeditioners from 1963 to 1974, Palinkas and colleagues found that sleep disruption increased mood disturbance when the external environment was the most severe (Palinkas et al. 2000), suggesting that lack of access to the external environment

may contribute to sleep-related mood disturbance. A study conducted by Weiss and colleagues demonstrates how the use of internal and external space may interact with sleep disturbance (Weiss et al. 2007). These investigators evaluated how individuals used space on the French polar station of Dumont d'urville in Antarctica. During this study, each expeditioner was assigned a private bedroom of approximately 9 m². The investigators found that the sleeping quarters and time spent outside the station were the only private spaces available to expeditioners and that individuals preferred to be alone approximately 30% of the time, but went outside the station less than 1% of the time during the harshest phase of winter. Although they did not provide information on sleep outcomes, they noted that the bedrooms were not soundproofed. Similarly, Yan conducted daily surveys from three out of four expeditioners living at an arctic research station in Greenland and found that sufficient mitigations were in place to provide protection against external forces, such as noise from wind (Yan and England 2001). However, there was insufficient insulation between the common area and adjoining sleep spaces, which led to noise from other expeditioners disrupting to sleep. Of note, all four individuals at the Greenland base personalized their bedrooms through the addition of shelving for storage of personal items.

Hoffman summarized the qualitative experiences of four Antarctic explorers during a workshop panel (Hoffman 2002). Three of the individuals provided their opinions about the habitability of the sleep environment during their overwinter deployment. One individual stated that sleeping arrangements were based on seniority. During the first winter at his base, he was assigned a sleeping cubicle in a shared sleep space, but after gaining seniority had a private room during the second winter. This expeditioner suggested that crew quarters for spaceflight need not be spacious, but should be private and quiet. This individual also reported that being able to personalize a space was important though this wasn't apparent to him before the overwinter stay. Another expeditioner on the panel thought that 8-10 m³ of personal space would be adequate for a bedroom, but noted the optimal size would be dependent on size of crew and sizing of general use spaces. This explorer also thought that cool temperatures in sleeping space of 5-10°C (41-50°F) were acceptable, and that personalization of space was less important than noise reduction from common spaces. Another expeditioner stated that personal space of 3 m² with a privacy curtain was adequate for sleep and felt that controlling light was more important than noise. The station where this expeditioner was deployed reportedly maintained cooler indoor temperatures (15°C, 59°F) and individuals wore sweaters, which helped minimize odors and the need for showering. These reports highlight the individual differences in what factors are important for sleep for different people.

Although a majority of time spent in Polar Regions involves sleeping in a designated station, during polar fieldwork individuals will often have to spend time in polar field tent shelters (Figure 2). In most cases individuals are issued a private tent for sleeping. In addition to the tent, expeditioners at some bases are provided with a "sleep kit" including a thick sleeping bag, an ensolite pad, a fleece sleeping bag liner, a thermorest mattress, a pillow, warm fleece pants, and a bottle for nighttime urination (Brucker 2011; Koenig 2011). Potter and colleagues surveyed expeditioners who slept in tents from 1-260 weeks in Antarctica and the Arctic region in order to determine how suitable such tents were for habitability (Potter et al. 1998). The survey revealed that noise from wind was a persistent problem during sleep irrespective of the tent shelter that was used. In addition, respondents reported that the tent fabric allowed too much light into the habitable area, which was particularly challenging during times of continuous sun exposure. In this study, sleep problems were associated with increased reports of depression,

restlessness, and nervousness. Of note, 51% of those surveyed reported that they personalized their tent space, which was associated with better satisfaction with the habitability of the tents. In a separate report, Yan and colleagues found that expeditioners felt it was desirable to use their sleeping tents for private work and leisure, but 50-80% of those surveyed felt the tents were too small to do anything other than sleep (Yan et al. 1998).

Carrere and Evans evaluated behavioral activity and preferences in habitats at Palmer Station in Antarctica. The percentage of a day spent sleeping decreased by almost two hours from the beginning of winter (41%) to the end of winter (33%; Carrere and Evans 1994). The overwinter crew also chose to spend a large amount of time alone. The researchers recommended that environments should be flexible and allow for varying personal and work-related activities. Customization of the station was important to the crew and was used to express personal and group character.



Figure 2. Polar tents. Scott tent in yellow, sleeping tents in red.

Source: <http://earthobservatory.nasa.gov/>

Underwater Environments

Underwater environments, like spaceflight, offer a constant source of danger from treacherous surroundings, which cannot be easily escaped. Aquanauts, much like astronauts, have the looming threat of decompression sickness, or "the bends," when venturing outside of their protected environment (National Aeronautics and Space Administration 2001). The key to survival rests upon technology, highly specialized skill sets, as well as communication and assistance from ground level support teams. These environments also include the rewards of exploration and potential for human-kind advancement.

SEALAB II

In 1965 the Navy conducted research with SEALAB II, operating at a depth of 205 feet (Radloff and Helmreich 1968). Three undersea crews comprised of 10 individuals spent 15 days aboard SEALAB II, except for one individual who stayed for 30 days (Lang and Smith 2006; Radloff and Helmreich 1968). The habitable space in SEALAB II was 37.9 ft³ (Stuster 1986). SEALAB II sat on the ocean floor with a 6-degree tilt. The environment was warm at 29.4°C (85°F). The air was helium rich, which modified the crew's voices and was reported to be distractingly amusing (the air mixture was ~78% helium). There was a high level of humidity of 60-90% due to the electric heaters. Crewmembers experiencing sleep disruption due to

environmental factors reported waking up simultaneously shivering and sweating. Beyond sleep disturbances, aquanauts also experienced skin rashes, ear infections, and headaches, which they attributed to the high level of temperature and humidity, although accumulation of carbon dioxide and carbon monoxide may have contributed to these symptoms. Due to the dense atmosphere aboard SEALAB II, greater effort was needed to breathe and was reportedly fatiguing. There were no objective noise measurements conducted, but SEALAB II was subjectively described as very noisy, and at times when the Arawak pumps were active, communication became close to impossible.

Tektite

The Tektite undersea habitat was a highly collaborative endeavor involving a number of industry, academic, and government bodies. Tektite was a moveable habitat and was lowered to the ocean floor by a support ship (Figure 3). The habitable environment featured a volume of 35 ft³ (Stuster 1986). The small amount of habitable space led to complaints from crewmembers about a lack of working room (Stuster 1986). Aquanauts stated that they would have appreciated a space for research, writing, and quiet reflection (Stuster 1986).

Tektite I

In 1969 the Tektite I mission began with the undersea habitat lowered to a depth of 43 feet. Four aquanauts spent 60 days in a nitrogen-saturated environment. The aquanauts sleep was measured with sleep logs, electroencephalogram (EEG), and electrooculogram (EOG) and was split into three groups (pre-dive, dive, and post-dive) to examine differences of sleep patterns from the period inhabited on Tektite to periods before and after (Naitoh et al. 1971). The Aquanauts slept for longer periods during their dive compared to both pre- and post-dive periods. Three of the four aquanauts showed a significant shift towards later bedtimes and later wake times during the dive. Sleep logs revealed that aquanauts felt that they achieved adequate sleep quality, however, some individuals noted that they felt sleep deprived during the mission. Notably, the Tektite I crew members experienced minimal intra-crew problems, but hostile attitudes were directed towards the topside crew (Miller et al. 1971).

Tektite II

In 1970 Tektite II, operating at a depth of about 50 feet, had 10 missions that were between 14-30 days long and included five aquanauts in each mission (Willshire 1984). The air mixture was 92% nitrogen 8% oxygen. The relative humidity was between 45% and 55% with a temperature between 25.6°C (78°F) and 28.3°C (83°F). During Tektite II the primary category of complaints from aquanauts related to habitability, in particular they felt there was inadequate privacy. Personal space was limited to bunks, which aquanauts felt were too small in size. Aquanauts complained about having insomnia and sleep disruption during the mission. They also felt there was too much noise, too much heat, boredom, no individual study space, objectionable odors, and inadequate selection of recreation equipment. These negative experiences were associated with a dampening of aquanaut emotions as the mission progressed and led to a reduction in work and increase in sleep from the beginning to the end of the mission, with teams averaging between 7.4 and 9.4 hours of sleep per day (Willshire 1984). Aquanauts who had higher levels of depression had more negative views towards both the habitat and the topside crew.

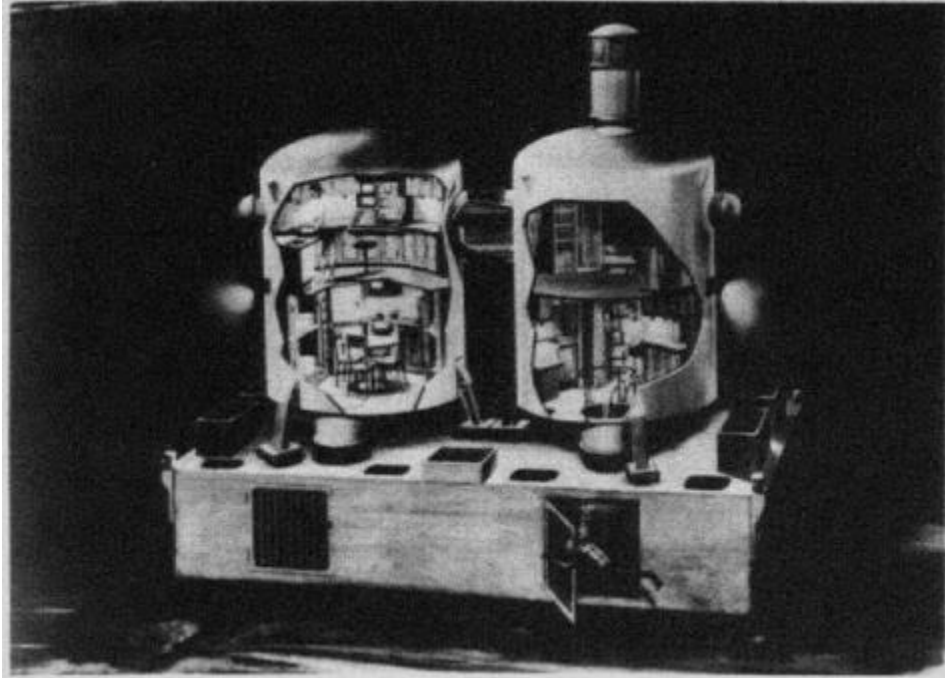


Figure 3. Tektite habitat. Source: http://history.arc.nasa.gov/Astrogram/astrogram_1970_7.pdf

La Chalupa

The *La Chalupa* undersea habitat was used as a research laboratory for over 30 days. The undersea station was at a depth of 30ft and featured 55.63 m³ of habitable volume (Vander Ark et al. 1994). The sleeping quarters included two suites and four bunks in total. One crewmember left habitat early due to flu-like symptoms. Although there were no reports of sleep outcomes during that mission, the crewmembers did report that they would have preferred private space to be alone in as well as more space for personal storage.

NEEMO

NASA Extreme Environment Mission Operations (NEEMO) has conducted undersea habitat space analog studies in a cooperative project with the National Oceanic and Atmospheric Administration (NOAA). This habitat, referred to as “Aquarius,” sits at a depth of 60 feet and is used as an analog for long-duration spaceflight (Todd and Reagan 2003). Aquarius is approximately 15 meters by 4.5 meters (Reagan et al. 2012). NEEMO missions tend to last between 10 and 14 days (Kanas et al. 2010). The aquanauts engage in extra vehicular activities (EVAs), in the form of SCUBA excursions, with three primary tasks: building underwater structures, conducting marine science, and maintaining communication equipment (Todd and Reagan 2003). Aquarius's environment includes high levels of humidity, typically around 75-80% (Todd and Reagan 2003). The ambient noise levels are reportedly low in Aquarius (Todd and Reagan 2003). The floor plan for Aquarius' habitat is shown in Figure 4.

Kanas and colleagues studied NEEMO crews 12 & 13 and examined the differences associated with crew performance with varying levels of autonomy (Kanas et al. 2010). When crews were provided with more autonomy, they reported lower levels of fatigue. These findings support the fact that factors other than the habitable environment must also be considered in order to ensure crewmembers maintain appropriate levels of alertness and performance. See Figure 5 for an Ocean view of Aquarius and Figure 6 for a view of the bunkroom.

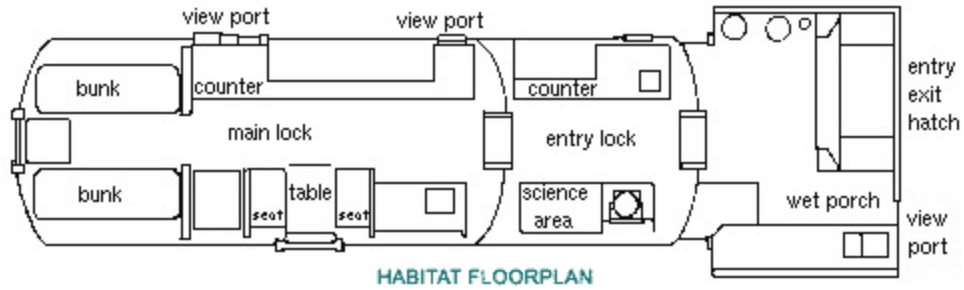


Figure 4. Aquarius' habitat layout.

Source: http://www.nasa.gov/mission_pages/NEEMO/facilities.html



Figure 5. NEEMO 12 Aquanaut in front of the Aquarius habitat. Source:

<http://spaceflight.nasa.gov/gallery/images/behindthescenes/training/html/jsc2007e21796.html>



Figure 6. Crew of NEEMO 5 laying in their bunks.
Source: <http://www.nasa.gov/missions/shuttle/neemo.html>

SPACEFLIGHT AND CONFINEMENT ANALOGS

The Skylab Medical Experiments Altitude Test (SMEAT)

The Skylab Medical Experiment Altitude Test (SMEAT) was conducted to evaluate the mission schedule, events and hardware in order to make changes to improve the spaceflight Skylab missions. The SMEAT lasted 56 days and included three crewmembers. The habitable volume of the chamber was 20 feet in diameter and 20 feet high and included a bunkroom, where two crewmembers slept and a wardroom, where the commander slept. Each bed included a pillow, blanket and sleep restraint to evaluate the comfort of the restraint for spaceflight. The chamber was depressurized to between 4.85-5.15 psia at 70% oxygen for the duration of the mission (Johnston 1973). The temperature was held between 19.4-25.6°C (67-78°F), with an air velocity of 15-30ft/min. Crewmembers were instructed to go to bed at 22:00 and wake at 6:00 each day of the experiment (Newkirk et al.). One of the experiments planned for the spaceflight Skylab missions was a sleep experiment, which was also evaluated during SMEAT. The investigators found several changes in sleep during the experiment relative to a baseline evaluation (Johnston 1973). They found that sleep latency increased from ~20 minutes during the pre-mission evaluation to over 60 minutes during the SMEAT experiment, with sleep latencies ranging from 17 minutes to 197 minutes during the study. This increase in sleep latency may have contributed to a reduction in the total sleep duration achieved by the crewmembers, who obtained an average of 6 hours and 26 minutes before the mission to 7 hours and 4 minutes during the mission and 5 hours and 6 minutes after the mission, despite their time in bed remaining the same. Slow wave sleep was reduced during the SMEAT, but REM sleep remained unchanged. The investigators reported that the pilot did not experience a change in sleep quantity or quality during the pre- or post-flight interval relative to during the mission.

The crewmembers participating in the SMEAT experiment provided regular ratings on the adequacy of the habitable environment (Johnston 1973). The commander and pilot rated the sleep restraint and reported that it was adequate (both rating it '3' on a scale from 1-5). All three crewmembers rated the sleep environment during the mission and provided mixed opinions on the suitability of the sleep environment (Table 5), with one crewmember rating the stowage volume as near unacceptable. The same crewmember rated the privacy curtain separating the crewmembers in the bunkroom as inadequate. The crewmembers were asked to rate their experiences with noise, temperature and light, but due to confusion regarding the scales this data was not reported. The crewmembers provided subjective reports on the habitability of the module and reported that noise from machinery was generally a problem that was amplified by the metal construction of the habitat. The crew reported that this construction caused noise generated in any area of the habitat to be heard in every other area of the facility. They also reported that the task lighting was not bright enough and that they would have preferred to have additional portable lights. They reported that the accommodations were suitable for the mission and that the atmospheric composition was almost unnoticeable. They stated that the temperature was comfortable, but that their feet got cold due to the metal floor. They also reported that they felt much less comfortable during a four-day period when the temperature was increased to 25°C (77°F), with humidity at 60%.

TABLE 5. SUBJECTIVE SCORING OF SMEAT DESIGN ISSUES

Crew	General rating	Volume	Ceiling/ Floor Proximity	Ingress/ egress	Trash	Stowage volume and access	Equipment restraints	Mobility aids
CDR	3	3	3	2	3	3	3	3
PLT	3	3	2	2	2	2.5		
SPT	3.5	3.5	3.5	3.5	3.5	4		

Adapted from NASA TMX-58115, Skylab Medical Experiments Altitude Test.

Note: 1 = Excellent, 5 = Unacceptable.

Biosphere 2

Biosphere 2 was a closed ecological system, which was inhabited by four men and four women for two years (from 1991-1993), with the goal of obtaining a greater understanding of environmental issues. The total enclosure for Biosphere 2 was 7,205,737 ft³ (Nelson et al. 1992). The total human habitat was 377,055 ft³ (Nelson et al. 1992). Some of the stressors encountered during Biosphere 2 included: restricted calorie intake, low oxygen levels, interpersonal dynamics, media encounters and reports, and reliance on a novel life support system for food, air, and water (MacCallum and Poynter 1995). According to the Biosphere 2 crewmembers, interpersonal conflict was the most significant problem (MacCallum and Poynter 1995). Additionally, the relationship between crewmembers and mission control members was perceived to be the most significant threat to safety and crew performance (MacCallum and Poynter 1995). Biosphere 2 featured lower levels of oxygen (a nadir of 14%), which lead to hypoxia in several crew members and, consequently, symptoms of fatigue, sleeplessness, and shortness of breath (MacCallum and Poynter 1995). Each crewmember had their own private room, which was found to be very important to all individuals.

Mars Analogs

Although missions in undersea and isolated environments provide a useful analog for spaceflight, such missions often differ in mission tempo, crew composition and size, and provisions available to crewmembers. In order to better simulate the unique features of a deep space mission, Mars analog missions have been conducted.

The Institute of Biomedical Problems in Moscow Russia designed a habitat to simulate long-duration Mars missions (European Space Agency 2010). Three studies were conducted in the facility, which lasted 15, 105 and 520 days, in order to test the feasibility of sending a similar-sized crew on a Mars mission in the future. The total habitable volume of the facility was 550 m³. Crewmembers each had individual crew quarters of 2.8-3.2 m², which were equipped with a bed, desk, chair and shelves (Figure 7). Each mission included six International, male crewmembers. The crews rotated through a watch schedule, with one crewmember being required to stay awake throughout the time while the others were asleep.

The 105-day and 520-day missions both included sleep experiments, however, neither study provided information on the crewmembers subjective preferences related to the habitability of the sleep environment. In the 105-day mission, crewmembers averaged around seven hours of sleep in the nights before the night shift, a two-hour nap on the day of the night shift and approximately 10 hours of sleep following the night shift. During the watch rotations, crewmembers reportedly brought additional lights into the room where they were completing the night shift (Barger 2014). These findings suggest that the crewmembers recognized the wake-promoting benefits associated with exposure to light during the biological night, however, such self-selected light exposure may account for the non-24 hour sleep patterns observed among some crewmembers during the Mars 500 mission. In that mission, not all of the crewmembers maintained a 24-hour schedule during the days that they were not scheduled to be on watch (Basner et al. 2013). One crewmember followed a split-sleep schedule, taking regular naps and another crewmember exhibited a free-running circadian rhythm, presumably due to self-selected light exposure causing a progressive delay in sleep-circadian timing. In addition to the varying sleep patterns that crewmembers experienced, they also experienced an increase in sleep duration from the beginning until the end of the study. The investigators speculate that this increase in rest was a symptom of torpor arising from a long-duration confinement. These findings highlight the importance of providing crew with private, sound attenuated quarters in order to facilitate self-selected sleep and changing sleep needs among crewmembers and also demonstrates that a regular light-dark cycle in common areas may be prudent in order to prevent circadian desynchrony between crewmembers.



