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Characterization of International Space Station Crew Members' Workload Contributing to Fatigue, Sleep Disruption and Circadian De-synchronization

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Table of Contents

List of Figures and Tables

Acronyms and Definitions

aka	also known as
BHP	Behavioral Health and Performance
CapCom	Capsule Communicator
CBT-I	Cognitive Behavior Therapy for Insomnia
ERI	Effort-Reward Imbalance
EVA	extra-vehicular activity
FA	function allocation
G	gravity
HFBP	Human Factors and Behavioral Performance
HRP	Human Research Program
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
KSAO	knowledge, skills, abilities and other characteristics
MCC	Mission Control Center
NASA	National Aviation and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
OOS	On-orbit Operations Plan
OpTIMIS	Operations Planning Timeline Integration System
OSTP	Onboard Short-term Plan
OSTPV	Onboard Short-term Plan Viewer
PayCom	Payload Communicator
POIC	Payloads Operation Center
POQ	Perceived Overqualification
PVT	psychomotor vigilance test
SHFH	Space Human Factors and Habitability
STP	Short-term Plan
TDRS	Tracking and Data Relay Satellite
WOC	work over-commitment

Characterization of International Space Station Crew Members' Workload Contributing to Fatigue, Sleep Disruption and Circadian De-synchronization

Bettina L. Beard

Abstract

The focus of this paper is to characterize how the International Space Station (ISS) crewmembers' workload may be contributing to sleep loss, circadian misalignment and fatigue. Both sleep quantity and subjective sleep quality are reduced in ISS crewmembers (Barger, Flynn-Evans, Kubey, Walsh, Ronda, Wang, Wright, & Czeisler, 2014). Evidence indicates that the use of hypnotic drugs does not appear to promote extended sleep duration.

Because sleep is often driven by psychosocial as well as somatic attributes, traditional therapies may only partially moderate the problem for some individuals. Accordingly, searching for additional abatement tactics is a sensible plan. Scientific studies have shown that sleep can be disrupted from work-related stressors. On the ISS, to optimize their time, the crewmembers follow prescribed, ambitious and rigorous schedules with shared deadlines. Here it will be argued that these human capital leveraging techniques may be undermining the astronaut's sleep, which could negatively impact performance. Along with half of the Earth-bound working population (Paoli & Merllié, 2001), ISS crewmembers may not be adequately recovering from their workload.

This paper begins with a characterization of the working conditions of ISS crewmembers, describes the development of rigorous schedules and portrays a typical workday. Terrestrially-based research is compiled to describe how full and partial sleep deprivation affect physical and cognitive performance and how ISS work characteristics may disrupt sleep and subsequent performance. The literature points toward potential solutions to astronaut fatigue that is related to their workload. Finally, throughout the text, evidence is provided from semi-structured interviews, biographies and textual databases to support the argument that astronaut workload is contributing to their sleep loss and fatigue and that research, development and mitigation strategies should focus on enhancing the restorative process.

1. Introduction

In fiscal year 2016, the National Aeronautics and Space Administration's (NASA) Human Research Program (HRP) was composed of five broad research elements. One of these, the Behavioral Health and Performance (BHP) element[1] identified the key risk of potential performance decrements and adverse health outcomes resulting from sleep loss, circadian de-synchronization and work overload. Although the traditional therapy for sleep loss, hypnotic drug use, has been implemented on the International Space Station (ISS), evidence demonstrates that sleep loss and fatigue is still experienced by crewmembers. Barger, Flynn-Evans, Kubey, Walsh, Ronda, Wang, Wright, & Czeisler (2014) reported that both sleep quantity and sleep quality were deficient in ISS crewmembers. Crew debriefs after a mission also indicate that crewmembers sleep less in space than they are used to on Earth "not because they want to, it is just because they have to." Because sleep problems are complex, often driven by psychosocial as well as somatic attributes, traditional therapies may only partially assuage the problem for some individuals. Accordingly, searching for additional abatement tactics is a sensible topic of research. It is not known to what extent the sleep deficiency can be explained by characteristics of crew workload. This paper focuses on the working conditions of ISS crewmembers and compiles terrestrially-based research to point toward potential solutions for crew sleep disruptions and subsequent fatigue that can contribute to task performance decrements. Comments made by crew, flight surgeons and schedule developers during informal interviews will be used to support the discussion.