**Figure 7. Photograph of a bedroom used during the Mars simulation missions conducted by Institute of Biomedical Problems in Moscow Russia.
Source: ESA_Mars_500infokit_31may2010**

Yuegong-1

Yuegong-1, or Lunar Palace 1, was an analog environment for a lunar base. The Yuegong-1 environment featured two cabins, a “comprehensive” cabin (42 m²) for living and a plant cabin (58 m²; Wang and Wu 2015). Crewmembers were provided with individual bedrooms which were narrow, but offered a bed and a small table (Wang and Wu 2015). In examining changes in crewmembers over time in Yuegong-1, Wang and Wu evaluated an 80-day three-person mission by quarters. Emotional states did not differ across mission quarters, however, fatigue was significantly more prevalent during the first quarter (Wang and Wu 2015).

EXTREME ENVIRONMENTS

Caves

The earliest studies on human circadian rhythms were conducted in caves, where individuals could be studied in the absence of time cues. Most early studies conducted in caves included a small number of individuals or just one single individual (*see* Halberg et al. 1970).

Halberg and colleagues studied two individuals, in two separate caves without access to external light, noise or time cues, over 85 and 125 days. The relative humidity was approximately 100% and the temperature ranged from 4°C (39.2°F) to 8°C (46.4°F). The participants slept in a tent, which sheltered a bed with supplies similar to those used during a camping trip (e.g. butane stove, canned food, tools, etc). Heaters were used to warm the tent

prior to sleep and were extinguished prior to retiring. Temperatures would reach around 21°C (69.8°F) before falling back to the caves' baseline temperature range throughout the subject's sleep period. A gas lamp was provided to each participant, which provided 50 lux of light. Participants also carried a lantern outside their tent that was reportedly low powered. Both participants, experienced free-running circadian rhythms, presumably due to self-selected light exposure and no external lighting cues. There was no specific information reported related to the cave environment on sleep quality. Of note, participants in the study felt that time passed more slowly than in reality, with one participant who felt the calendar was approximately one month earlier. Similar findings were reported in cave studies conducted by Kleitman (Kleitman 1965), and Siffre (Siffre 1988). These findings highlight the importance of maintaining a regular light-dark cycle of sufficient intensity to maintain normal circadian entrainment.

Mountaineering

Mountain climbers frequently experience awakenings and poor sleep quality during expeditions.

The majority of studies that have been conducted comparing sleep outcomes in individuals sleeping at sea level compared to those sleeping at altitude have found that sleep duration is not affected by sleep at altitude, but sleep is more disrupted compared to sleep at sea level (Reite et al. 1975; Salvaggio et al. 1998; Selvamurthy et al. 1986). Szymczak and colleagues studied 32 individuals (28 male, 4 female) over two expeditions in Nepal, Himalayas. Subjective sleep quality and sleep timing was measured at both sea-level and at a high altitude (M = 4524 meters above sea-level; Szymczak et al. 2009). Participants displayed a decrease in both sleep quality and sleep onset during the high altitude measurements. Participants also reported sleep disturbances due to awakenings, temperature-related discomfort, and breathing difficulties. Sleep duration was not different at altitude relative to sea level.

The impact of sleeping at altitude on sleep stages is unclear. Comparisons of sleep between high altitude natives to acclimatized lowlanders and unacclimated lowlanders sleeping at 3500 m showed that all three groups had significantly less SWS compared to unacclimated lowlanders at sea level (Selvamurthy et al. 1986). In contrast, another group reported a non-significant trend towards increased SWS among unacclimatized lowlanders over four weeks at an altitude of 5050 meters (Salvaggio et al. 1998). It is possible that the variation in sleep stage disruption observed among individuals at altitude relates to susceptibility to mountain sickness. Selvamurthy and colleagues found that acute mountain sickness was prominent among unacclimated lowlanders who did not experience a reduction in SWS while at altitude (Selvamurthy et al. 1986). It remains unclear whether physiological disturbances (e.g. headaches, mountain sickness) account for some proportion of the sleep disturbance or whether the sleep disturbance results from a direct effect of atmospheric pressure.

Oxygen enrichment may be a countermeasure for improving sleep at altitude. A study investigating oxygen enrichment at altitude showed that it leads to increased deep sleep and fewer apneas (Luks et al. 1998), but no change in sleep duration for sea-level acclimated individuals (Barash et al. 2001).

Aircraft

The standards for crew rest facilities in commercial aviation vary based on the length of a flight and the number of pilots operating the flight. There are three classes of rest facilities, with

Class I facilities allowing for the longest flight duty time (19 hours with four crewmembers; Federal Aviation Administration 2011). A Class I facility means a bunk or other surface that lies flat and is separated from both flight deck and passenger areas. It must allow crewmembers to control light and temperature and provide isolation from noise and disturbance. Some control of communications is also recommended to minimize disturbances to rest periods. The volume for the facility should be 35 ft³ per individual user with additional adjacent free space for access and changing of clothes (Federal Aviation Administration 2012). The dimensions for each sleeping surface should be 78x30 inches (SAE International 2006). A Class II facility is a seat in an aircraft cabin that allows for a flat or near flat sleeping position that is separated from passengers by minimum of a curtain to provide darkness and some sound mitigation. It should be “reasonably free from disturbance” and could be a group of seats shared only by flight crew. Specifications for the seat are that it should recline to at least 45° and have a seat width of 20” with leg and foot support. This could be considered as a ‘normal’ business class seat in a commercial aircraft. This type of crew rest facility allows for an 18 hour flight with four crewmembers. A Class III facility is a seat in an aircraft cabin or flight deck that reclines at least 40° with leg and foot support. This type of crew rest facility allows for a 15.5-hour flight with four crewmembers. The regulations also state that ‘intrusive noise, odors and vibration’ should be minimized. Controls of airflow and temperature provide for a well-ventilated space (Federal Aviation Administration 2011). Noise level during cruise is suggested to remain in the range of 70-75 dBA (SAE International 2006).

The International Federation for Airline Pilots Association (IFALPA) published a position paper that included additional recommendations for crew rest facilities based on the pilot perspective on what features would be important for crew rest (International Federation of Air Line Pilots’ Associations 2013). These recommendations included that rest facilities should be in proximity to the cockpit in case of emergency response situations. They also recommended that the facilities be convenient to the lavatory. They also recommends that at least 39” (1000 mm) of unencumbered space should be provided above a bunk sleeping surface for ease of use, and that sleeping surfaces should provide support and resilience such as to avoid complete compression at pressure points (shoulders, hips) with thickness of 100 mm. Importantly, the position paper highlights the importance of minimizing intermittent noise and recommends that random noise disturbances should be minimized, so that they differ from background noise by only 3-5 dBA. IFALPA also recommends airflow volume of 0.7 cubic meters per minute per occupant (minimum of 0.3) to ensure a uniformly ventilated rest facility. The velocity of air passing over sleeping surfaces is recommended to not exceed 12 meters/minute and relative humidity should be at an equivalent level as to the cockpit. IFALPA also notes that guidance exists for vibration levels of low frequency z-axis oscillations to manage motion sickness potential.

The majority of studies conducted to examine the quality and quantity of sleep on an airplane to that on the ground support the notion that sleep is better on the ground relative to in an aircraft. Sletten and colleagues studied the impact of sleeping in on-board rest facilities during flight to sleep at home among 71 commercial airline pilots. They found that sleep efficiency was significantly lower (~69%) compared to sleep at home (~82%). They also found that activity during sleep was significantly higher and sleep quality was rated as significantly worse during sleep on an airplane compared to sleep at home (Sletten et al. 2002).

There have only been a small number of studies that have compared the quality and quantity of crew rest during flight in different sleep locations (e.g. in a bunk, in a seat). Researchers at NASA surveyed 1,404 long-haul pilots from three US commercial carriers in order to determine what factors were associated with sleep disruption during flight. Factors that promoted sleep in the bunk were physiological (readiness for sleep), physical environment (bunk size, privacy), and personal comfort (blankets, pillows). Factors that interfered with bunk sleep were environmental disturbances such as background noise, and turbulence, lighting, personal disturbances, the need to use the bathroom, random thoughts, environmental discomfort, including low humidity and cold, and interpersonal disturbances including other crewmembers using the crew rest facility. Respondents suggested that the bunks could be improved through larger and thicker mattresses, cloth sheets and pillowcases, and bigger pillows and blankets (Rosekind et al. 2000). In a separate study, researchers at NASA conducted a field study of in-flight sleep quantity and quality with 38 long-haul pilots. Different bunk configurations existed in the aircraft types that were studied with a permanent bunk facility with an upper and lower bunk located just aft of the cockpit (B747), and a convertible semi-permanent facility located between the business and economy class cabins (B767). Two 747 flight crew used the facility at a time, while the 767 pilots used the facility one at a time. A pillow and wool blankets were available in all facilities. Differing schedules led to longer and shorter bunk periods in the different aircraft averaging 258 and 108 min. There were no specific differences in sleep outcomes reported between the two bunk spaces. Total sleep time, measured by polysomnography, averaged 155 and 70 min, respectively, with similar sleep efficiencies in both bunks of 78% and 84%. Slow wave sleep averaged about 11% of sleep in the longer bunk sleep, likely due to the longer sleep opportunity. REM sleep was measured in over half of all bunk sleeps (Rosekind et al. 1997).

Two studies have been conducted that directly compare specific sleep configurations relative to sleep outcomes. Spencer and Robertson compared sleep by flight crew in a bunk to a third seat on the flight deck. Most pilots were able to sleep in the bunk (82%), while only about 2 in 3 did so in the seat (65%). Sleep quantity (1.2 vs 0.6 h) and quality (4.5 vs 5.4 with 7= 'extremely poor') was better in the bunk than in the seat. The seat was reported to be uncomfortable and leg support was poor while complaints about the bunk included a hard mattress and inadequate bedding (Spencer and Robertson 2000). Nicholson and colleagues compared the sleep of nine men in bed, in a 'sleeperette' (49.5° recline to the vertical; 'first class seat'), in a reclining seat (37° recline; 'business class seat'), and an armchair (17.5° recline; 'economy class'). They found that sleep in the sleeperette did not significantly differ from sleep in a bed (total sleep time= 425 vs 437 min, sleep efficiency= 89% vs. 90%). They found that individuals slept less (406 min) and had more awakenings in the reclining seat, while sleep in the armchair was the worst. The authors concluded that better sleep was related to a back angle approaching 40° or more to vertical (Nicholson and Stone 1987).

Military

Service members from all branches of the military experience sleeping in isolated, confined and hostile environments during deployment. Each branch of military has established separate requirements for berthing areas and mission-related sleeping environments. Few studies have been conducted to evaluate the impact of the various sleep environments on sleep quality, alertness, and performance.

Army service members experience a wide array of sleep environments, including sleep in locations that were not designed for sleep, such as in army vehicles and in temporary encampments. In addition to lacking basic features to allow for sleep (e.g. bedding), such environments often feature extreme temperatures, varying light exposure and poor air quality. For example, Goldman and colleagues reported that the temperature inside combat vehicles ranges from 26.7-35°C (80-95°F), leading to the potential for sleep disruption and heat stress (Goldman 1982). In a collection of interviews compiled by Ritchie and Small, tank crewmembers at the National Training Center reported that they rarely slept inside armored vehicles due to excessive temperature (Ritchie and Small 1987), poor airflow and physical discomfort due to lack of space to stretch out. Instead, they reported that they would take a foam pad and sleeping bag stowed within the vehicle and sleep on top of the vehicle.

In the Army Combat and Operation Stress Control Manual for Leaders and Soldiers, the recommended sleep environment includes control over ambient noise, with provision of earplugs or white noise to block ambient sounds, a dark environment, with provision of an eye mask for sleep locations that cannot be completely darkened, and provision of extra clothing and blankets for cold environments and fans for hot environments to maintain a suitable sleep temperature (Department of the Army 2009). The manual also provides recommendations on optimal schedule design and use of caffeine and hypnotics. It is unclear, however, to what extent the recommendations outlined in the manual are deployed in operational scenarios. For example, when on patrol, army service members are issued a sleeping bag that may be used at temporary encampments. This sleeping bag is described as "lightweight, designed for temperatures in the range 30-50°F with dimensions of 90x36." An adjustable hood helps keep warmth in or bugs out and a reversible zipper allows for top or bottom ventilation. A draft flap is designed to prevent heat loss and a draw cord on the hood allows for adjustments and control for heat retention (Best Glide), however, there are no reports on how sleep quality is affected by using the sleeping bag. Similarly, according to an Army Sergeant who was deployed to Iraq, the tent that served as sleeping quarters were right next to noisy diesel generators and that 20 personnel were bunked there, with the lights always on and personnel regularly coming and going due to different work schedules (Green 2015).

Military aviators experience unique challenges and are frequently required to sleep on aircraft or in temporary sleep locations. Work hour guidelines for tanker transport allow for a flight duty period of 24 hours, provided the aircraft has a rest facility and augmented crew. Guidance on rest facilities on military aircraft is generally lacking, with requirements stating that "rest facilities should provide adequate privacy and noise levels to obtain suitable rest." (Wolters 2015). Similarly, Air Force procedures for U-2 flight operations note that crew rest facilities should be "climatically controlled, quiet" and easily accessible. At deployed locations, inspection by command personnel determine compliance with requirements for sleep spaces (Department of The Air Force 2000).

Caldwell and colleagues surveyed 241 Army aviators and 120 enlisted crewmembers and found sleep rated as poor by 26% of aviators and 36% of crewmembers while deployed (Caldwell et al. 2000). Respondents indicated that sleeping quarters were perceived as inadequate; with day and night crews sharing the same tent facilities, which were often located near areas where noise from aircraft and personnel working interfered with sleep. They also reported that daylight was poorly controlled, also disrupting sleep and that crew-rest policies were not followed as closely during a mission as when at home base. In contrast, in a report to

the Air War College, Watt described experiences with pilot fatigue during deployment in Middle East operations. Crew rest quarters were located in a trailer-like facility with private air-conditioned rooms (Watt 2009). Air conditioners were effective for white noise and windows were blacked out, doors padded, and hallways ruffled as much as possible to minimize noise (i.e. boots walking). Private rooms were deemed necessary to minimize disturbances from a roommate on a different schedule entering or exiting the room (scheduling was a significant challenge in this operation). Restrooms were located in a separate building, which posed a challenge for daytime sleepers due to the need to exit sleeping quarters and enter a bright environment. Given the need to drink a large volume of water due to outdoor temperatures typically exceeding 100°F, crew often resorted to use of disposable “aircrew relief devices” instead.

The Manual of Naval Preventive Medicine provides guidance on the sanitary requirements for berthing areas on ships and barges, mandating that berthing spaces be clean, well ventilated, and well illuminated (Bureau of Medicine and Surgery 1995). There is no provision for private sleep spaces within berthing areas and the size and privacy of sleeping quarters are based on rank, with E 1 recruits being allotted 72 square feet of living area in an open bay, with a central bathroom. The guidelines provide specific requirements for pillows and mattresses in order to reduce fire hazards and require that a supply of clean linen be available. During periods of work, the Navy Occupational Exposure Limit for noise is 84 dBA, time-weighted over an 8 hour day (Department of the Navy 2002). The noise limit in Naval berthing areas is currently 70 dBA (Department of the Navy 1995). These recommendations are substantially higher than the American Bureau of Shipping (ABS) Guide for Crew Habitability on Ships, which recommends noise levels in berthing areas not exceed 50 dBA (American Bureau of Shipping 2001). The ABS further recommends that the relative humidity be controlled to between 30% and 70% with an ambient air temperature between 18-26.5°C (64.4-79.7°F). They state that the air velocity should not exceed 0.5 m/s and the amount of lighting during periods of sleep is recommended to not exceed 30 lux (American Bureau of Shipping 2001). Early reports on the habitability of the sleep environment on Navy ships found that service members reported sleep disruption due to noise, inadequate climate control, overcrowding, and uncomfortable bunks (U.S. Navy Atlantic Fleet Inspector General 1969). In addition to habitability concerns present within the local sleep environment, factors associated with ship movement and working location have been shown to reduce sleep quality and duration. Rough seas have been identified as a major source of sleep disruption during Navy operations. In response to rough seas, crewmembers aboard ships may experience motion sickness and seasickness syndrome, which symptoms include drowsiness, lethargy, mild depression, and difficulty focusing (Matsangas et al. 2015). Matsangas and colleagues studied the impact of rough seas on sleep and found that as sea conditions worsened, sailors slept significantly longer hours (Matsangas et al. 2015).

The location of work aboard a ship influences the amount of sunlight that workers are exposed to and can affect sleep quality and duration. Miller and Nguyen conducted a study evaluating the impact of exposure to natural light on sleep (Miller and Nguyen 2003). They studied two aircraft carriers that were working in-tandem to create round-the-clock operational abilities, with one carrier conducting missions at night and the other during the day, in aid of Operation Enduring Freedom. They found significant differences in amount of sleep that individuals achieved between the two carriers. In particular, those who worked topside (i.e. on or above the deck) of the carrier and were exposed to sunlight immediately prior to sleeping

obtained 4.72 hours of sleep per day, while those who worked below deck, and experienced very little sun exposure, obtained 7.35 hours of sleep per day. These findings support the notion that exposure to bright light at inappropriate times of day relative to shift schedules can reduce sleep duration.

Work on submarines poses numerous habitability challenges, including lack of daily light exposure and limited space for living and working. In response to the space constraints present on most submarines, "hot bunking" was a common practice in the past. Hot bunking entails the shared use of a bed by two or three individuals during shiftwork operations, whereby one individual occupies the bed while the others are working and the sleep space is rotated between the occupants by shift. "Hot bunking" has generally been abandoned due to the fact that it limits privacy among crew members and creates problems related to personal space and hygiene (Stuster 1986).

Strategic use of lighting improves sleep outcomes during submarine operations by promoting circadian alignment in the absence of a natural light-dark cycle. Submariners in the US Navy have historically worked 18-hour days, with six hours on duty and 12 hours off (Duplessis et al. 2007). Young and colleagues conducted a study comparing florescent lighting to high correlated color temperature (CCT) florescent light sources in patrolling submariners working on a 24-h schedule (Young et al. 2015). The use of high CCT light sources during periods of duty was related to better behavioral alignment with a 24-hour rhythm with convergent validity of a wide variety of objective and subjective measures.

THE SPACEFLIGHT SLEEP ENVIRONMENT

Vostok

Vostok was a spherical space vehicle for one individual with a habitable volume of between 2-3 m³ (Wieland 1994). Vostok's air mixture was similar to that of sea-level with a O₂/N₂ mixture and had a 14.7 psia (pounds per square inch absolute) atmosphere (Wieland 1994). The internal cosmonaut controlled temperature ranged from 12-25°C (53.6-77°F) with a relative humidity ranging from 30-70% (Wieland 1994). In 1961, Yuri Gagarin flew in Vostok 1, the first ever spaceflight vehicle for humans, completing one complete orbit around the world. On Vostok 2, the first person fell asleep during space, Gherman Titov. In total, there were six manned Vostok flights (Wieland 1994).

Mercury

Mercury was the first space vehicle for the United States that completed an orbit around Earth. Mercury had a habitable volume of 1.02 m³ (National Aeronautics and Space Administration 1991). The air mixture composition was 100% O₂ with 5 psia (Daues 2006). Temperature was recorded on the Mercury-Atlas 7 mission and ranged from 27.8-42.2°C (82-108°F; White and Berry).

Voskhod

The Voskhod space capsule was used for two spaceflight missions in 1964 and 1965 (US Congress 1983). Voskhod had a habitable volume of around 2-3 m³ (Wieland 1994). Like Vostok, Voskhod had a cosmonaut controlled temperature ranging from 12-25°C (53.6-77°F) and Voskhod 1 flew with three cosmonauts and Voskhod 2 flew with two cosmonauts. Voskhod's habitable volume, which was comparatively sized to Vostok, was increased due to the fact that the cosmonauts did not wear large space suits and instead wore overalls. Additionally, the

ejection seats and railing were taken out (US Congress 1983). This was primarily done to fit more than one cosmonaut on a mission (Wieland 1994).