1.1. Characterization of ISS Crew Workload

In this paper the term workload refers to more than just the physical and cognitive demands of a task, it includes the length of the workday, the use of deadlines, schedule rigor, personal control over work time, cultural norms about work's priority and the additional responsibilities that are incurred when working on a team. A high workload is the extent to which one must work at a rapid pace or work very hard to complete a high volume of work.

1.1.1. Schedule Development

Part of understanding ISS crewmember workload is gaining an understanding of their schedules and how they are developed. Operational schedules are highly constrained. The ISS schedule planning process must take into consideration the unique requirements of all International Partners. There are a set of rules shared by the Partners for resource distribution and management, extra-vehicular activity (EVA) planning, trajectory planning, robotics operations planning and integrated Earth-to Orbit vehicle joint operations. The basis of the schedule is further constrained by crew time (i.e., the number of crew onboard the ISS), available power (i.e., number of operational solar arrays) and communication resources (i.e., availability of the NASA tracking and data relay satellite).

Because of its complexity, the scheduling process is performed in three steps: Strategic, Tactical and Increment planning. Strategic planning covers a five-year period. Tactical planning covers a

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[1] As of fiscal year 2017, this element is referred to as the Human Factors and Behavioral Performance (HFBP) Element due to the merger of Space Human Factors and Habitability (SHFH) with Behavioral Health and Performance (BHP).

period of approximately one year, generally from the first manned launch in the calendar year until the first launch of the next calendar year. The third planning step is Increment planning and, as its name implies, is for increment-specific operations. To prepare for the increment, flight crews, Mission Control Center (MCC) flight controllers, ground processing, training and management use this plan. Increment planning is further divided into two major planning phases: pre-increment planning and planning during the increment. An overview of all activities is developed during pre-increment planning. Planning during the increment details one- to two-week portions of an increment.

The On-orbit Operations Plan (OOS) is a listing of activities being performed on a weekly, sometimes daily, basis. The OOS is further developed into the Short-term Plan (STP). The STP is developed the week prior to execution and includes a set of detailed, integrated timelines for tasks to be performed by astronauts, cosmonauts, flight controllers and automation. Timelines also show the 90-minute day/night cycle and when there is communication coverage via Tracking and Data Relay Satellites (TDRS) and ground stations throughout the course of the week. The activities reflected in the STP (see Figure 1) are categorized into those to be carried out sometime within the week (providing some flexibility in the schedule), those to be carried out on a particular day of the week, and those that are scheduled to start at a particular day and time.

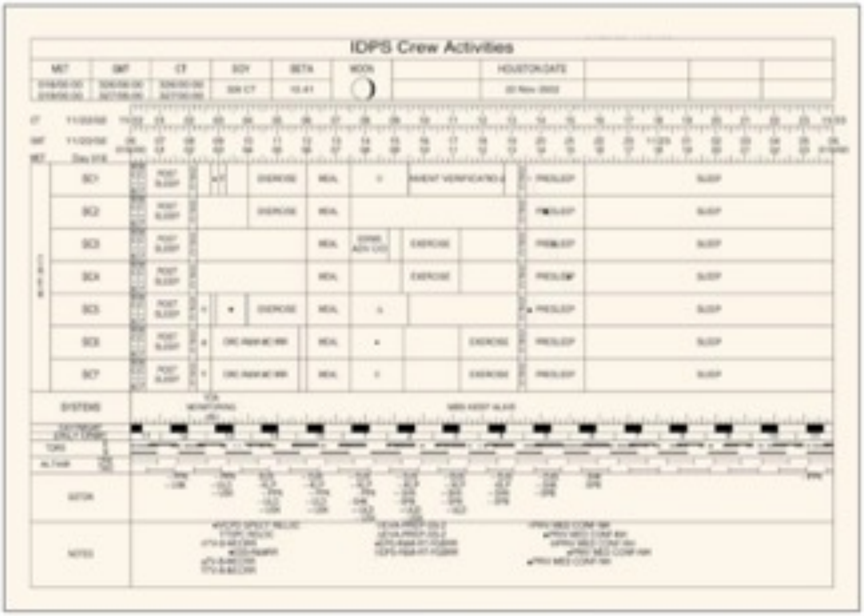

Figure 1. Example of a Short-term Plan (STP).

The STP is used to derive the Onboard Short-term Plan (OSTP). The electronic OSTP viewer (OSTPV) presents the schedule as a graphic timeline (i.e., a series of discrete, color-coded, horizontal bars) of what is happening and who is involved at any given time on the ISS. OSTPV enables the ISS crew to electronically indicate execution of timeline steps, launch electronic procedures needed to execute a task, and provides a capability to insert optional comments about any lessons learned in the execution of the schedule (i.e., Crew Notes[2]).

Figure 2 shows the Operations Planning Timeline Integration System (OpTIMIS) viewer. It is a newer generation of OSTPV that may be used on an iPad and is therefore more interactive allowing for limited self-scheduling. It was recently developed and tested on the NASA Extreme Environment Mission Operations (NEEMO) underwater analog station and has been used by a limited number of crewmembers on ISS. The OpTIMIS look is quite similar to OSTPV; rows indicate the schedule for each crewmember, day and night light conditions and TDRS availability are indicated and there is a vertical red-line indicating the current time-of-day.

Figure 2. Screenshot of the OpTIMIS viewer prototype.

While the Johnson Space Center operations planners schedule ISS maintenance, EVAs, robotic operations, meals and exercise, there is a team of payload planners at Marshall Space Flight Center who integrate the scientific experiments schedule. Every week, crewmembers, operations planners and payload planners modify the schedule and make last-minute adjustments. In addition to scheduled activities, the OSTP contains Job Bar (or Task List) activities which do not need to be performed at a specific time but may be performed at the crew's discretion.

1.1.2. Description of a Work Day

At any given time, the OSTP contains about three days—yesterday's, today's, and tomorrow's—of activities. New, previously unplanned, activities are uplinked daily. Interviews with crewmembers indicated that their job is to complete all of the items on his/her timeline. When all

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[2] Throughout this review, relevant Crew Notes, Crew Comments and Astronaut Journal entries (Stuster, 2010; Stuster, 2016) will be provided as real-world examples of the point being made.

capabilities are available, the OSTP can provide a very powerful planning and execution tool for the crew and MCC. But what are the ramifications of this perpetual, rigorous, deadline-oriented schedule on the crewmembers?

Figure 3 is a screen shot from a YouTube video of ISS Crewmember Garrett Reisman using the OSTPV. Flight Engineer Reisman is taking the Youtuber through a typical day on the ISS. He has just awakened. Here is a quote from the video:

> *"I next check the daily schedule. The bars, oh the bars. These bars run my life! They control everything, right here. This is what controls everything. The red line in the center is the current time, so it's five minutes after 7:00am. It tells me if it is day or night, it tells me what I'm supposed to be doing, it tells me if I am late or if I'm early—which rarely ever happens. It tells me if I have communication coverage. I can look at my whole day by scrolling ahead. It tells me when I'm going to be getting email, it tells me everything. The bars, they just run your life! And they go by so fast, you can't stop them! And the red line, no matter what I do, it just keeps moving and moving to the right and I can't stop it! [Hits fist against computer]. I just [pause] can't." Then he turns around to face the camera and says "Sorry, sorry about that. I'm OK now."*

Figure 3. Astronaut Garrett Reisman is viewing the schedule for the day on ISS.