Gemini

There were no considerations given to the quality of the sleep environment during the Gemini missions. Gemini had a total habitable volume of 2.55 m³ (Cohen 2008). The atmosphere composition was 100% O₂ (Daues 2006). In general, the astronauts for each of the Gemini missions rested in place, as there was only a single habitable zone in the capsule. The Gemini missions highlighted the need for improving the astronaut sleep environment. The Gemini astronauts primarily complained of noise pollution during their sleep opportunities; specifically that radio noise and automatic thruster firing woke them (Hacker and Grimwood 1977). On Gemini IX, the astronauts complained about lights from the cabin disrupting their sleep and on Gemini X, the astronauts reported having difficulty sleeping due to a strange odor, which emanated from their suit fans (Hacker and Grimwood 1977). After they turned one fan off, the smell was tolerable.

The interaction between crew schedules and sleep habitability was also an issue. On Gemini IV, the astronauts were supposed to sleep in four-hour shifts, with one crewmember sleeping while the other was awake (Hacker and Grimwood 1977). This did not work, because ground control kept in frequent communication with the astronaut who was awake, which woke the sleeping astronaut. A similar problem was apparent on Gemini V, but given the severity of the astronaut's sleep disruption due to the poor sleeping environment, the astronauts worked with mission control to change their schedule and allow them to sleep at the same time. This resulted in each astronaut experiencing a longer, more consolidated sleep (Hacker and Grimwood 1977). The Gemini VI astronauts were aware of the difficulty experienced by astronauts sleeping in shifts on prior missions. The Mission Director for Gemini VI allowed the astronauts to abandon a formal timeline and instead provided the astronauts with an outline of tasks. This allowed the astronauts to follow a 24-hour pattern, maintaining their sleep during the night (Central Standard Time) and their work activities during the day (Hacker and Grimwood 1977). Although the astronauts reported improved sleep when they were both able to sleep at the same time, the missions required that one astronaut remain in his flight suit at all times. The flight suit was not designed for sleeping and the astronauts complained that it was too hot. On Gemini VI, this led to one astronaut having continually disrupted sleep due to overheating.

Despite the well-documented issues associated with astronauts sleeping in shifts in a confined space, mission planners for Gemini VIII recommended that the astronauts return to sleeping in shifts (Hacker and Grimwood 1977). The astronauts protested this recommendation, but it was denied by mission managers and the astronauts were scheduled to sleep at offset times. This highlights the need for objective data collection regarding the impact of operational decisions based on prior missions.

The functional consequences of the astronauts' accumulated sleep loss due to poor habitability, poor scheduling and high workload were realized on Gemini X, when one astronaut fell asleep during an EVA and floated asleep on the tether, while the other astronaut simultaneously fell asleep inside the capsule (Hacker and Grimwood 1977).

Soyuz

Soyuz has played an integral part in spaceflight history, dating back to 1967. Soyuz, however, has gone through various modifications through the years. After 12 years of Soyuz operations, a new design, Soyuz T, made its inaugural flight in 1979 (US Congress 1983). The Soyuz T had a habitable volume of approximately 10 m^3 (US Congress 1983). A modified version of the Soyuz T can be seen in Figure 8. The newest model is the Soyuz TMA. The Soyuz TMA's Orbital Module and its Descent Module have a habitable volume of 6.51 m^3 and 3.99 m^3 , respectively (Wright 2010). The atmosphere composition is similar to sea-level and has a psia that ranges between 13.7-16.4 (Daves 2006). Like earlier Soviet capsules, Soyuz has a cosmonaut/astronaut controlled ambient temperature ranging from $12\text{-}25^\circ\text{C}$ ($53.6\text{-}77^\circ\text{F}$) with a relative humidity range of 30-70% (Wieland 1994).

Prior to Soyuz 11, cosmonauts did not wear pressurized suits. However an accident due to a pressure valve failure resulted in the introduction of space suits on Soyuz missions (Wieland 1994).

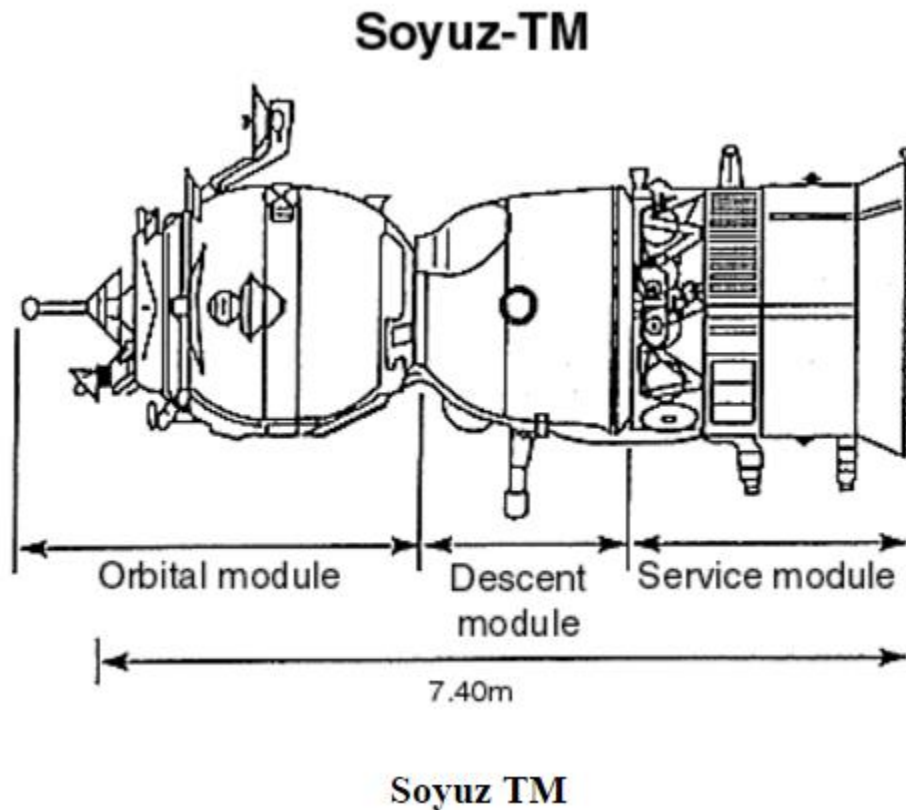


Figure 8. Diagram of Soyuz-TM.

Source: <http://history.nasa.gov/SP-4225/diagrams/mir/mir-diagram-11.htm>

Apollo

The Apollo missions are unique relative to all other NASA spaceflight missions to date. These missions involved three crewmembers, including two pilots and a mission commander. The Apollo missions are important to consider when evaluating habitability, because the Apollo missions involved two habitability chambers - the Command Module (CM) and the Lunar

Module (LM). This design most similarly mimics the type of arrangement that may be employed during future missions to the Moon, Mars or an asteroid, where astronauts will experience both microgravity and partial gravity.

The CM and LM environments were distinct from each other and included very different features. The CM remained in orbit around the moon, with the CM pilot on board, while the LM landed on the moon carrying the Mission Commander and the LM pilot. The CM had a habitable volume of 5.95 m³ and the LM had a habitable volume of 4.5 m³ (National Aeronautics and Space Administration 1991). The habitable volume for the CM and LM can be seen in Figure 9. After Apollo 1, the atmosphere composition inside the vehicle during launch was changed from 100% O₂ to 60% O₂ and 40% N₂ with 5 psia (Daues 2006). Post launch, the Command Module and the Lunar Module had an atmosphere composition of 100% O₂ with 5 psia (Daues 2006). The nominal temperature range for Apollo missions was 21-24°C (70-80°F) with a relative humidity of 40-70% (Wieland 1994). However, much more variability actually occurred during missions. From Apollo 7 to Apollo 17, the Command Module cabin temperature averaged 17.2-22.8°C (63-73°F) with a recorded low of 6.1°C (43°F; excluding Apollo 13, the low was 12.8°C or 55°F) and a high of 27.2°C (81°F; Hawkins and Ziegleschmid 1975).

There was little attention given to the sleep environment during Apollo 11, but sleeping conditions were incrementally improved for subsequent missions following feedback from astronauts. The Apollo Command Module's sleep restraints can be seen in Figure 10.

Apollo 11

On Apollo 11, there was no separate chamber for sleep in either the CM or the LM (National Aeronautics and Space Administration 1971). In the CM, the astronauts slept side-by-side and did not report any major issues with sleep; however, they did report some anxiety about entering a gimbal lock during sleep, which may have led to sleep fragmentation. Despite this anxiety, according to the Apollo 11 Mission Report, the astronauts averaged 8 hours of sleep a night without using sleep medications.

In the LM, there was no attention given to the sleep environment. The Commander slept on the ascent engine cover and the LM pilot slept in place (National Aeronautics and Space Administration 1971). Although these sleep locations would be awkward in full gravity, the astronauts reported that the partial gravity environment made these unconventional sleep locations acceptable for sleep. The astronauts were instructed to keep their flight suits on at all times, including their gloves and helmets due to anxiety about a potential loss of cabin pressure. The astronauts reported that they were too cold due to the cooling systems in the flight suits. This cold temperature led to sleep fragmentation. When they turned off the cooling system, the environmental control system in the LM was insufficient to heat them to a comfortable temperature. Noise was also a significant issue during the Lunar sortie. The astronauts reported that a sporadic, high-pitched noise from the glycol pumps woke them frequently. Light pollution was also a major issue on board the LM. The window shades did not completely close, there was light from display and warning lights and light shined through the telescope directly into the astronauts' sleep space. The LM sleep environment can be seen in Figure 11.

Apollo 12

Mission planners obtained feedback from the Apollo 11 crew and made modifications to aid in improving sleep hygiene for the astronauts on Apollo 12 (National Aeronautics and Space Administration 1971). The primary modification was the addition of sleeping hammocks and blankets on the LM. The astronauts in the LM were required to sleep in their flight suits, which they found uncomfortable. They did not use the garment cooling system during sleep, which allowed for a more comfortable sleeping temperature. As in the Apollo 11 mission, the astronauts complained of noise disruption during sleep episodes due to the glycol pump. The mission engineers were unable to replicate the source of the sound on Earth, highlighting the need for thorough testing of noise levels generated by equipment on Earth and in space. The crew was required to shift their sleep 7-9 hours from their Earth-based sleep timing, which may have contributed to their difficulty sleeping on the Moon. In order to counteract the effects of the poor sleep environment and misaligned schedule, the Lunar pilot took sleep medication during every night of the mission, however, he was still only able to obtain ~3 hours of sleep per night.

Apollo 13

This mission was aborted due to a fire in one of the oxygen tanks at 56 hours into the mission (National Aeronautics and Space Administration 1970). During the first two days of the mission, the crewmembers reported sleeping well in the CM. After the incident the CM temperature dropped to approximately 55°F and the astronauts were only able to obtain fragmented sleep until they landed at approximately 143 hours into the mission. They also reported intermittent noise that disrupted their sleep emanating from the glycol pump as in prior missions. Similarly, they reported that frequent communication with Flight Controllers disrupted their sleep.

Apollo 14

The sleep environment on the CM and the LM for the Apollo 14 mission was similar to that in the Apollo 12 mission, where the astronauts had hammocks available for sleep in the LM (Shepard Jr 1972). The LM landed on an uneven surface and settled at a 7-degree tilt for the duration of the mission. This reportedly caused the astronauts a great deal of discomfort and anxiety. One astronaut reported frequently looking out the window to make sure that the module was not going to tip over. The astronauts on the LM reported experiencing significantly more sleep disruption and pain than on prior missions, however it is unclear whether that was due to an uncomfortable sleep environment or to the near inversion of their sleep schedule.

Apollo 15

Mission planners made several changes to the sleep environment on the Apollo 15 mission. As in the Apollo missions after Apollo 11, the crew slept in hammocks, but they reported that the hammocks should be larger for future missions. Unlike prior missions, the crew was not required to wear their flight suits and instead were provided with a “constant wear garment” when they were inside the module. This change resulted in a significant improvement in sleep quality and duration while on the LM. In addition, the temperature was stabilized throughout the mission and the crew reported that the temperature was ideal for sleep. This crew was also provided with earplugs and mission planners established an environmental control checklist to aid in reducing noise pollution during sleep times. The windows were modified with

improved shades, but the crew reported that the light leaking through the window shade stitching caused sleep disruption. Although the improved sleep reported among Apollo 15 astronauts was attributed to a better sleep environment, this crew did not shift their schedule from their Earth-based habits, which may have also contributed to better quality sleep.

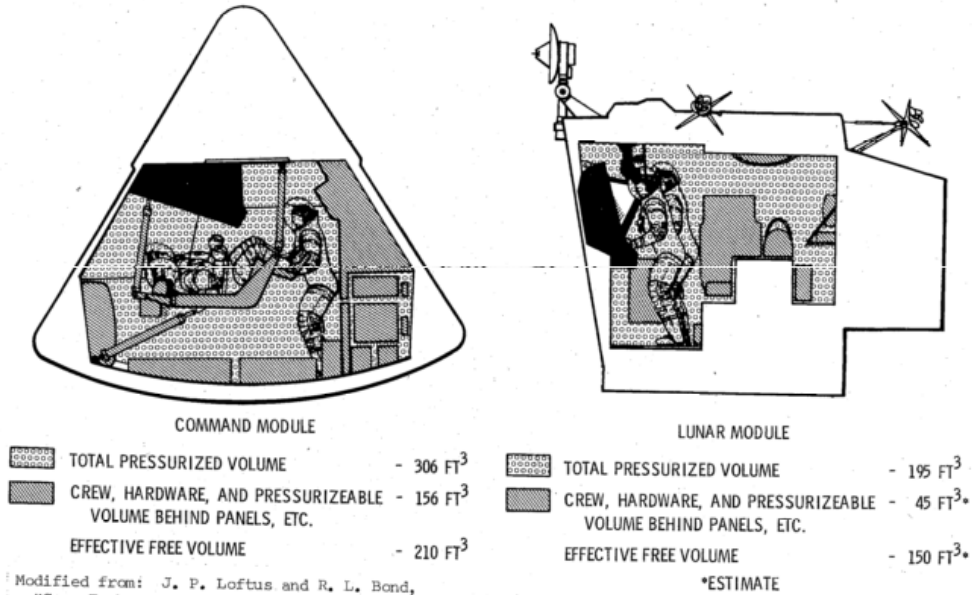
Apollo 16

Sleep on Apollo 16 was thought to be generally good. The first sleep period was around eight hours. Liquid cooled garments were provided to crew during Lunar sleep periods (three days). Only one astronaut wore the liquid cooled garments the first night, but both wore them the second and third night. The lunar module pilot took Seconal to aid in sleep during the first sleep period, but was awoken three times, twice by master alarms and once from a communication issue which created noise in his earphones (National Aeronautics and Space Administration 1972). During the traverse to and from the Moon, the astronauts found that the constant wear garment in addition to the sleeping bags was suitable for sleep. However, while the Lunar Module was operating on the surface, the Command Module cooled significantly for the remaining pilot, which resulted in the need for extra layers. Upon return of the other two astronauts, the Command Module rose in temperature.

Apollo 17

Unlike the crew of Apollo 16, the astronauts on Apollo 17 preferred to not wear the liquid cooled garments. The astronauts felt that they were too dirty and too tight-fitting. The constant wear garments were worn instead for sleep periods. All astronauts used Seconal as a sleep aid in at least some sleep periods. It was noted that changes to the flight plan likely affected the quality of sleep. The astronauts slept around six hours each day of the mission, except for the first day where only three hours was attained. The commander made a point to state that sleep periods should be scheduled for eight hours each day (National Aeronautics and Space Administration 1973).

Figure 29
VEHICLE VOLUMES



Modified from: J. P. Loftus and R. L. Bond, "Crew Tasks and Training," *Lunar Landing Symposium* (Houston, Texas: NASA-MSC, 1966).

Figure 9. Apollo Vehicle Volumes. Source: Jerry R. Goodman (2010).

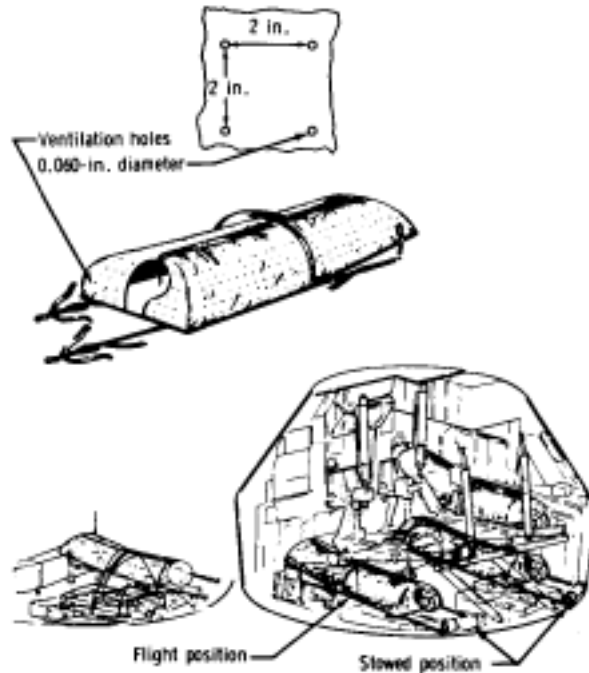


Figure 10. Apollo Command Module sleep restraints (reproduced from McAllister 1972).

LM SLEEP STATIONS

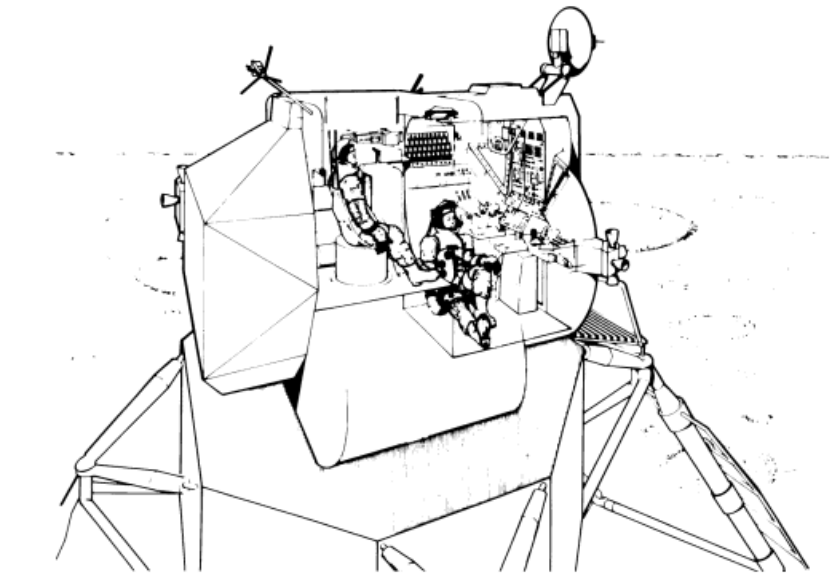


Figure 11. LM sleep station.

Source: <http://www.hq.nasa.gov/pao/History/SP-4205/images/c150c.gif>

Salyut

The habitable volume for Salyut 1, 3, 4, 6, and 7 was 90 m³ and 100 m³ for Salyut 5 (Portree and Center 1995). The atmosphere composition was comparable to sea level and had a psi of 13.5-16 (Daus 2006). The temperature could be set by cosmonauts between 15°C (59°F), and 25°C (77°F; Wieland 1994).