It is almost impossible not to be concerned when you are falling behind the redline even though instructed not to do so (crewmember interview, 2016). Flight directors, principal investigators and other ground personnel are following along as the crewmember moves through the schedule. This constant surveillance can reportedly be stressful.

Tasks performed on a typical ISS workday include a morning conference with MCC, housekeeping, personal hygiene, preparing meals, two-and-one-half hours of exercise, scientific experiments, photography of earth's weather systems and filming ISS activities for public relations purposes. Tasks performed a bit less frequently but that are still routine include taking air samples or microbial samples from surfaces, repair of ISS hardware and changing the carbon dioxide scrubber canister. Operations may include resupply, crew exchange dockings and EVAs, all of which require days of preparation time and high concentration during the operation. Occasionally the crew must evacuate into a docked Soyuz for close calls with space debris, toxic spills or fire.

Much of the astronaut's workday is guided by step-by-step procedures that are linked to each task represented on the OSTPV timeline. As mentioned, as the astronaut works through a procedure, he or she can input Crew Notes in real time into that same computer. An analysis of these notes reveals that procedure clarity can influence the amount of time it takes to complete a task. Other factors, such as difficulty finding items that have been stowed and insufficient time allotted to perform the task in microgravity can also cause delays. Below are a few examples of Crew Notes and Astronaut Journal entries depicting how difficult it is to keep to the schedule:

> *"This activity takes at least double the allocated time. Many items and many locations...Requires proper attention to each, in order not to lose anything. Stowing the items...should be directly after disconnecting and cleaning. Having them all temporarily stowed creates risk to lose them."* Crew Notes entry.
>
> *"This took 1.5 crew hours. Mostly due to the procedure being a little vague."* Crew Notes entry.
>
> *"It seems like I spent all day today working as fast as I could only to keep falling behind."* Astronaut Journal entry (Stuster, 2010).

Crew were sometimes required to slam-shift, or sleep at a time many hours before or after their nominal bedtime, in order to have scheduled wakefulness coincide with mission events. These abrupt shifts in the imposed sleep-wake schedule can induce circadian misalignment (Mallis & DeRoshia, 2005). In current operations, slam shifting is less common than in the days of when the ISS was being constructed; with an increase in visiting vehicles planned, however, slam shifting may reemerge as a major stressor.

> *"The time shift is starting to make the end of the day tough. We are pretty tired right now having shifted about 6 hours over the weekend."* Astronaut Journal entry (Stuster, 2010).
>
> *"We started sleep shifting back to the left about 8.5 hours…I was pretty tired and figured I would [have a problem] falling asleep. I was correct, but failed to anticipate that I'd wake up a few hours into the sleep period and not be able to fall back asleep."* Astronaut Journal entry (Stuster, 2010).

2. Methods

2.1. Literature Search Strategy

For the interim report on this project, the key words workload, work, job, sleep, sleepiness, circadian and fatigue were combined with each of the terms performance, shift work, deadlines, extended work, schedule, rumination, pain, human capital, slam shift and flextime to run searches in the computerized database Google Scholar. Following semi-structured interviews, a review of the Crew Notes, Crew Comments and Astronaut Journals and after receiving feedback on the interim report, a second literature search was performed using different combinations of the terms workload, interruptions, task performance, performance decrements, work-rest cycles, sleep deprivation, partial sleep deprivation, sleep restriction, headache, backache, exercise, vigilance, working memory, executive function and cognitive models.

2.2. Research Selection Criteria

A total of 2,775 (from the original search) and 1327 (after the interim report and interviews) abstracts were retrieved. Duplicates and studies not relevant to the review (based on the abstract) were removed and abstracts of original experimental designs and reviews were retained. The complete articles were then either downloaded directly or resourced through the NASA Ames Research Center's Life Sciences Library and uploaded to Zotero. Zotero is a free and open-source reference management software system used by the U.S. library system. It permits all invited members to upload citation information and documents directly from a Firefox Internet browser with a single click. A hand search of the reference lists of each article revealed additional relevant articles. One hundred eighty studies met the inclusion criteria for this project.