Aboard Salyut 1, cosmonauts used sleeping bags attached to the walls and on Salyut 3 they used a foldaway bunk for sleeping (Häuplik-Meusburger 2011). The sleeping bags were insulated with bed-sheet inserts and had air vents and fasteners that could open to release heat (Häuplik-Meusburger 2011). The Russian crew quarters, Kayutas, was introduced on Salyut 6. This configuration was carried forward to both Mir and the ISS Service Module (Broyan Jr. et al. 2008). The Kayutas sleeping facility was located in the widest portion of Salyut (Bluth and Helppie 1986). Despite this fact, it was reported that one cosmonaut's height, Valery Ryumin, caused problems. He had to strap his bed to the floor and tuck his arms in because he was unable to squeeze into his allotted sleeping area on the ceiling. The beds in Kayutas were heat insulated and also offered air vents with fasteners that could be opened for heat reduction (Bluth and Helppie 1986). For sleeping, the cosmonauts reported that they would usually take their clothes off and put on fur boots, because weightlessness prevents normal blood circulation to the feet and they reported that their feet would get cold (Bluth and Helppie 1986). There was minimal airflow on Salyut 6 and 7. Cosmonauts have reported that they felt like they were suffocating at times due to slow air movement (Bluth and Helppie 1986). In order to avoid breathing dust or mechanical particles during sleep, a special screening was developed to enclose the sleeping area (similar to a mosquito net). The noise levels in the living quarters on Salyut 6 and 7 were 35-40 dB for the day and 25-30 dB at night (Bluth and Helppie 1986), however, other reports suggest that the actual noise levels were much higher prompting a retrofit of some of the equipment during Salyut 9 (Kidger 1979 cited in Wilshire 1984). The individual crew quarters in Kayutas provided a 20cm window for the cosmonauts, which resulted in increased radiation exposure

(Broyan Jr. et al. 2008). It is possible that light pollution was problematic, but there are no reports documenting whether or not the cosmonauts felt this was a problem.

Sleep disturbance was prevalent during the Salyut missions, but may have related to the schedules that cosmonauts were required to work. On Salyut 4, the cosmonauts were scheduled to sleep only when they were out of radio contact with Moscow (Yegorov 1979). This led to a forced desynchronization between the cosmonauts' sleep opportunities and their circadian rhythms. Due to the sleep issues experienced by the crewmembers on Salyut 4, the crew schedule was changed for Salyut 6, where all crewmembers were scheduled to sleep during the Moscow night. It is also notable that during Salyut 6, cosmonauts were scheduled for a 9-hour sleep episode.

Salyut had many obstacles preventing ideal habitable conditions. The treadmill used by cosmonauts for exercise was reportedly noisy and even caused the entire space station to vibrate during use (Hendrickx 2002). Additionally, special space suits designed to be worn during exercise that would simulate gravitational effects by drawing blood to the legs had issues, which limited exercise in general. In terms of safety aboard Salyut, there were several notable occurrences including, a case of a fire that prompted cosmonauts to board Soyuz and prepare for a launch before the situation was put under control (Hendrickx 2002).

Skylab

The Skylab era featured four missions. Skylab I involved putting the station into orbit and included no astronauts, while Skylab II, III and IV each included crews of three astronauts. The atmosphere composition aboard Skylab was 72% O₂ and 28% N₂ with 5 psia (Daves 2006). The primary habitable environment was the Orbital Workshop (OWS). The OWS was a cylindrical container with a length of 15 meters and a diameter of 6.5 meters and a volume of 275 m³ (Belew and Stuhlinger 1973; National Aeronautics and Space Administration 1991). The total habitable volume of Skylab was over 360 m³ (National Aeronautics and Space Administration 1991). The OWS was created with the intention that crew members would spend the majority of their time there conducting experiments, making observations, eating, and sleeping (Belew and Stuhlinger 1973). The OWS featured individual sleep stations for each crewmember. The sleeping frames were attached vertically to the wall in each sleep compartment. The largest sleep compartment was 1.76 m³ and the smallest, 1.33 m³ (National Aeronautics and Space Administration 1974). The sleeping frame was designed so that it could be removed and placed in different locations if desired by the crewmembers (Gillespie and Kelly 1974). Ambient temperature in the OWS was maintained at 23.9°C (75°F; MSFC Skylab Structures 1974). The Skylab habitat, as a whole, ranged in ambient temperature from 20.1-23.9°C (69-75°F; Wieland 1994). Skylab's average acoustic levels was 58 dBA and a NC-55 (noise criterion) curve across the habitable volume; the sleep area had a NC-43 curve and 45 dBA (Allen and Denham 2011). During Skylab missions, crewmembers were allotted eight hours to sleep every day (Belew and Stuhlinger 1973). The sleep chambers were designed so that during sleep periods, astronauts could quietly leave their partitioned crew quarters without waking one another. However, noise from the waste management system, in particular the urine separators, was disrupting to the sleeping crew (MSFC Skylab Structures 1974). See Figure 12 for a view of an astronaut in his sleep chamber and Figure 13 for an overview of Skylab.

The sleeping environment aboard Skylab was viewed as a considerable improvement upon earlier spaceflight habitats. Skylab contained enough space, so that were designated areas

for working, exercising, eating, and sleeping (Frost et al. 1975). Despite these improvements, there were still challenges presented by both the environment and the workload. Operational demands often had astronauts completing tasks right up to their designated sleep period, creating difficulties with sleep onset as there was little time to relax (Stuster 1986). Each Skylab mission also involved a four-hour forward adjustment in sleep schedules a week prior to completion in order to prepare for re-entry and splashdown related activities (Frost et al. 1975).

Astronauts on pre-Skylab missions commonly complained of insomnia, and in some cases periods of sleep loss degraded crew performance. In response, Skylab astronauts completed a sleep monitoring experiment, MI33, which was the first objective measurement of sleep during spaceflight (Johnston and Dietlein 1974). The Skylab experiment was conducted by Frost and colleagues, who collected objective sleep measurements of EEG, electrooculography (EOG), and head-motion signals.



Figure 12. Astronaut Dr. Joseph Kerwin strapped into sleep restraint aboard Skylab.
Source: https://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=413

Skylab 2

During Skylab 2, a 28-day mission, 12 of the nights included in-flight monitoring of sleep (Frost et al. 1975). Sleep latency was reduced both in-flight and post-flight relative to pre-flight (Frost et al. 1975). Average in-flight sleep time was 6.04 hours. This was less than both pre-flight and post-flight average sleep times (6.9 & 8.5 hours, respectively; Frost 1976). Post-flight sleep time was also significantly greater than pre-flight and in-flight times (Frost 1976). Frost (1976) notes that the reduced in-flight sleep time was primarily due to a lower amount of time spent resting in general (Frost 1976).

Skylab 3

During Skylab 3, a 59-day mission, 20 nights included in-flight monitoring (Frost et al. 1975). No significant differences in sleep latency were found between pre-flight, in-flight and post-flight periods. Average in-flight sleep time was found to be 6.31 hours. Though this was

less than both pre-flight and post-flight average sleep times (6.4 & 6.58 hours, respectively), the difference was not statistically significant (Frost 1976).

Skylab 4

Crewmembers deployed on Skylab 4, an 84-day mission with 18 nights of in-flight monitoring, had varied sleep latency through the mission (Frost 1976). Sleep latency differed from the first half to the second half of this mission (21.4 min & 9.7 min, respectively; Frost 1976). In contrast to the trends in observed in Skylab 2 and Skylab 3, during Skylab 4, the average in-flight sleep time was greater than post-flight sleep time (6.69 & 6.53 hours, respectively), but still less than average pre-flight sleep time (7.29 hours), though these differences were not statistically significant (Frost 1976). During the first 19 days of the mission, rest periods were 1.2 hours less than the pre-flight average (Frost 1976).

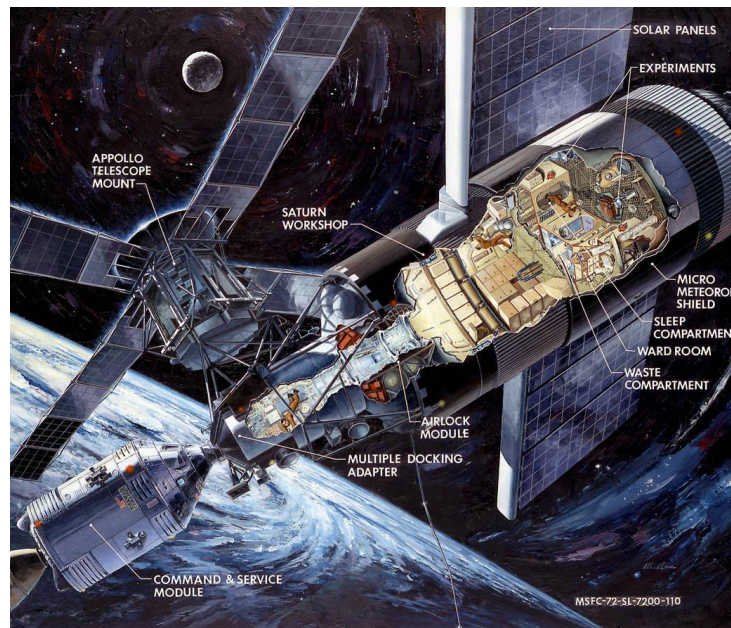


Figure 13. Skylab artist's concept.

Source: <https://www.nasa.gov/topics/history/features/skylabartistconcept.html>

Space Shuttle

The total habitable volume of the Space Shuttle varied, with each Shuttle having a slightly different design, but each was around 71.5-74 m³ (Wieland 1994; Young et al. 2011). With the addition of the Spacelab module, used in The Shuttle's Cargo Bay as a space laboratory, the habitable volume could be increased. The nominal ambient temperature range was 18.3-28.9°C (64.9-84°F) in The Space Shuttle and the Spacelab module was between 18.3-26.7°C (65-80°F; Wieland 1994). The atmosphere composition aboard Shuttle was 78% N₂ and 22% O₂ (psi=14.7; Daues 2006). During Space Shuttle missions, astronauts slept in various locations, including: middeck, flight deck, and the airlock. Astronauts slept in sleeping bags, sleep boxes, and flight deck chairs. Earplugs and eye masks were provided to astronauts to aid with sleep. STS-9 was the first flight that included the sleep station (Legler and Bennett 2011). A photograph of astronauts sleep aboard Shuttle can be seen in Figure 14.

Missions on The Space Shuttle exposed crewmembers to a 90-minute light-dark cycle due to passing around the Earth in low Earth Orbit (LEO). Due to this, light levels aboard The

Space Shuttle fluctuated to extremes. In one study, a high illuminance of 79,000 lux was recorded on the flight deck, with a low of 73 lux when the shades were drawn (Dijk et al. 2003). In contrast, the middeck, where astronauts primarily slept, had a recorded high of 93 lux and an average of 9 lux during periods of sleep. It is notable that these measurements were attained via sensors on the interior walls and do not necessarily represent the experienced luminance by the astronauts as they moved around.

Noise measurements were made aboard STS-2 using a noise criterion (NC) curve of 50 for work areas and a NC-40 curve for sleep areas. The flight deck was found to feature a noise range from 61-67 dBA; the mid-deck noise range was 68-87 dBA (Willshire 1984). These measurements exceeded the noise requirement limits in both locations. Improvements were made over time to lessen ambient noise. Objective noise levels aboard the Space Shuttle were gathered on STS-50. The middeck featured the lowest levels of background noise (dBA = 60; Koros et al. 1993). The recommended noise limit for the middeck at the time of the measurements was 68 dBA. Background noise levels for Spacelab and the flight deck were 61 and 64 dBA, respectively (Koros et al. 1993). The STS-50 crew complained about noise emanating from air flow in the flight deck aft (Koros et al. 1993). Notably, activity in the middeck by astronauts during sleep periods was reported by the entire crew as disrupting to sleep. One of the sources of disturbing noise was due to the opening and closing of lockers. Flynn-Evans and colleagues quantified sleep disturbance on Shuttle and found that 60% of crewmembers reported that their sleep was disturbed, with noise contributing to disturbance on 23.8% of nights, while sleep was reportedly disturbed due to crewmembers being too hot 18.6% or too cold 2.6% of the time for each (Flynn-Evans 2010; Table 6).



Figure 14. Astronauts resting aboard Shuttle. Source: On the Wings of a Dream: The Space Shuttle.

TABLE 6. SHUTTLE CREWMEMBERS' REPORTED CAUSES OF SLEEP DISTURBANCES

Reported cause of sleep disturbance	Percentage of disturbed nights			
	L-90	L-11	In-flight	R+7
Voids	50.0	49.0	42.1	38.8
Noise	21.4	11.9	23.8	11.3
Too cold	5.2	4.6	2.6	2.5
Other crewmembers	0.0	0.0	3.2	0.0
Too hot	5.2	2.6	18.6	5.0
Mission duties	5.2	6.0	10.0	10.0
Physical discomfort	12.3	9.9	10.9	11.3

Unpublished data from Flynn-Evans, Barger and Czeisler. Used with permission.

Beyond the challenges imposed by the habitation factors, astronauts were often required to dramatically shift their sleep schedules in order to fulfill duties. This process is referred to as "slam shifting" and sometimes involved shifts in sleep schedules of up to 12 hours (Dijk et al. 2003). Trouble sleeping during The Shuttle missions was reflected by astronauts choosing 'sleep' as the number one reason for pharmaceutical use (Putcha et al. 1999), which was further supported by Dijk et al. (2003) who found the most commonly used medication among astronauts aboard The Space Shuttle was sleeping pills. In one study, astronauts (N = 5) slept approximately 6.5 hours with a minimum as low as 3.8 hours a night (Dijk et al. 2003).

Aboard The Space Shuttle, the pilot and commander would sometimes sleep in their chairs on the flight deck (Dijk et al. 2003). Although some astronauts had access to a personal "sleep cabinet," it was more common that astronauts slept in either The Spacelab or middeck with the use of Velcro attached to the walls (Dijk et al. 2003). Shuttle sleep station provisions can be seen in Figure 15.

STS-115 was the first flight that used an Airlock Campout Prebreathe Protocol, which was used to prevent any episodes of "the bends" (i.e. decompression sickness) while on an EVA. Astronauts spent their sleep period in the Quest Airlock at a reduced air pressure (Legler and Bennett 2011).

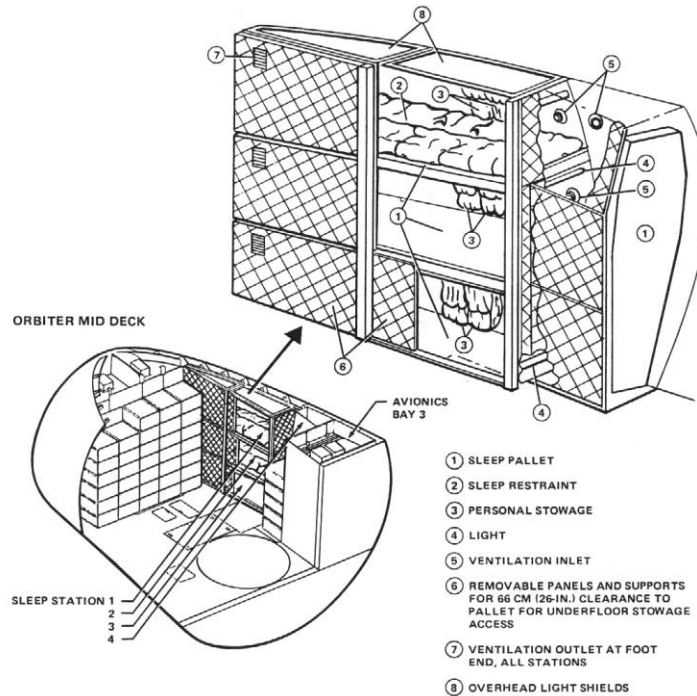


Figure 15. Shuttle sleep station provisions. Source: <http://history.nasa.gov/diagrams/shuttle.htm>

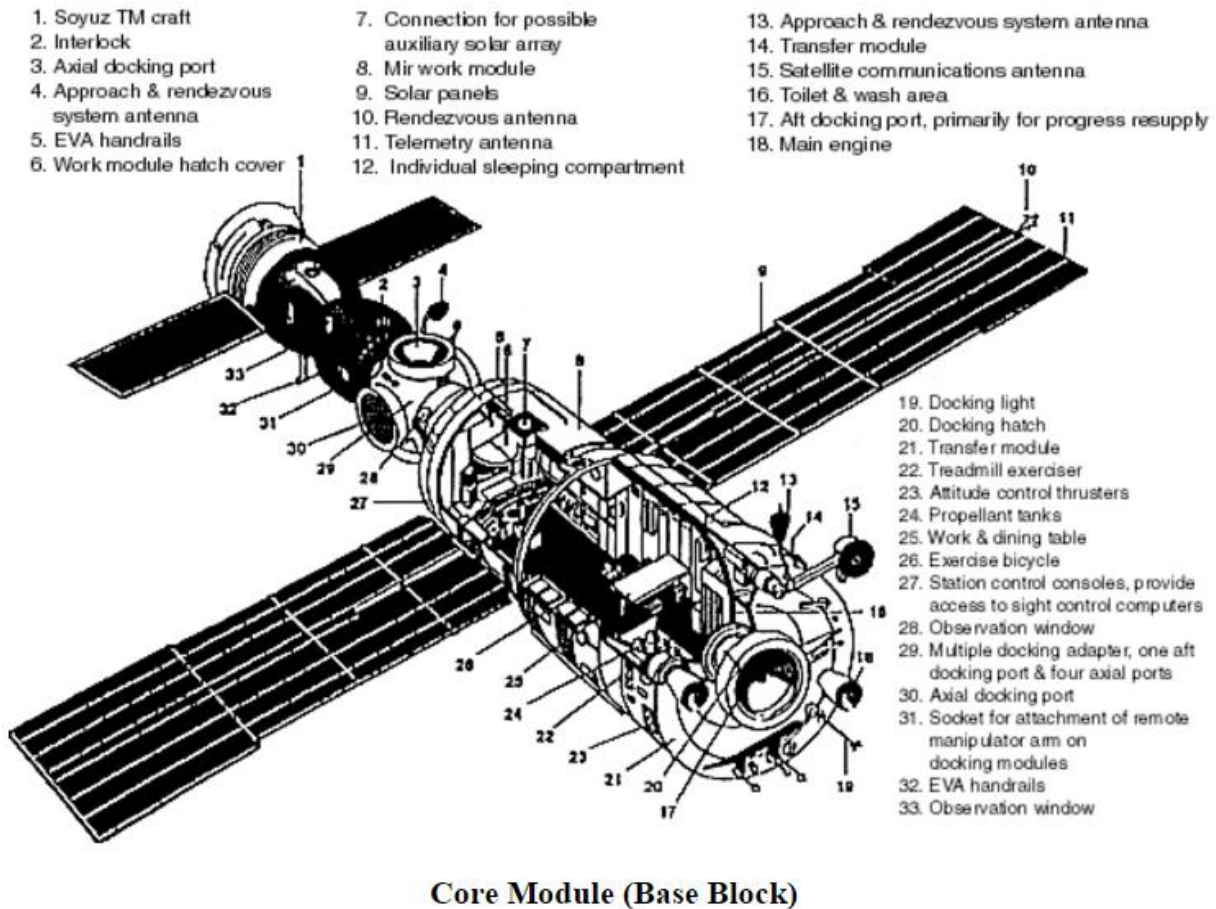
Mir

The Mir space station, like the International Space Station, was built in stages. Mir's base block (core module) had a habitable volume of 90 m³ (Portree and Center 1995). The Mir complex, which was comprised of Mir base block, Kvant, Kvant 2, and Kristall, with docked Soyuz-TM and Progress-M spacecraft, was 372 m³ (Portree and Center 1995). The core module on Mir had an ambient temperature range of 17.8-28.8°C (64-82°F) with a relative humidity of 20-70% (National Aeronautics and Space Administration). Mir's Atmosphere composition mimicked a sea-level atmosphere, with up to 78% N₂, 21-40% O₂ (psi = 6.8). See Figure 17 for an overview of the pressurized volume of space vehicles up to 1990.

The crew quarters, Kayutas, were used on Mir. Kayutas had two individual crew quarters with sleeping bags; additional crew would use hammocks (Häuplik-Meusburger 2011). Noise measurements were taken during the STS-74 mission, of the Shuttle-Mir era. The NC-50 curve requirement was surpassed in every location except the Kvant-2 airlock (Parsons).

In an interesting habitability-related occurrence, Mir experienced problems with its water recycling system and had too little water for crew showers. It was discovered that materials aboard Mir were absorbing water via the air's humidity (Wieland 1994). Materials used for sound and thermal insulation were particularly apt at absorbing water. In response, the water-soaked materials created a suitable home for bacteria, which fed on the adhesive binding the materials to the wall and eventually started dislodging materials and leaving an autotroph-filled green slime on the walls.

Mir Core Module



Core Module (Base Block)

Figure 16. Diagram of Mir's core module.

Source: <http://history.nasa.gov/SP-4225/diagrams/mir/mir-diagram-1.htm>

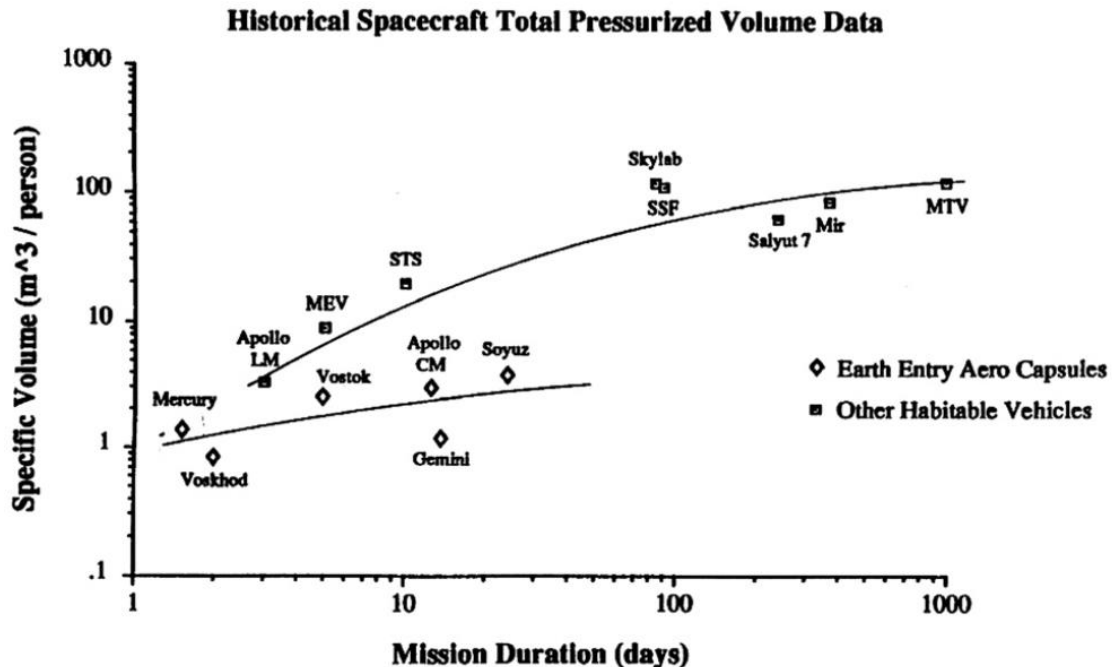


Figure 17. Pressurized volume per crew member and mission duration

Source: Sherwood & Capps (1990). Long Duration Habitat Trade Study: Space Transfer Concepts and Analyses for Exploration Missions.

Shenzhou

Shenzhou is a capsule style space vehicle built by the People's Republic of China. Shenzhou cabin diameter at its widest is 2.5m, making it larger than Soyuz TM which is 2.2m in diameter (People's Daily Online). The capsule has the capabilities to transport three astronauts on a mission (People's Daily Online).

International Space Station (ISS)

The International Space Station has a habitable volume of 388 m³ (National Aeronautics and Space Administration). For a summary of the Human Spaceflight Data Set as of July 18, 2006, see Table 7. An overview of spaceflight mitigations can be seen in Table 8.

The ISS has made notable improvements in the habitable space environment compared to previous space vehicles. For example, the cabin air assembly is programmed to reduce the temperature to 18.3°C (65°F) about one hour before sleep and is maintained at 22.2°C (72°F) during awake operations (Balistreri et al. 2007). The ISS has had two iterations of sleep chambers in the United States Orbital Segment (USOS). The first was The Temporary early Sleep Station (Espie et al.) and the second generation was Crew Quarters (CQ). In the Russian Segment is Kayutas, which has been used in both Mir and Salyut.

Kayutas. Kayutas, initially developed for use in Salyut 6 (Broyan Jr. et al. 2008), is the sleep station in the Russian Segment of the ISS. Kayutas has accommodations for two crew members (Broyan Jr. et al. 2008). Two of the Russian Segment modules have been found to have high acoustic levels. The Docking Compartment (DC-1) and Mini Research Module 2 (MRM2) had an ambient output of around 67 dBA (Allen and Denham 2011).

The Temporary early Sleep Station. The Temporary early Sleep Station was created to house astronauts prior to the completion of Crew Quarters and was located in United States Operational Segment (USOS) of ISS (Espie et al.). The habitable volume of TeSS was approximately 2.2 m³ and was able to accommodate one astronaut at a time (Goodman 2010; Keener et al. 2002). The inlet air temperature for TeSS was 12.8°C (55°F) and the general ambient temperature within TeSS was around 23.9°C (75°F; Keener et al. 2002). The estimated maximum CO₂ level near an occupant's head was 0.5% (Keener et al. 2002). TeSS was designed with openings for electrical cables and to allow external alarms to be heard, which resulted in the intrusion of some noise and light pollution within the sleep chamber. Some crewmembers reported discomfort due to the ventilation system in TeSS which was limited and did not allow for personal customization of air flow, which arrives from air ducts (Imhof et al. 2010).

Crew Quarters. A great deal of effort went into the design and implementation of the ISS Crew Quarters (CQ), located inside of the module Node 2. The ISS Crew Quarters were designed to fit in a standard rack on the station. This allows for 2.1 m³ of internal space. The door to CQ was designed to minimize transmission of light and noise from the outside of the chamber to the inside. Inside Node 2, the sound levels are below the NC-50 requirement, with the four individual sleep stations within Node 2, experiencing sound levels ranging from 36.8 to 43.8 dBA (Allen and Denham 2011). The door opens to 51 cm x 102 cm and has been reported to be acceptable to the crew (Broyan Jr. et al. 2008). CQ offers ventilation control to its inhabitants, which flows towards a crewmember's head for maximum efficiency in cooling if a crewmember is in a sleeping bag (Broyan Jr. et al. 2008). However, CQ can only adjust temperature by increasing air flow rate and has no other cooling method (Broyan Jr. et al. 2008). The ambient noise level also increases with additional air flow rates (Broyan Jr. et al. 2008). CQ receives air from ventilation in front of the individual sleep stations. Node 2 typically fluctuates between 18.3°C (64.9°F) and 20°C (68°F) and CQ can reach temperatures as low as 20°C (68°F). CQ also features florescent lights that can be dimmed and shaded (Broyan Jr. et al. 2008). The sleeping bags have two D-rings for its attachment and offer 125 Velcro attachments (Broyan Jr. et al. 2008). During the development of CQ, many design changes were made in response to user feedback. One such design change involved the fact that the larger unit was preferable in order to provide more head room. Improvements affecting CQ over the years have included changes to ISS's Pump Package Assemblies, which were modified to reduce noise output (Allen and Denham 2011). A photo of CQ can be seen in Figure 18.



ISS026E012169

Figure 18. Crew Quarters on the International Space Station. Source:
http://www.nasa.gov/mission_pages/station/multimedia/gallery/iss026e012169.html

TABLE 7. SUMMARY OF THE HUMAN SPACEFLIGHT DATA SET AS OF JULY 18, 2006

Spacecraft Type	Category	Number of Missions	Max. Mission Duration	Min. Mission Duration	Max. Volume Per Crew	Min. Volume Per Crew	Max. Crew	Min. Crew
Mercury	Capsule	6	1.43	0.02	1.70	1.70	1	1
Gemini	Capsule	10	14.00	0.21	1.28	1.28	2	1
Apollo CM with and w/o LM	Capsule	11	12.75	6.00	4.27	2.22	3	3
Apollo LM Lunar Landing	Capsule	7	3.21	1.00	3.33	3.33	2	2
Apollo-Soyuz	Capsule	1	9.04	9.04	3.33	3.33	5	5
Vostok	Capsule	6	5.00	1.04	5.73	5.73	1	1
Voskhod	Capsule	2	1.08	1.00	2.87	1.91	3	2
Soyuz	Capsule	42	14.00	0.43	1.28	1.28	2	2
Shenzhou	Capsule	2	5.00	1.00	17.00	8.50	2	1
Space Shuttle	Shuttle	89	17.67	2.25	35.75	8.94	8	2
Shuttle-Spacelab/SpaceHab	Shuttle	25	16.90	4.00	42.70	14.66	8	5
Skylab	Station	3	84.00	28.00	120.33	120.33	3	3
Salyut	Station	17	237.00	16.00	55.25	33.50	3	2
Mir	Station	25	437.75	72.82	181.35	45.00	3	2
ISS	Station	12	195.82	128.86	201.13	85.17	3	2

Note: Duration values are in days; Volume values are in cubic meters. Volume values were calculated as a function of crew size.

Reprinted from: Cohen (2008), "Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume," with permission from SAE International.

TABLE 8. SPACEFLIGHT REVIEW TABLE: MITIGATIONS

Mitigations							
Mission	Sleep Location	Volume/Size	Ambient Temperature	Comfort Objects	Airflow/Quality	Noise	Light
Vostok	Not Known	~2-3 m ³	Cosmonaut controlled: 12-25°C (53.6-77°F) Relative humidity: 30-70%	Not Known	Sea-level atmosphere (O ₂ /N ₂ mixture) 14.7 psi	Not Known	Not Known
Mercury	Strapped to couch	Habitable volume: 1.02 m ³	Mercury-Atlas 7: 27.8-42.2°C (82-108°F)	Not Known	Atmosphere composition: 100% O ₂ (5 psia)	Not Known	Not Known
Voskhod	Not Known	~2-3 m ³	Cosmonaut controlled: 12-25°C (53.6-77°F) Relative humidity: 30-70%	Not Known	Sea-level atmosphere (O ₂ /N ₂ mixture) 14.7 psi	Not Known	Not Known
Gemini	Strapped to couch	Habitable volume: 2.55 m ³	Not Known	Not Known	Atmosphere composition: 100% O ₂ (5 psia)	Not Known	Not Known
Soyuz	Not Known	Orbital Module: 6.51 m ³ Descent Module: 3.99 m ³	Cosmonaut controlled: 12-25°C (53.6-77°F) Relative humidity: 30-70%	Not Known	Atmosphere composition: sea-level atmosphere (O ₂ , N ₂ mixture; psia = 13.7-16.4)	Not Known	Not Known
Apollo 11 12 13	Command module / lunar module	Command Module's habitable volume: 5.95 m ³ Lunar Module's habitable volume: 4.5 m ³	Apollo 7-17: Command Module cabin temperature average: 63-73°F (low: 43°F; high: 81°F) Nominal Range: 21-24°C (70-80°F); relative humidity: 40-70%	Command Module: sleeping bags, couches, "curled up," hammocks	Command Module atmosphere composition: 100% O ₂ (during launch: 40% N ₂ , 60% O ₂) Lunar module atmosphere composition: 100% O ₂ (both habitats: 5 psia)	Not Known	Not Known

Salyut	Large-diameter work compartment, on the wall; orbital compartment	Salyut 1,3,4,6,7 habitable volume: 90 m ³ Salyut 5 habitable volume: 100 m ³	Temperature could be set by cosmonaut between 15°C (59°F), and 25°C (77°F)	Sleeping bags with sheet inserts, bunks	Atmosphere composition: sea-level atmosphere (O ₂ , N ₂ mixture; psi = 13.5-16)	Not Known	Not Known
Skylab	Private Crew Quarters in OWS	Smallest CQ: 1.33 m ³ Largest CQ: 1.76 m ³ OWS habitable volume: 275 m ³ Total habitable volume: 360 m ³	OWS: 75°F Habitat Range: 20.1-23.9°C (69-75°F)	Sleeping frames, blankets, pillows, sleep restraints	Atmosphere composition: 72% O ₂ , 28% N ₂ (5 psia)	Skylab acoustic Levels (three missions) were NC-55, 58 dBA averaged over the habitable volume and NC-43, 45 dBA in the sleep area	Not Known
Shuttle	Varies: middeck, flight deck, airlock	Habitable volume: 71.5-74 m ³	Spacelab: 18.3-26.7°C (65-80°F) Nominal Range: 18.3-28.9°C (64.9-84°F)	Sleeping bags, sleep boxes, flight deck chairs	Atmosphere composition: 78% N ₂ , 22% O ₂ (psi = 14.7)	Mid-deck: NC-64 and 68 dBA Flight-deck: NC-58, 63.4 dBA	Shades over windows; eye covers provided
Mir	Individual cabins in Mir base block	Service Module: 2.4 ft x 2.8 ft x 6.2 ft Habitable volume: 90 m ³ Mir Complex (Mir base block-Kvant, Kvant 2, and Kristall) with docked Soyuz-TM and Progress-M spacecraft) habitable volume: 372 m ³	Core Module: 17.8-28.8°C (64-82°F); Relative humidity: 20-70%	Two Sleeping bags; other crew would use hammocks	Atmosphere composition: sea-level atmosphere, up to 78% N ₂ , 21-40% O ₂ (psi = 6.8)	Not Known	Private sleeping cabins had windows

ISS	Crew Quarters, Kayutas, Temporary early Sleep Station	TeSS (~2 m ³) CQ: 2.1 m ³ Habitable volume: 388 m ³	CQ: >20°C Node 2: 18°C	Sleeping bags	CQ: Personalized air flow; .42-5.1 m ³ /min of air flow TeSS: Inability to direct air flow reported as a source of discomfort Atmosphere composition (American segment): 21.5% O ₂ , 78.5% N ₂ (psia = 14.7) Atmosphere composition (Russian segment): similar to Mir	CQ: Changes to Pump Package Assemblies (PPAs); At all speeds the CQs are close to the NC-40 continuous noise requirement for sleep CQ: 36.8 to 43.8 dBA; (quiet) TeSS: Acoustic blankets were used to mitigate noise; astronauts reported that it was too noisy	Zvezda has windows TeSS: light pollution was a reported problem
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Note: psia = pounds per square inch absolute

QUALITATIVE INTERVIEWS WITH SUBJECT MATTER EXPERTS

Interview with Navy Personnel

Navy SME 1 is a Navy scholar with extensive experience in fatigue research. In addition to Navy SME 1's scholarly work, Navy SME 1 has also spent time on small to carrier size ships for up to five weeks at a time.

Navy SME 2 is also a Navy scholar, drawing upon 25 years of Naval experience. Navy SME 2 has served as a Commanding Officer with primary experience aboard Fast Attack Ships. In particular, Navy SME 2 has extensive knowledge in human performance in Naval operational environments.

Navy SME 3 is a lieutenant commander of the US Navy. Navy SME 3 has held several Navy leadership positions in the Navy.

Navy missions are similar to spaceflight operations, whereby there are often long durations of time when assignments include maintenance of the vessel, followed by episodic bouts of high activity associated with pulling into port or performing a war maneuver. Boredom can be a tremendous problem, particularly for smaller teams, and can exaggerate the stress experienced by crewmembers during episodes of high activity.

The typical naval deployment is currently 8-9 months, however, the US Navy fleet are designed for "Underway Replenishments", where food and fuel are transferred from a supply ship to a warship, and could be continually lived in until the ship needed to be pulled in to dry dock for repairs. Given the size of some Navy ships, it is possible for individuals to work and live below deck for days or weeks at a time, this is often referred to as "mole mentality." Sometimes fellow crewmembers recognize this state and suggest that an individual spend some time topside in order to gain some sun exposure. Caffeine use is prevalent among Navy personnel. Energy drinks are often consumed by young crewmembers, while coffee is more frequently used by older crewmembers.

There are very diverse sleeping quarters across naval environments. Most ships have multiple bunkrooms. They are divided between males and females, but are not organized by schedule, so there is frequent disruption from individuals coming into the bunkroom for personal items while others are sleeping. There are generally fewer people assigned to the female bunkroom, given the ratio of men to women on a typical Navy ship. Despite this, crewmembers are provided with a very limited amount of personal space within the bunkroom whatever the available volume may be.

There have been some circumstances where the original design of a vessel was inadequate for sleep habitability. For example, the Littoral Combat Ship (LCS) was designed for two females to be in one room and included two foldaway sleeping racks. However, it was later realized that more crewmembers were needed aboard the ship. As a result the bunkrooms were retrofitted to accommodate bunks for six individuals in a space that was originally designed for two. The retrofit of the LCS involved installation of cloth curtains to divide personal space and individual bunks separated by a narrow aisle that is less than an arm's length distance from one another.

The standard issue sleep bunk includes a mattress comprised of a dense cotton-like material, a pillow, sheets and a blanket. There is a thin curtain that can be drawn to enclose the bunk space, but it does not provide insulation, sound attenuation or protection from light

pollution. Crewmembers are not supposed to modify their sleeping environment, because all of the standard issue items have been tested for use on a ship and have specific flammability requirements. Although crewmembers are not supposed to bring their own supplies, many crewmembers find the bunk space uncomfortable and bring foam toppers and personal bedding for their bunks. Many also bring thick curtains to hang along the side of their bunk to provide better privacy, sound attenuation and to block out light. In addition, many of the curtains that crewmembers bring themselves are specifically made with pockets to house personal belongings. Without these pockets, crewmembers have limited space to store personal belongings.

Navy ships tend to be very cold in berthing spaces. There is no personal temperature control on Navy ships. In some cases, crewmembers will bring additional items to keep warm.

The berthing spaces for officers typically accommodate two individuals and include a small space for a desk. The Executive Officer and Commanding Officer typically have their own private sleeping quarters.

Commanding Officer crew quarters may have a window, but typically there is no outside light in berthing compartments. However there is a lot of light pollution from flashlights and phones in berthing compartments. There are constant checks of lights in berthing compartments, which can disturb sleep. There are small florescent lights available for reading in bunks.

A great deal of light exposure is based on where people work. In one case where crewmembers were working night shifts, people who worked below deck stopped smoking, because they could only smoke above deck and they 'didn't want their clocks ruined by finding out what time of day it really was'.

Navy SME 2 stated that the sleeping quarters in ships have changed over time. Ships commissioned before World War II tended to be all metal, without any wood, and you could see all of the piping. Navy SME 2 noted that newer ships have slightly larger bunk rooms and that the pipes are enclosed in the walls, making the visual appearance of the space more similar to a finished room.

Hot bunking, which is the practice of two or more alternating shift crewmembers sharing a space, primarily only occurs with submariners. However it can occur in surface vessels when areas within a ship are being situated or repaired. Privacy is a really big issue with hot bunking and people do not like it.

Noise is a constant issue aboard naval vehicles. Noise can be categorized into external noise and internal noise. External noise includes: mechanical noise, air containers, people working, and certain areas being busy during certain times (dependent on shift schedule). Internal noise includes: snoring crewmembers, individuals on different shifts entering the room to get personal items, individuals in the bunk room listening to music, watching television and talking.

External noise can be continuous or intermittent. Aboard aircraft carriers, crew who sleep under the 'trap' feel the rumbling of the steam aircraft catapult, which is used to assist in aircraft launch. The steam catapult during launches, the wires and hook during landings, and jet engines all create a lot of noise. Noise from the carrier deck can be extremely disruptive and was described as sounding similar to an explosion every time an aircraft launch or landing occurred. It was also noted that on aircraft carriers, berthing compartments tend to be closer to the deck,

which leads to an even higher decibel level during sleep. The level of noise that crewmembers experience is associated with noise-induced hearing loss, especially on carriers.

External noise can also emanate from alarms and speakers. The public announcement (PA), or 1Main Circuit (1MC), provides announcements throughout all shifts and announcements are not suppressed in the bunkrooms. Crews find it very difficult to manage this need to hear announcements of importance with the need to sleep through announcements that are not important. Crewmembers can use earplugs, but many individuals have a fear of oversleeping or missing an important announcement while wearing them.

Internal noise, that is noise emanating from within the bunkroom, can also be a problem. Navy SME 1 described a personal experience where Navy SME 1's sleeping quarters were adjacent to a hallway with a soft drink machine. Navy SME 1 reported that you could hear intermittent noise from cans dropping out of the machine 24 hours a day. Navy SME 1 also reported that the sound of steel-toe boots hitting the floor would amplify the sound typically generated by an individual walking down a hallway.

In addition, many bunkrooms are designed so that the beds can be lifted and stowed out of the way or so that they can be lifted to access a storage compartment below. The sound of the bunks being lifted and released can be a noisy process and can be especially disruptive if the bunk slams down. This type of noise is a frequent disruptor due to the number of individuals sharing a bunkroom.

Air quality can be a major issue on Navy ships. Fumes and odors are ever-present and engine spaces often have noxious fumes emanating out. Additionally, body odor from crewmembers has been reported as an issue, particularly in the berthing areas. Humidity is typically not an issue, however, air ducts can 'blast' cold air, which can be uncomfortable.

Ship motion is also disrupting to sleep. During combat missions individuals can feel safety concerns and stress related to both previous harrowing missions and exposure to noises that could work as triggers for emotional distress.

Navy SME 1 stated that in his opinion the three most critical factors to habitability to consider are privacy ("in order to prepare for sleeping and to cool down"), ship motion, and external noises.

Interview with a Commercial and Military Pilot

Aviator SME is a commercial pilot with more than thirty-four years' experience as a rated pilot. The aviator SME was commissioned in the United States Air Force in the early 1980s. Aviator SME's career began as a pilot training student. A Distinguished Graduate of F-16 training, aviator SME eventually transitioned to the United States Air Force Reserve. Aviator SME retired as a Fighter Squadron Commander with over 3000 hours in Fighter and Attack aircraft, including 88 combat missions in the F-16. Aviator SME has been flying for a major commercial airline for more than two decades. Aviator SME holds Flight Engineer rating's on the B-727 and DC-10 aircraft as well as Airline Transport Pilot rating's on the B-757, B-767, and B-777 aircraft. Aviator SME currently flies ultra-long-haul passenger routes on the Boeing 777-200 and 777-300.

Aviator SME has slept in a variety of locations during tenure as a commercial airline pilot. Aviator SME has slept in designated sleep bunks, business class seats that lay flat, first class seats that lay almost flat, and economy cabin seats that offer a modest recline. It was

reported that aviator SME finds the bunk spaces to be the most comfortable. Although the lie flat seats allow for sleeping in the horizontal position, they do not allow for much movement during sleep. Aviator SME reported that in lie flat seats it is difficult to sleep on one's stomach or side due to pressure placed the lower back. It was reported that sleeping in any seat elsewhere in the cabin leads to poor quality sleep, even when passengers are sleeping, due to trying to sleep in an elevated position and due to noise and movement from passengers.

Aviator SME reported that the size of bunks and orientation of bunk spaces vary from aircraft to aircraft. Each type of bunk presents different benefits and challenges. Aviator SME finds that the bunk aboard a 777-300 is a little cramped to get into, but felt there was enough space for sleep once laying down. In contrast, the interior dimensions of the lower bunk in a 777-200 are smaller with less overhead room. Aviator SME said that sometimes bunk spaces are a little smaller than guidelines recommend, because the FAA will sometimes provide a waiver for size requirements of a bunk space if the area is within a couple of inches of the designated space goals.

The amenities in the bunks are similar between aircraft. Each bunk has a curtain and door to buffer sound and to block out light and noise. Aviator SME reported that the 777-200 mattresses are thin and hard, which makes them uncomfortable. Aviator SME said that most pilots will take a mattress pad and several blankets from the passenger cabin and lay them on the bunk for more padding. Aviator SME reported that pilots usually also bring multiple pillows from the passenger cabin due to inadequate pillows in the bunk. Some aircraft have better quality mattresses with more padding, but pilots usually lay blankets down on top of the mattress due to issues with cleanliness. Although aircrafts are serviced after each flight, only the bedding is thoroughly cleaned and replaced, while the interior of the bunks typically do not get a thorough cleaning. This leads to the buildup of dirt and dust in the bunk. Some pilots cannot sleep in the bunks due to dust allergies and those that do use the bunks cover as much of the mattress as possible with blankets to minimize the disturbance of dust when sleeping in the bunk.

Privacy concerns influence what pilots wear in the bunks. Most pilots will leave their uniforms on or partially on during sleep in order to be able to respond quickly in an emergency. Aviator SME will sleep with pants on, only removing the uniform shirt, which is not how aviator SME sleeps at home. Taking more clothes off would delay response time in an emergency, but creates a trade-off with comfort as the pants create uncomfortable friction.

Aviator SME felt that noise was the most significant obstacle to quality sleep on a flight. The 777-300 has bunks in the top section of plane, located above first class. Aviator SME feels those bunks are better for sleep because they are isolated from noises in the main cabin and wind passing over the exterior of the aircraft creates white noise. In contrast, the 777-200 bunks are next to the galley. The flight attendant jump seats are located on the outside of the bunk on the 777-200, and because they are spring loaded, they often slam against the wall and make a lot of noise in the bunk. Aviator SME said the bunk was designed in a way that it ends up amplifying the sound of the seat slamming, acting like a "sound chamber." Similarly, in some aircraft the flight attendant intercom or lavatory are located near the bunk, which can cause significant noise disruption during sleep.

The PA system can also be disruptive to pilots in the bunk. Aviator SME noted that the operating pilots control whether PA announcements are transmitted to the bunk or to passengers. Aviator SME said that this is so that in the event of an emergency, the operating pilots can reach

the resting pilots. Sometimes the operating pilots will not realize that they are transmitting messages to the bunk and will accidentally wake resting pilots by making general announcements meant for the passengers.

In order to mitigate the impact of noise on his sleep quality, Aviator SME reported often wearing headphones for periods of sleep. The headphones play white noise from a phone app. Aviator SME feels that the headphones playing white noise cancel out 80-90% of the noise disturbances. Aviator SME stated that blocking out noise is central to staying in deep sleep and getting quality rest.

The curtains in the bunk do a good job at blocking out light. The bunk facility features an overhead light and a reading light that can be switched on/off. There are small indicator lights present in the bunk that other pilots cover up with tape during sleep, but aviator SME is not bothered by the indicator lights. Eye masks are available for pilots to aid with sleep, but aviator SME felt they were more bothersome than helpful.

The bunks allow for some climate control. Each bunk has a thermostat that can be controlled by the occupant. Aviator SME reported preferring the room to be cold for sleep and keeping the thermostat on the coldest setting possible. Aviator SME would rather use a few extra blankets versus being hot.

Aviator SME reported that there are generally no issues related to the intrusion of smells or 'stuffiness' in the sleep bunk. There is an airflow vent directly above the head of a pilot in the bunk. This vent can be open/closed and directed to suit a pilot's needs; for example, the vent can be rotated, so that it does not blow in the face but still creates air flow. Aviator SME noted that there are issues related to air quality that stem from altitude differences. Aviator SME reported that when aircraft fly at lower altitudes, they are more humid, which makes it easier to sleep. Aviator SME said that the pilots who fly the 787 feel that their sleep quality is much better than in the 777 due to the higher humidity and lower altitude. In order to mitigate the negative effects that come from working and sleeping in a dry environment, aviator SME reported drinking a lot of water throughout a flight.

Movement from the aircraft does typically disrupt sleep. Aviator SME noted waking up during light turbulence, defined as bumpiness accompanied by slight erratic changes in altitude and/or attitude, but can usually go back to sleep if the air stays smooth. Aviator SME reported having never been on a rest break during severe turbulence, defined as large and abrupt changes in altitude and attitude, with momentary loss of control, but has been the operating pilot during severe turbulence while others are on rest breaks. Aviator SME said that pilots who are in the bunks during severe turbulence state that they have to brace their arms and legs against the ceiling of upper bunk to keep from being thrown around the bunk, even when cinched tight. They are unable to leave the bunks during such episodes and sleeping is impossible.

Military Experience

Aviator SME spent 27 years in the Air Force, flying F16, and A10 aircraft during five combat tours. During this time, Aviator SME was exposed to many different sleep situations.

During deployment aviator SME would sleep in air-conditioned tents near a runway and cargo ramp. The pilots slept on army cots with a thin layer of foam and a sleeping bag. It was stated that while Aviator SME isn't sensitive to the comfort a sleeping surface, that this bedding was comfortable. Aviator SME felt that noise caused the biggest disruption to sleep due to 24-

hour operations at the bases. Aviator SME said that cargo aircraft would fly in and leave their engines running in order to take-off after dropping cargo. This often led to so much noise from plane engines running near the sleep space and from frequent take-offs and landings that achieving quality, restorative sleep was impossible.

Temperature was also an issue during deployment due to the hot climate. Aviator SME said that when the air conditioners were running the sleep environment was adequate, but when they broke, the temperature would quickly rise to over 100°F, making sleep impossible. Aviator SME stated feeling that noise and temperature control are the biggest factors that facilitate sleep.

Aviator SME said that the experienced sleeping environments were not sterile like at home, but felt that they were suitable for sleep. Aviator SME noted that on one deployment the base was mortared and shelled multiple times a day and at night. Noise from the explosions would wake aviator SME and it would be difficult to go back to sleep. In these circumstances, aviator SME would get so fatigued that sometimes air base attacks would be slept through. Aviator SME noted that there aren't really any countermeasures sufficient to promote sleep in those situations, but that having a healthy diet and regular exercise help improve sleep quality in anxiety-inducing situations. Aviator SME also noted that the majority of airmen would take zolpidem in order to get quality sleep during deployment.

Even with the use of medication, aviator SME stated sometimes not realizing the level of fatigue being experienced until returning home. It was reported that after a 90 day deployment of sleeping 3-4 hours each night, aviator SME slept 18 hours a day for four days upon returning home.

Interview with Oilrig Engineers

Oilrig SME 1 began working in the oil field in 1993 after a tour in the Army. Oilrig SME 1 has held several different positions for three different companies and has worked on fixed leg or floating oil rigs for nine years.

Oilrig SME 2 has been working in the oil field for over 20 years. Oilrig SME 2 has worked on many different types of offshore rigs including platform rigs, jack-up rigs and semi-submersible rigs where the accommodations varied widely in size and quality.

The habitable environment on an offshore rig varies based on the design of the platform. Shallow water fixed platforms have cramped quarters and little communication. Facilities on the platforms are often portable, with bunks stacked as much as three high. In contrast, deep-water vessels are large, with new, better habitability and are the size of ocean cruise liners.

The deployment to a rig varies by individual. Some people are on for 28 days, then off for 28 days, some are on for 14 days and off for 14 days. Some individuals are deployed for an indefinite amount of time, "until the job is done." A 12 on, 12 off schedule is typical for the rig crew, although some individuals have to work shifts up to 16 hours a day. Contractors will come in and work for close to 72 hours straight and then leave. These individuals just catch naps whenever they can.

On most rigs individuals have a private bedroom, but up to four rooms will share one bathroom. Senior staff will often have a private bathroom. Many of the sleep rooms are small, with little space for personal items, although some of the newer rigs have sleep rooms "the size of a nice office" for everyone. Hot bunking or "hot sheeting" used to be a common practice on bunks, but is rarely done at the present time. Each rig has catering crews that clean the rooms

and take care of meals for the crew. The bedding that is provided is not very comfortable and most individuals bring their own pillows and blankets. Some of the mattresses were described as being “horrible” for sleep and as a result crew who are deployed for long durations of time will often bring their own mattress. Both oilrig SMEs emphasized that providing a uniform sleep space does not work. Everyone has different needs and sleep accommodations should allow for a flexible, customizable sleep environment.

Oilrig SME 1 stated that everyone needs to have a place to get away, be alone and not be disturbed. Oilrig SME 1 said that it is very important to be able to possess certain things and have your own space even if it’s just a bed in a shared room. Oilrig SME 1 noted that having one’s own space helps with morale. Oilrig SME 1 said that you don’t feel as important when you are sharing a space.

The rooms have windows with pull down airplane-like shutters. Both oilrig SMEs agreed that it is not a good idea to have windows in dedicated sleep spaces. They both felt that it is very important to have a dark environment for sleep, particularly when one is required to sleep during times when the sun is out.

Erratic noises are a problem, particularly as they relate to other crewmembers. Individual differences in sleep timing and leisure activities result in noise from awake crewmembers disturbing sleeping individuals. It is also a big problem when one crewmember snores, because that disrupts the sleep of everyone in the area. Some machine noise acts as white noise and is not a problem for sleep, but some machines vary in pitch or volume, which causes sleep disruption. There are generally more noises that could disrupt sleep during the day, when helicopters are landing and there is generally more activity. This can be a problem for people who have to work at night. Earplugs help as a mitigation against noise, although some people find them uncomfortable to use. The alarms are loud and piercing and some alarms have flashing lights, so they can easily be heard through the earplugs.

Temperature fluctuates by time of day and the area where one is stationed on the rig. The temperature in interior rooms can be widely different than the temperature in exterior rooms. Most individuals do not have control of the ambient temperature and the rooms are generally perceived as cold, although not so cold that sleep is disrupted. Individuals will customize the temperature of their sleep environment by modifying their bedding.

There are no notable issues associated with air quality, but personal hygiene and body odor can be a problem that results in sleep disruption.

Both oilrig SMEs offered many suggestions for creating an optimal sleep environment in an isolated and confined environment. Oilrig SME 1 remarked that “A poor sleep environment is a form of torture.” They suggested that maintaining an appropriate light-dark cycle and staying on schedule would be key to future expeditions. They suggested that they would want the lighting to turn on and off with a regular schedule to maintain a connection to the “day.” They said that it would be good to have a manual override of the lights, but that having a replication of a regular light-dark cycle would help keep everyone sleeping well. They felt that when shiftwork is necessary, individuals should be given very specific schedules, because erratic schedules lead to sleep disruption. They also felt that sleep spaces should be located away from common spaces in order to reduce sleep disruption due to other people.

They recommended that the habitable environment should allow for expression of individual differences. They said that they have observed that unpredictable events can cause a great deal of stress. For example, they said that on one work rotation they ran out of soda after five days. As a result, people started complaining and morale went down. They notice that different crew respond to mental and physical stress in different ways and that individuals need their own private environments. They also felt that personalization of the sleep environment was very important in reducing stress.

Interview with Sleeping Bag Design Team Engineers

The JSC sleeping bag design team conducted a trade study on sleeping bag design. With the goal of improving upon the sleeping bag design currently used on the International Space Station (ISS), the team reviewed different sleeping options including COTS (commercial off the shelf) and a wide array of sleeping bags (63 in total). Through this process they down selected to a few of the most promising candidates. Ultimately none of the options fully met the criteria specified for the ISS environment. Two common problems encountered with the candidates were that the insulating materials had allergens and were too warm.

Prior versions of the spaceflight sleeping bags have featured metallic rings where the sleeping bag connects to the wall. This design created frequent noise complaints. The new sleeping bag rings will be made out of plastic to eliminate this particular issue. Approximately a quarter of the astronauts reported to the design team that use ear plugs to reduce noise levels while sleeping.

Temperature regulation has been a primary concern in the design of the sleeping bags. Most of the time the ISS temperature fluctuates around mid-seventies degrees Fahrenheit. As a result, the sleeping bags that were used on Shuttle (a colder environment) were too warm.

American astronauts have been using the Russian sleeping bags for many years on ISS. Crewmembers reported some small problems with these bags. For instance, astronauts would cut off some parts of the sleeping bags deemed unnecessary (e.g. straps). The crewmembers also generally reported that these bags were also too warm. Due to the narrowness of the Russian sleeping bag, taller crewmembers reported that there was not enough room in the sleeping bags to sleep with the knees up towards the chest, which is one of the favored sleeping positions by astronauts. Despite these issues, the Russian sleeping bag is generally well-liked. The undertaking of designing the new sleeping bag entailed incorporating many of the well-liked features in the Russian sleeping bag while adding a few changes and more customization for the crew.

In researching the sleeping bag re-design, the team found that the Apollo missions were the first missions where accommodations were made for the sleep environment. They found that during these missions there were lots of complaints about initial sleep harnesses. In Space Shuttle missions, approximately a third of the crew reported that the most important part of the body during sleep to be concerned with was the head, because the head can nod during sleep, waking astronauts and creating soreness. The ability to rotate one's head without tilting while strapped is ideal. In discussions with crewmembers, they found that crews tend to not like internal restraints (e.g. bungees), but they appreciate external restraints. External restraints press against you, securing the astronaut, and create a feeling closer to that of sleeping in gravity. Movement in sleep is important during periods of arousal and too much restraint, may conflict with this behavior (possibly why astronauts tend to not use internal straps). In these discussions,

crewmembers requested several modifications to the sleeping bag design. Based on this feedback, the new sleeping bags will feature head restraints and a ventilation flap for feet.

Accommodating crew requirements for cleanliness and hygiene was also an important component in the re-design of the sleeping bags. Currently, crewmembers are given their own sleeping bags and liners. The sleeping bags are disposed of after each mission. The sleeping bag liners, like bed sheets, are removable, but are difficult to clean aboard the ISS. It is much easier to simply remove and replace them. The liners are provided by Russia and there are not always enough liners available to accommodate the crew changing them regularly. Typically, American crewmembers use the same liner for approximately 90 days. The new sleeping bags will be provided with liners to be changed every 3-4 weeks.

Currently, there are four Crew Quarters aboard the ISS. As a result, there are not enough Crew Quarters for every astronaut that may be present. This offered unique challenges to overcome for the design team. Sleeping bags in the Crew Quarters do not have to meet the same level of flammability safeguards as the sleeping bags outside of the enclosed area.

The team noted that the differences in requirements in different areas of ISS highlight the importance of planning new hardware specific to a mission. They speculated that a new design would likely be necessary for deep space missions and suggested that long-duration sleeping bags might need to be constructed with anti-microbial material in order to maintain cleanliness without increasing payload.

Interview with ISS Crew Quarters and TeSS Engineers

ISS engineer SME 1 is an engineer who was involved in the development of the Temporary Sleep Station. This project began as a concept in the engineering discipline for using structural material that could be deployed in orbit. Later they were given a flight project to build TeSS using the same concept. A crew representative was involved in the development process and crewmembers looked at the design and provided feedback on it. TeSS was built and certified for spaceflight in approximately nine months, but the entire project from conception to deployment took a few years in total. TeSS was designed to be temporary and installed in the laboratory module of ISS.

ISS engineer SME 2 was tasked with designing the Crew Quarters (CQ) for ISS. This project began when Node 2 was added to ISS. ISS engineer SME 2's group had to coordinate the development process with contractor teams and the habitability design center team. In order to coordinate effort from these groups, they set up an open, integrated project team, where team members could present different aspects of the plan throughout the process. The space radiation group and human factors group contributed to each element of the project. The acoustic office and lighting office evaluated the design plan as well. These groups would present their requirements and then engineering would work to meet the requirements. The process was iterative, with the engineering team creating three prototypes prior to completing the final design. The team delivered four CQ, which were identical, except that two were mirror images of each other. The design plan and implementation was supposed to last two years, but was stretched a few months longer, because the CQ was deployed in phases with two CQ deployed together and two more being deployed separately during later missions.

Despite the rigorous work to create mock-ups for the study, there were no pre-deployment studies of sleep in either of the sleep stations. The design teams for both the CQ and

TeSS made thorough evaluations of sleep hygiene and habitability concerns through feedback generated from the brief experiences of subject matter experts and crewmembers in the sleep chambers.

Although TeSS and CQ are the same size, TeSS had a larger habitable volume than the CQ due to the absence of ductwork in the bulkhead of the chamber. This change was thoroughly evaluated by the engineering teams due to the resultant reduction in habitable volume. The engineers needed to determine how to incorporate five cubic feet of ductwork into the design. They considered consolidating it in the “floor” area and the “head” area, as well as along the back of the chamber. The crew indicated that they did not like the ductwork near their head, because the perceived habitable volume was smaller. The final design incorporated all of the ductwork in a bump out. Ultimately the crewmembers reported that the habitable volume of both TeSS and CQ was sufficient. The teams did not systematically collect information regarding crew feedback, but they report that they did hear from some crewmembers that there is no need to make future CQ any bigger due to the fact that some crewmembers like to use their elbows to hold themselves in a desirable location.

Temperature regulation was an important consideration for both TeSS and CQ. Neither the TeSS team nor the CQ team gave much consideration to what the crewmembers would be wearing, because they considered that crew choice. Instead, they approached temperature regulation by creating a cool ambient temperature in the sleep stations relative to the rest of the space station. The crew debriefing statements suggested that Kayutas (the Russian sleep station) was too warm for sleep and as a result, some crewmembers would leave the door to the sleep station open, which in turn led to light and sound pollution within the sleep chamber. For the CQ they tried to offer a range of temperature options and it was designed to reach thermal equilibrium within 20 minutes.

The regulation of airflow within TeSS and CQ was one of the most important issues that the engineers faced, due to CO₂ washout, but the airflow system also allowed for some temperature regulation within both sleep chambers. TeSS drew air from a vent duct from the station air assembly with three speed settings for airflow, but TeSS had no mechanism for redirecting air within the chamber. For the CQ, there were also three speeds, and the direction of the airflow could be manipulated by the crewmember. This functionality was guided by CFD modeling for airflow and crewmember perspective on how acceptable the speed and temperature was in the mock up.

There were many concerns that the developers faced when designing the airflow systems for TeSS and CQ. The primary issue was related to the need to ensure that it was not possible to develop pockets of dead air within either chamber. A second issue was that as they increased fan speeds to reduce the temperature, the fans generated increasing noise. For this reason, they designed the three speed controls, so that both an acceptable temperature and sound level could be achieved.

There were many acoustic requirements that guided the design of TeSS and CQ. The lining of the CQ and TeSS were designed to be sound attenuating. The egress was designed to shut securely in order to prevent sound pollution from entering the chamber. The CQ team focused specifically on reducing continuous noise, not on reducing impulse noise. On ISS, the way that modules fit into the racks only allows for loose attachment on orbit. Therefore, if

someone grabs the handrail on the outside of a CQ it could rattle and potentially wake someone up.

The current lighting in CQ is a general lighting assembly (GLA), however, there are plans to deploy a solid-state lighting assembly (SSLA) in the future. The GLA was designed to be dimmed, but it was determined that turning the light down shortens its life. Due to this operational constraint, the deployed GLA could not be turned down, so the designers added a fabric shade on rails to go over the light. The fabric shade allows for manual dimming of the light.

There is also light generated from indicator lights within the CQ. Originally there were six green LED lights that were included in the design, but due to the light intensity with the chamber, they reduced the number of lights to just a few. These lights are near power supply in the exit air duct to keep them cool. There are also emergency egress lights that illuminate over the door if there is a power outage or emergency. During sleep episodes, there is typically one crewmember on duty who gets all of the alarms. Only the light comes on for a Class 1 alarm, but Class 2 and Class 3 alarms include an auditory component.

There were many considerations made for comfort in both TeSS and CQ. In the design phase the teams considered having different colors for crewmembers, they evaluated materials for comfort and hygiene. Ultimately they decided that all of the chambers needed to be white in order to provide for a sufficient light intensity within the chamber. They chose soft, non-flammable Velcro squares and provided 120 patches within CQ, however, they have heard that some crewmembers sew additional patches into the chamber.

The CQ was designed to have easy to clean liners although in theory they could be replaced. The blankets can be cleaned and removed, but each CQ has 60 lbs. of blankets (due to the rubber lining that is used to block sound), which creates payload constraints. The blankets often get dirty due to the sloughing of skin during spaceflight and it can be difficult to thoroughly clean the blankets. As a result, the engineering team created duvet covers for the blankets, so that each crewmember could have a new, clean surface for sleep. The Velcro patches can be used to hold the blanket in place within the sleep chamber. Dander and dust can build up in the nooks and crannies of the CQ and cleaning is an important part of ensuring crewmember comfort and there have been reports of crewmembers doing unscheduled housecleaning before they move in, suggesting that cleanliness between individual uses of the sleep stations is desirable.

The engineering teams also included several features to improve the comfort of the crewmembers within the chamber during waking activities, including foot restraints, an arm to attach things over the right shoulder, an arm for a computer and an extra power supply.

In summary, the development teams have received primarily positive feedback regarding the use of TeSS and CQ, suggesting that these types of sleep chambers provide an adequate sleep environment during spaceflight.

Interview with a Skylab Astronaut

Astronaut SME 1 is one of nine individuals who spent time on Skylab. During this mission, crewmembers operated on a 24-hour sleep-wake schedule synchronized with each other and with mission control. Occasionally, the astronauts were awake during their scheduled sleep episode, but when this happened they remained synced with one another.

The sleep stations within the Skylab sleep chambers had many features. There was a control panel inside the sleep chamber that allowed crewmembers to communicate with mission control without leaving the sleep chamber if needed. There were storage lockers across from the sleeping frames that could be accessed while strapped in. Astronaut SME 1 appreciated this and said that crewmembers could conveniently place watches, books, or other personal items there. Crewmembers were only allowed to bring six personal items during this mission.

No crewmembers swapped sleep chambers during the mission. Cleanliness of Skylab was not an issue during astronaut SME 1's habitation, but it was noted that the third manned Skylab mission reported issues associated with cleanliness. Specifically, the crew mentioned that the wardroom and air locks were becoming dirty. Astronaut SME 1 noted that the sleep chambers were sometimes used as brief storage areas for trash, but due to the lining of materials and short duration of stowage this did not cause a problem.

Astronaut SME 1 did not feel that the personalization of private areas was important on this mission. The mission was not long enough to get "cabin fever" and there was little use of private areas besides for sleep.

The sleep chambers included bedding for each crewmember. A sheet was attached to an aluminum frame with elastic straps, from which astronauts would strap themselves in to sleep. The sleep chamber also included a blanket as well as a soft elastic strap an astronaut could place across their forehead to their ear brows to keep the head parallel to the body. The arms could float or be put under straps. Astronaut SME 1 found this to be comfortable and felt that it featured enough stability. The harnesses were adjustable and astronaut SME 1 did not feel that they were irritating to the skin.

Astronaut SME 1 spent every night, after the first three, in the sleep chamber and at the designated orientation. Astronaut SME 1 remarked that another crewmember detached his aluminum sleeping frame from his sleep chambers and moved it to different places around the Skylab habitat during the first week. After the first week he placed his sleeping frame back in the sleeping chamber and remained there the duration of the mission. This implies that the sleeping chambers were the preferable sleeping location aboard Skylab.

When asked about the size of the sleeping chambers aboard Skylab, astronaut SME 1 recalled that it felt fine and was neither too large nor too small. Astronaut SME 1 also thought that it could have been narrower without causing any issues.

The crewmembers slept in the command module for the first three nights, because the workshop was too hot to sleep in. This was due to the solar shield being ripped off upon Skylab's launch. Astronaut SME 1 recalled the temperature being around 130 degrees Fahrenheit in the workshop where the sleep chambers were located. The workshop was only habitable for a few minutes at a time until the area was cooled. Once the parasol, a cloth shade deployed as a substitute for the heat shield, was deployed over the sunny side of the workshop, the temperature slowly began to drop to approximately 80 degrees Fahrenheit. However, one corner of the parasol didn't completely spread out and as a result one corner in astronaut SME 1's sleep chamber was a bit warmer. He reported that this did not disrupt his sleep and that he avoided that area.

Astronaut SME 1 never felt too hot or too cold during sleep. He noted that hands could get a bit cold, but could be placed under a strap or a blanket to resolve the issue. The astronauts

slept in t-shirts and shorts during sleep. The command module remained cooler at around 70 degrees Fahrenheit and the crew sometimes needed a jacket or trousers to stay comfortable in that part of the station.

Inside the sleeping chambers air flowed from the bottom of the sleep chamber to the top. Astronaut SME 1's found the force generated by the airflow to be gentle and was not bothered by it. Astronaut SME did not report any concerns about inadequate airflow.

The sleep chambers did not have any windows, removing the possibility of sunlight exposure during sleep. Once the curtain at the side of the sleep station was drawn, there wasn't much light in the workshop. Astronaut SME stated that light wasn't an issue during sleep. There was a small light available to astronauts if needed, or when called from Houston.

When Skylab instruments were turned off the sleep chambers were very quiet at approximately 50 dB. The sleeping chambers featured partitions between one another to create individual private areas. The partitions could not open to each other and each had their own exit. Despite the partitions only being a privacy barrier and not a sound barrier, astronaut SME 1 stated that disruption due to other crewmembers was not an issue. No crewmembers on astronaut SME 1's mission snored, but if they had, astronaut SME 1 felt that could have been an issue. If crewmembers got up and left the sleep chamber quietly during the sleep episode, then others would not wake. However, the waste management system was loud and would wake other crewmembers when used.

A reoccurring issue started during one sleep episode, where a loud banging noise woke all three crewmembers. The source of the noise took a few days to identify with the help of mission control. They found that the noise was emanating from the exterior aluminum panels which were springing out when heated and sprang back when cooled, making a loud noise.

Interview with a SMEAT and Shuttle Astronaut

Astronaut SME 2 was a part of the Skylab Medical Experiments Altitude Test (SMEAT), a high fidelity ground simulation of the environment in Skylab. Additionally, astronaut SME 2 flew on three separate Shuttle missions, the first as pilot and the last two as commander. Each Shuttle mission was aboard a different vehicle (Challenger, Discovery, and Atlantis). In total, astronaut SME 2 logged 386 hours in space.

Experience with SMEAT

Astronaut SME 2 felt that the analog environment was helpful in the knowledge gathered related to noise, temperature, and comfort, despite the limitations related to gravitational differences. SMEAT was depressurized to a level of 5 psi. The depressurization affected speech, but astronaut SME 2 did not feel it affected sleep. The SMEAT sleeping environment included two sleeping cots in one room, separated by a curtain partition. One of the crewmembers slept in a different area, on the other side of an airlock.

Astronaut SME 2 slept horizontally on a bunk within the airlock, choosing not to use the sleep restraints that were available and nor modifying the bunk in any manner. Astronaut SME 2 stated being a very good sleeper and can fall asleep anywhere. Astronaut SME 2 did not recall any notable issues with temperature, airflow, light or noise during the SMEAT.

Experience with The Space Shuttle.

Astronaut SME 2 reported that the habitable volume of space was reduced from the beginning to the end of a mission, as it was burdensome to place everything back in lockers after they had been removed. As a result, many objects were stored in various locations throughout the Shuttle. In addition, the size of the crew impacted the amount of habitable space. Astronaut SME 2 recalled that on one flight, which included seven crewmembers, feeling the presence of the reduced living space. There were also differences between the shuttles, which changed the usable space in the shuttle; for example, Columbia included a large cabinet that reduced its habitable volume. Astronaut SME 2 reported never having any problems sleeping in the open environment aboard Shuttle. As commander, astronaut SME 2 would allow the crew autonomy to choose their preference of sleep locations. Astronaut SME 2 noted that crew members would personalize their environment by bringing things like college flags, which they would hang in the lower deck.

On astronaut SME 2's first mission, he slept tethered to the wall in the middeck. On the following two missions astronaut SME 2 preferred to be in the commander's chair in the flight deck. Astronaut SME 2 reported sleeping in the chair, with the buckle loosened and all of the straps stretched out, which was likened to "floating in a cage." Unlike reports from some other crewmembers, astronaut SME 2 did not have any issues related to head movements during sleep periods.

Astronaut SME 2 recalled that during the first mission the thermostat didn't work very well and had to be manually adjusted. Although there was difficulty remembering if it was too warm or too cool, astronaut SME 2 reported often sleeping with a jacket on and that the temperature was not too much of an issue. Astronaut SME 2 felt that blankets were less useful compared to wearing a jacket. Astronaut SME 2 did not recall any issues related to air flow during the Shuttle missions.

Astronaut SME 2 reported usually wearing a sleeping mask to limit light exposure during sleep. Although the Shuttle included shades to cover the 10 windows, covering the windows was often seen as a difficult chore and generally at least some of the windows were left uncovered. Sleep masks were used by most crewmembers instead of covering the windows as a more convenient alternative.

Astronaut SME 2 reported that the background ambient noise level was not disturbing to sleep. The crew would often turn off fans to turn off the CO₂ canisters behind them, which created a very quiet sleep environment. Although it could be difficult to communicate from the flight deck to the bottom deck, over background noise, it could be done with some effort and was made easier while looking down the hatch. There was generally not an issue communicating with crewmembers due to ambient noise.

The teleprinter, which was used to receive directives from Mission Control, would start printing two orbits before wake time so that Mission Control would have time to send another message if the first one failed prior to the crew starting their day. Astronaut SME 2 reported that the printer was very loud and receiving messages would be disruptive to sleep and would wake astronauts. Astronaut SME 2 did not recall any noise issues related to waste management use by other crewmembers during sleep periods. Astronaut SME 2 also stated choosing not to use earplugs during sleep as well.

Astronaut SME 2 recalled being awoken by other crewmembers on several occasions. One recalled experience was when astronaut SME 2 was sleeping in the commander's chair and was awoken several times from sleep by a clicking and buzzing noise that emanated from other crewmembers cameras. Astronaut SME 2 reported that the astronauts would come and go to take pictures of Earth as the end of the mission was approaching and it was "the last chance to see Earth."

Interview with a NEEMO, Shuttle, and ISS Astronaut

Astronaut SME 3 has flown on three Shuttle missions, been a part of one ISS Expedition, and led one NEEMO mission. In spaceflight missions, astronaut SME 3 worked as a mission specialist, flight engineer, and science officer. Astronaut SME 3 played a critical role in the building of Crew Quarters and contributed to several other habitability improvements to the ISS. Astronaut SME 3 has extensive experience with a wide range of sleeping environments.

NEEMO

During NEEMO missions aboard the underwater station, Aquarius, the sleeping quarter was a single room featuring three bunk beds on either side of the room with no dividers between sleeping locations. Aquanauts had their own bed and there was no "hot bunking." The six aquanauts living in close quarters in Aquarius made differences in individual's habits (e.g. preferred sleeping times) central to habitability concerns. One of the challenges in Aquarius was managing of belongings. Astronaut SME 3 stated that one of the important things to learn is how to "manage your stuff." "What do you want in your personal space? How are you going to manage your clothes/hygiene items? What did you need handy?"

Astronaut SME 3 reported being a light sleeper and stated a tendency to not need much sleep. Astronaut SME 3 did not have trouble sleeping, but felt it was very important to not disturb others who may have longer sleep needs. Astronaut SME 3 slept on a top bunk and would have to climb down over other aquanauts when needing to use the restroom during a sleeping period, which involved going into the water as the waste area was outside the immediate habitat.

The station was cluttered due to the amount of equipment present and there was minimal space for personal belongings. Although not as clean as Shuttle, Aquarius was not particularly dirty, astronaut SME 3 likened it to more like a submarine. Hygiene was not a concern and there was a checklist for routine cleaning. Conscientiousness was important in dealing with cleanliness and the limited space, as was working within a team. The dynamic of a bunk room could be a problem with several individuals on different sleep schedules in the same space. Managing personal belongings can be a big issue and there must be space for individuals to store personal items. In addition, mixed gender crews may require accommodations for private spaces to change. Astronaut SME 3 found that it could be challenging to find a place to change. However, the close proximity was not felt to be too much of a problem. Given the short nature of the mission, astronaut SME 3 said it felt similar to camping. Astronaut SME 3 speculated that for longer missions the need for personal space would become greater. Astronaut SME 3 stated that from a psychological standpoint, it is reassuring to have your own space with your own belongings that you control.

Astronaut SME 3 did not recall having any issues with airflow or quality. Astronaut SME 3 did not experience any headaches or any other ailments that could be attributed to air quality.

Astronaut SME 3 stated both that Aquarius was a cold environment and also a tendency to be cold in environments where others feel fine. Astronaut SME 3 reported difficulty sleeping with cold feet, which was sometimes the case on Aquarius. There were no accommodations for modifying the sleep environment on Aquarius, so individuals were required to anticipate their needs. Astronaut SME 3 noted that access to an extra blanket or pair of socks may have facilitated better sleep for some crewmembers.

There was no sound attenuation on Aquarius and the bunk room was separated from the habitation room by a curtain, making it possible for noise generated by crewmembers in the habitation area to disturb the sleep of those sleeping in the bunk room. Astronaut SME 3 highlighted the issue of individual differences posing a problem in this situation. Astronaut SME 3 noted that some crewmembers who preferred a later sleep schedule could disrupt the sleep of crewmembers who preferred an early sleep schedule and vice versa. As a result, if a crewmember wanted to sleep it was important that other aquanauts tried to be quiet.

Astronaut SME 3 does not recall any issues with snoring crewmembers, but noted that this could have been an issue given the open sleeping environment. Outside of aquanauts talking and moving throughout sleep periods there were no other issues reported relating to noise.

Within the sleep environment, light would come through the curtain, which partitioned the bunk room from the rest of station. Astronaut SME 3 did not feel this was an issue personally, though it may have had deleterious effects on sleep quality for some of the aquanauts. Astronaut SME 3 did not use an eyeshade during sleep, but noted that some of the other crewmembers did choose to wear one.

Shuttle

All crewmembers slept inside the middeck for all of astronaut SME 3's Shuttle missions. Astronaut SME 3 slept with a sleeping bag attached to a Shuttle wall. Astronaut SME 3 felt it was helpful to feel constrained and a tendency to sleep on his/her side. It was noted that on Shuttle it wasn't possible to fasten one's self as tightly as on the ISS. Astronaut SME 3 indicated a preference to restrain the head during sleep.

During the Shuttle missions astronaut SME 3 found that other crew members tended to go to bed earlier than s/he did. Astronaut SME 3 stated not sleeping very well on first mission. However, astronaut SME 3 felt the body adapted and remembered the last visits to space and on later missions astronaut SME 3 slept much better. However, astronaut SME 3 reported feeling fatigued by flight day six or seven.

Astronaut SME 3 preferred to sleep near the galley, because it was the warmest place on the Shuttle. Astronaut SME 3 noted that the galley was "shut down" during scheduled sleep episodes, so that other crewmembers could not use it.

Astronaut SME 3 recognized a personal sensitivity to noise during sleep. As a result, astronaut SME 3 brought a noise-cancelling headset for the last mission in order to block out noise during sleep.

The crew always used the window covers on the middeck, which removed light from the sleep environment. Astronaut SME 3 reported that there were no issues with instrument lights disturbing sleep.

International Space Station

Astronaut SME 3 had several experiences sleeping on ISS. On two occasions astronaut SME 3 spent time on ISS as a visiting Shuttle crewmember and was an ISS crewmember for one expedition. Each of these experiences was associated with unique sleep habitability experiences.

After docking with the ISS during one shuttle mission, astronaut SME 3 reported that there were not many sleeping locations available due to the large crew size (6 astronauts from Shuttle, 3 from ISS expedition). Astronaut SME 3 slept in a Shuttle sleeping bag in Node 2 and attached bungee cords to handrails along the module floor in order to stay connected to a flat surface. Astronaut SME 3 chose this location because it was close to the Shuttle. On astronaut SME 3's last Shuttle mission, which was after an ISS expedition, astronaut SME 3 slept inside the Japanese Experiment Module for one night and spent two nights in the European Module. Astronaut SME 3 used prior ISS experiences to guide the decision of a sleep location for this mission and chose the JEM and European modules to avoid sleeping in areas where crewmembers might be moving through (e.g. to use a toilet) during the sleep episode. Astronaut SME 3 ultimately left the JEM because the shutters over the windows in JEM had light coming through which was a problem during sleep.

During astronaut SME 3's stay aboard the ISS, during the expedition, there were only three crew members present for most of the time, which meant that there was a large habitable volume available for each person. Astronaut SME 3 slept inside of Temporary Sleep Station during Expedition 18. One of astronaut SME 3's tasks was to help construct Crew Quarters (CQ), which was to be an additional sleeping environment.

Overall, astronaut SME 3 felt that TeSS was an excellent sleep environment, particularly due to its' warmer sleep environment. The temperature inside TeSS was warmer than that of CQ, which astronaut SME 3 found to be too cold. Astronaut SME 3 strongly preferred to be warm upon initiation of sleep and developed strategies to warm up prior to sleep episodes. For example, astronaut SME 3 would often put his/her feet between two CPU fans to warm them up or would enter the sleeping bag early to achieve warm feet.

Astronaut SME 3 reported that TeSS was "more cozy" and provided a smaller habitable volume than CQ, but this was not an issue. Astronaut SME 3 reported having no issues keeping TeSS or the sleeping bag clean. Astronaut SME 3 also did not feel that the airflow inside of TeSS was an issue and preferred the softer airflow of TeSS to the strong airflow in CQ, which made the CQ chamber cooler. Astronaut SME 3 noted that crewmembers sleeping in the Russian Kayutas often complained of the chambers being too hot for sleep, which required them to leave the doors to the sleep stations open to increase airflow and cool down the chambers. This eliminated the sound attenuation and would allow for disruption to noise due to other crewmembers passing by to use the waste management system.

In comparison to Aquarius, astronaut SME 3 felt the visits to ISS did not involve as much noise pollution from other crewmembers due to the large volume of the station and relatively few crewmembers sharing the space. Astronaut SME 3 reported that during the ISS expedition it was generally quiet during sleep periods. Despite this, there were occasional noises generated by

crewmembers and a mix of continuous and erratic noise emanating from station systems. Astronaut SME 3 reported discovering a sensitivity to noise during sleep while aboard the ISS. Astronaut SME 3 reported experiencing disrupted sleep due to noise for two weeks aboard ISS, but then started wearing a noise-cancelling headset, made available for making phone calls. Astronaut SME 3 found that this greatly improved sleep quality and duration. Astronaut SME 3 reported having no problems wearing the headset and hearing alarms. Astronaut SME 3 noted that an alarm clock would be attached to the headset to wake him/her and that there was no issue related to not hearing ISS alarms due to them being "long, loud, and annoying." Astronaut SME 3 also noted not realizing noise would be a problem before experiencing sleep disruption due to noise and was glad that the noise-canceling headsets were available to modify the sleep environment.

Astronaut SME 3 highlighted the importance of the sleep chamber as serving the need for privacy during long-duration missions. Astronaut SME 3 noted that due to space constraints, TeSS would be used for bathing at times. Astronaut SME 3 also reported that having one's own space was also important for personal time, which might include reading or talking to a family member on Earth.

Astronaut SME 3 noted that how belongings are managed is very important. Astronaut SME 3 stored some essential belongings within TeSS and then kept surplus items in cargo transfer bags (CTB). Astronaut SME 3 noted that there were wide individual differences associated with the management of belongings. For example, astronaut SME 3 would roll up all clothing in an organized way and would put hygiene-related items in zip lock bags. Astronaut SME 3 noted that others would tie their belongings to a string and let it float outside of CQ.

Astronaut SME 3 also described how individual differences in sleep preferences affected scheduling activities. Astronaut SME 3 noted that some individuals preferred to go to sleep late and wake up at the scheduled wake time. In contrast, astronaut SME 3 typically woke before the scheduled wake time. As a result there was often a crewmember awake while others were asleep. Astronaut SME 3 would arrange movement aboard the ISS in order to not disturb other crewmembers on a different wake-sleep schedule. Astronaut SME 3 stated choosing not to use the treadmill in the morning because it was next to the CQ for other crewmembers. Due to being concerned that going to the galley in the morning might lead to waking other crewmembers, astronaut SME 3 would bring breakfast to TeSS in the evening to avoid bothering the other crewmembers who were sleeping.

Interview with a Spaceflight Psychologist

Psychologist SME is a spaceflight psychologist at NASA. Psychologist SME has supported spaceflight missions for Mir, Shuttle, and the ISS. Psychologist SME also has extensive experience supporting missions in analog environments. Psychologist SME has been involved in astronaut selection, training, in-flight monitoring, and debriefing crewmembers.

Psychologist SME reported that one of the central issues associated with habitability is that everyone does things at different times. Psychologist SME noted that often astronauts do not have control of their sleep space. Psychologist SME reported hearing that crewmembers have distracted one another by moving around while others were sleeping.

Psychologist SME reported feeling that hammocks were not as good as sleep stations for long duration missions. Psychologist SME said that sleep stations are not just for sleep; they are

a private area where an individual can have some control over his or her environment. Psychologist SME emphasized that having a private sleep station allows a sense of control, by having a place where no one else goes. Psychologist SME noted that having personal space is often a coping mechanism for living in confined spaces. Psychologist SME suggested that introverted individuals may be good candidates for long-duration missions, but that such individuals will need to be able to control their level of social interaction and having individual quarters will allow for that privacy. Within a shared sleep space, individual differences can be amplified and can lead to tensions and irritability between the crew. Psychologist SME felt that shared sleep space would likely not be a workable option for long-duration spaceflight.

When asked about the availability of sleep stations leading to individuals self-isolating, psychologist SME reported that the benefit/risk ratio does not benefit getting rid of sleep stations. Psychologist SME said that individuals should not use private spaces to isolate themselves as a response to interpersonal problems. Crewmembers should aim to resolve issues with each other, especially with a team leader. Psychologist SME also noted that one cannot use engineering to force team cohesion.

Psychologist SME noted that while individuals may take actions for noise cancelling during sleep, it is important they do not block out so much noise that they cannot hear alarms and ground call-ups, which are lower in volume than alarms. Psychologist SME said that having the option to turn on white noise may be helpful for buffering noise for some crewmembers during sleep.

Psychologist SME felt that the position for sleep in space is important. Psychologist SME said that crewmembers have to work to test different options to find a sleep position strategy that works (e.g. crunching up in a corner, use of bungees/harnesses while on back, etc).

Mir

Crewmembers on Mir had sleep stations, but psychologist SME reported that the astronauts did not tend to have very good sleep on Mir. Psychologist SME likened sleep on Mir to 'sleeping in a car in a sketchy neighborhood versus sleeping in a car in your own driveway.' Psychologist SME said that there were frequent, sometimes very serious alarms and emergencies that occurred on Mir. Some of these alarms and emergencies included loss of power, going into free drift, and fires. In many cases the meaningful alarms were directly related to habitability. Psychologist SME stated that the need to feel secure in an environment is important.

Due to a crash with the Progress M-34 space vehicle and Mir's module Spektr, one astronaut lost his sleep station along with personal belongings. Psychologist SME emphasized the importance of contingency planning for situations where sleep quarters may be lost. Psychologist SME suggested that even a portable sleep space should have some control of light, ventilation, and noise.

ISS

Psychologist SME reported that the astronauts are better rested on the ISS than they were on Shuttle or Mir and this is a direct by-product of their habitable environment. In early missions, when ISS was being constructed, astronauts were often extremely sleep deprived. Psychologist SME reported that the crew quarters on ISS are used not just for sleep, but for

making personal calls, bathing, changing, and having alone time. Psychologist SME felt the privacy afforded by the ISS sleep stations would be essential for deep space missions.

Sleep is now generally recognized by crewmembers as being incredibly important. However, the scheduling of work is a big threat to quality sleep on ISS. Psychologist SME feels that more can be done to account for the way individuals and teams interact with their environment. Psychologist SME reported that mission support personnel have not progressed to being able to address individuals sleep needs, although they are known to exist. For example, long versus short sleepers are not yet managed well with respect to expectations on the part of the mission support teams. Psychologist SME reported that this could change if productivity was the outcome that mission support managed rather than the timeline. Similarly, psychologist SME noted that it is sometimes a problem when people require very little sleep, because the individuals will get up and work out, but then they throw off the schedule. Occasionally short sleepers feel under loaded with work. Long sleepers can feel guilty in that they need 8-9 hours of sleep a day. Longer sleepers can also feel obliged to stay up and help a short sleeper work, leading to the accumulation of sleep debt.

Psychologist SME felt that it would be good for individuals to experience 2-3 nights sleeping with a tape of the current noise environment on ISS. Psychologist SME said that anything you can teach someone about sleep to protect their future sleep is very important, especially to work out coping mechanisms.

Analog Environments

Analog environments are useful for studying sleep habitability. Psychologist SME reiterated that personal space is very important in analog environments. Having one's own space where people don't trespass on is a human need and coping mechanism. If a habitat needs to be rearranged for any reason, a new personal space should be designated. Psychologist SME said that individual compartments are more important for long-term missions.

Psychological Impact of Sleep

Psychologist SME reported that sleep is a foundational component to living and working in a team. Psychologist SME said that if one isn't getting enough sleep it can extend to all fronts. Points of natural division or desynchrony within the crew like culture, gender, military/non-military can reduce sleep and cause more splitting along natural fault lines. Personality and irritability increases without sleep. Sleep helps avoid problems that occur in other areas, such as intra-team relationships. Sleep also helps maintain a sense of self and a sense of effectiveness.

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.

The location of the sleep station within the vehicle is key to reducing noise and light pollution. Many of the individuals that we interviewed reported that their sleep had been disrupted due to the proximity of a sleeping area to a common area (Hoffman 2002; Astronaut SME 3 interview; Aviator SME interview; Navy SME interview; Oilrig SMEs interview). 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 (Yan and England 2001; Basner et al. 2013; Astronaut SME 3 interview; Aviator SME interview; Navy SMEs interview). 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 reported experiencing sleep disruption due to other crewmembers using the waste management system during scheduled sleep (MSFC Skylab Structures 1974; Yan and England 2001; IFALPA 2013; Astronaut SME 3 interview; Aviator SME interview; Navy SMEs interview). 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 (Hacker and Grimwood 1977). According to our interviews and studies of military personnel and pilots, locating the sleep chambers for off-duty crewmembers away from the command and communication area is desirable (Caldwell et al. 2000; Watt 2009; IFALPA 2013; Green 2015; Astronaut SME 2 interview; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview). However, the sleep chambers should be positioned near enough to the vehicle command center that crewmembers may quickly respond in an emergency situation (IFALPA 2013).

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 or common bunkrooms are associated with frequent sleep disruption due to other crewmembers (Caldwell et al. 2000; Astronaut SME 2 interview; Astronaut SME 3 interview; Navy SMEs interview; Oilrig SMEs interview). 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 (Stuster 1986; Caldwell et al. 2000; Navy SMEs interview; Oilrig SMEs interview). All of those whom we interviewed agreed that private quarters should be available for individuals during long duration missions. We found that subject matter experts viewed their sleep location not just as a place for sleep, but also as their only space for privacy (Johnston 1973; Willshire 1984; Stuster 1986; Koros et al. 1993; Carrere and Evans 1994; Vander Ark et al. 1994; MacCallum and Poynter 1995; Rosekind et al. 2000; Hoffman 2002; Weiss et al. 2007; Hendrickx 2002; Green 2015; Astronaut SME 3 interview; Oilrig SMEs interview; Psychologist SME interview). Access to a private space was viewed as critical to the psychological well-being of individuals living in isolated and confined environments (Astronaut SME 3 interview; Oilrig SMEs interview; Psychologist SME interview). Similarly, provision for storage of personal items within the sleep chamber was viewed as highly desirable (Yan and England 2001; Yan 1998; Astronaut SME 1 interview; Astronaut SME 2 interview; Astronaut SME 3 interview; ISS engineer SMEs interview; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview). In addressing this issue, the recommended minimum habitable volume for extended duration missions (i.e. longer than one year) was determined to be 25 m³ (883 ft³) per person; Whitmire et al. 2015). Additionally, the consensus panel recommends 5.4 m³ per crew quarter since, while the size of the ISS crew quarters is often regarded as adequate, the current volume is based on a 4 to 6-month mission and relative to a much larger vehicle. For exploration missions, given the unprecedented distance, the relatively small-sized vehicle, and the resulting need for

increased privacy, a recommendation for the near doubling in size of the crew quarters to 5.4 m³ was made (Whitmire et al. 2015). These recommendations were derived using a specified set of assumptions and parameters including variables related to crew demographics and size, autonomy from mission control, and duration. A critical assumption in this recommendation is that crew members need more space as missions become longer, a sentiment reflected in our SME interviews. The sleep chambers for deep space vehicles should also allow crewmembers to customize the space with personal items and reconfiguration of stowage compartments (Yan and England 2001; Astronaut SME 3 interview; ISS engineer SMEs interview; Navy SMEs interview; Psychologist SME interview).

There have been situations where crewmembers have been displaced from private quarters during spaceflight missions (Psychologist SME interview). In these situations it is very difficult for the displaced individuals to obtain adequate sleep (NASA 1970; NASA 1971; Shephard Jr. 1972; Aviator SME interview; Psychologist SME interview). 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.

The crew quarters that are presently on ISS appear to provide enough habitable volume for crewmembers to move as desired during sleep (Broyan Jr. et al. 2008; Allen and Denham 2011; Astronaut SME 3 interview; ISS engineer SMEs interview). We found one case where a crewmember was too large to fit in the assigned sleep chamber during spaceflight (Bluth and Helppie 1986). We also found that the current Russian sleeping bags are too narrow for individuals to move as desired (Sleeping Bag SMEs interview). 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 (Yan et al. 1998; Hoffman 2002; ESA 2010; Oilrig SMEs interview). 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 (Hoffman 2002; Astronaut SME 1 interview; Astronaut SME 2 interview; Astronaut SME 3 interview); however, even during such short excursions private crew quarters would be preferable (Yan et al. 1998).

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 (Czeisler and Gooley 2007). Exposure to light at inappropriate times leads to circadian misalignment, which causes sleep disruption (Flynn-Evans et al. 2016). Similarly, exposure to light is alerting and suppresses the drive to sleep (Lockley et al. 2006). The intensity, spectra, duration, and timing of light determine the magnitude and direction of phase shifting and potency of acute alerting (Lockley 2005). 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 (Lockley et al. 2003). Exposure to green light is capable of enhancing alertness and suppressing sleep (Lockley et al. 2006), while exposure to red light has the weakest effect on alertness and circadian phase shifting (Mien et al. 2014). 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 (NASA 1971; Hacker and Grimwood 1977; Potter et al. 1998; Caldwell et al. 2000; Dijk et al. 2003; Bierman et al. 2011; Figueiro and Rea 2012; Cho et al. 2013; Grandner et al. 2013; Figueiro et al. 2014; Thompson et al. 2014; Zeitzer et al. 2014; Green 2015; Astronaut SME 3 interview). 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 (Mien et al. 2014).

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 (Kleitman 1965; Halberg et al. 1970; Siffre 1988; Miller and Nguyen 2003; Arendt 2012; Basner et al. 2013). 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 (Duplessis et al. 2007; Young et al. 2015; Navy SMEs interview; Oilrig SMEs interview). 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 (Barger et al. 2014).

Noise is ever-present on space vehicles. We found that noise has been a major cause of sleep disruption throughout the history of spaceflight (NASA 1971; Johnston 1973; Hacker and Grimwood 1977; Flynn-Evans 2010; Astronaut SME 1 interview; Astronaut SME 2 interview; Astronaut SME 3 interview; Psychologist SME interview). The current guidelines allow for exposure to continuous noise above the WHO recommended guidelines (Broyan et al. 2008; World Health Organization 2009). In addition, the current NASA guidelines do not provide mitigations against impulsive or intermittent noise (Broyan et al. 2008; ISS engineer SMEs interview). We found that exposure to intermittent noise is at least as disruptive to sleep as continuous noise exposure (NASA 1971; Johnston 1973; Hacker and Grimwood 1977; Watt 2009; Flynn-Evans 2010; Fyhri and Aasyang 2010; IFALPA 2013; Schmidt et al. 2013; Astronaut SME 1 interview; Astronaut SME 3 interview; Navy SMEs interview; Oilrig SMEs interview). 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 (World Health Organization 2009). 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 (Stanchina et al. 2005), 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 (DOA 2009; Legler and Bennett 2011; Astronaut SME 3 interview; Aviator SME interview; Oilrig SMEs interview). 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 (Kawada and Suzuki 1999; Muzet 2007; Rechtschaffen 1966; Navy SMEs interview; Oilrig SMEs interview; Psychologist SME interview).

Early space vehicles have varied greatly in ambient temperature. 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; Okamoto et al. 1998; Okamoto-Mizuno et al. 2003; Astronaut SME 3 interview). 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 (Haskell et al. 1981; Lin and Deng 2008; Häuplik-Meusburger 2011; Astronaut SME 2 interview; Astronaut SME 3 interview; Navy SMEs interview). 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 (Van Someren et al. 2002; Sleeping Bag SMEs interview). Warming of proximal and distal skin temperature has been associated with faster sleep onset (Kräuchi et al. 1999; Raymann et al. 2005; Raymann et al. 2008) and crewmembers have reported having difficulty sleeping due to cold feet and hands (Johnston 1973; Bluth and Helppie 1986; Astronaut SME 1 interview; Astronaut SME 3 interview), 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% (Johnston 1973). The presence of humidity in the environment changes the perceived temperature. Higher humidity, with high temperatures are disruptive to sleep (Okamoto-Mizuno et al. 2005). Therefore, lower humidity of 50-60% is optimal for sleep, particularly when ambient temperature is increased.

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; Robin et al. 1958; Reite et al. 1975; Gothe et al. 1981; Stuster 1986; Schiffman et al. 1983; Selvamurthy et al. 1986; MacCallum and Poynter 1995; Salvaggio et al. 1998; Lo et al. 2006; Daues 2006; Szymczak et al. 2009; Strøm-Tejsen et al. 2015). Similarly, the optimal air pressure during sleep is equivalent to the pressure on the Earth at sea level (Miller and Horvath 1977; Mizuno et al. 1993; Aviator SME interview). Air mixtures that deviate from these conditions, such as what mountaineers experience during expeditions, results in disrupted sleep and periodic breathing (Reite et al. 1975; Selvamurthy et al. 1986; Mizuno et al. 1993; Salvaggio et al. 1998; Dietz 2001; Muza et al. 2004). In depressurized environments, such as at elevation on Earth, supplemental oxygen can reduce headaches, periodic breathing and can improve sleep outcomes (Luks et al. 1998; Barash et al. 2001). Airflow is also associated with positive sleep outcomes and aids in the reduction of CO₂ (FAA 2011; Strøm-Tejsen et al. 2015; ISS engineer SMEs interview) and intrusive odors, such as body odor, food, and mechanical smells (Hacker and Grimwood 1977; Bluth and Helppie

1986; Strøm-Tejsen et al. 2015; Navy SMEs interview). 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 (NASA 1971; Bluth and Helppie 1986). 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.

Involuntary movement due to turbulence is associated with sleep disruption (Mantsangas et al. 2015; Aviator SME interview; Navy SMEs interview). 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 (Astronaut SME 1 interview; Astronaut SME 2 interview; Astronaut SME 3 interview; ISS engineer SMEs interview). Several crewmembers have stated that harnesses within the sleeping bag are uncomfortable (Sleeping Bag SMEs interview), therefore, harnesses should be provided to crewmembers on the outside of bedding to be used if desired. Similarly, separate attachments should be available to secure the sleeping bag to the wall of the sleep chamber if desired. 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.

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. We recommend that the Behavioral Health and Performance Element advise investigators to collect standardized questionnaires regarding sleep habitability and preferences from study participants living in such environments. 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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13. ABSTRACT (Maximum 200 words) As NASA prepares to send astronauts on long-duration, deep space missions, it is critical that the habitability of the sleep environment provide adequate mitigations for potential sleep disruptors. We conducted a comprehensive literature review summarizing optimal sleep hygiene parameters for lighting, temperature, airflow, humidity, comfort, intermittent and erratic sounds, and privacy and security in the sleep environment. We reviewed the design and use of sleep environments in a wide range of cohorts. We also reviewed the specifications and sleep quality data arising from every NASA spaceflight mission, beginning with Gemini. We conducted structured interviews with individuals experienced sleeping in non-traditional spaces. We also interviewed the engineers responsible for the design of the sleeping quarters presently deployed on the International Space Station. Modifiable sleeping compartments are necessary to ensure all crewmembers are able to select personalized configurations for optimal sleep. Individual sleeping quarters should be designed for long-duration missions. In a confined space, the sleep environment serves as a place to sleep, and 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.				
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