2.3. Spaceflight Evidence

Qualitative data were gathered from four sources to systematically characterize workload on the ISS (i.e., that crewmember's sleep is disrupted from work-related stressors, that the ambitious, rigorous schedules with shared deadlines are disrupting their sleep and that the crewmembers are not adequately recovering from their high workload). These sources were:

1. *Crew Notes.* This refers to brief, voluntary, written statements crewmembers can submit about a task. An option on the OSTPV is provided so that crew can submit a note while working through a procedure or viewing their schedule. Over 6000 Crew Notes were read and categorized to acquire evidence for work overload, work underload and crew fatigue or frustration.
2. *De-identifiable Astronaut Journals*. Entries from both Journals studies on the topics of workload and sleep were provided by Dr. Jack Stuster. The supplied entries were placed into sub-categories to provide evidence for crew sleep loss, work overload, underload or fatigue.
3. *Crew Comments.* This database refers to de-identifiable information gathered during post-flight debriefs. Questions asked during the debrief represent long-term memories of events. Susan Schuh, the Crew Comments Database lead, provided Crew Comments on the topics of workload and sleep. The supplied comments were segregated into sub-categories to provide evidence for crew sleep loss, work overload, underload or fatigue.
4. *Group representatives.* Twenty-two representatives from ten operational groups were interviewed including four crewmembers, four payload planners, three flight controllers, two MCC Capsule Communicators (CapComs), two Payloads Operation Center (POIC) Payload Communicators (PayComs), two flight surgeons, two Operations planners, one flight psychiatrist, one biomedical engineer and one playbook software engineer.

3. Effects of Sleep Loss and Fatigue on Task Performance: Terrestrial Data

Sleep disruption and fatigue are known to contribute significantly to performance decrements, incidents and accidents. In the next four sections the effects of full and partial sleep deprivation on physical and cognitive task performance will be discussed.

3.1. Physical Performance after Sleep Deprivation

Studies investigating the effects of total sleep deprivation on physical performance often use treadmill running and weightlifting as dependent variables. One or several nights of sleep deprivation can affect endurance exercise performance that is thought by some researchers to be due to reduced motivation to endure discomfort (Souissi, Sesboüé, Gauthier, Larue, & Davenne, 2003; Symons, Bell, Pope, VanHelder, & Myles, 1988; Blumert, Crum, Ernsting, Volek, Hollander, Haff, & Haff, 2007; de Zwart, Bras, van Dormolen, Frings-Dresen, & Meijman, 1993). Task performance requiring short-term high-powered anaerobic output is largely unaffected (Thun, Bjorvatn, Flo, Harris, & Palleson, 2015). Although short-term tasks also require motivation, this motivation is only required for a limited amount of time.

The results are highly dependent on the metrics used. Subjective ratings of perceived exertion underestimate actual performance decreases (Skein, Duffield, Edge, Short, & Mundel, 2011; Oliver, Costa, Laing, Bilzon, & Walsh, 2009). Physiological indicators are also not appropriate metrics since cardiovascular, respiratory and metabolic changes after sleep deprivation are negligible (Skein et al., 2011; Oliver et al., 2009; de Zwart et al., 1993).

3.2. Physical Performance after Partial Sleep Deprivation

Sleep restriction refers to reduced sleep duration. Crew and flight surgeon interviews suggested that chronic partial sleep restriction is the most common form of sleep deprivation on ISS. The effect of partial sleep deprivation on physical performance depends upon when sleep is restricted over the course of the night, how many nights that sleep is restricted, the specific exercise and when that exercise is performed. Delaying bedtime without changing rise time does not affect physical performance (Vardar, Öztürk, Kurt, Bulut, Sut, & Vardar, 2007; Mougin, Bourdin, Simon-Rigaud, Didier, Toubin, & Kantelip, 1996; Souissi, Souissi, Souissi, Chamari, Tabka, Dogui, & Davenne, 2008) whereas early awakening does have an impact (Souissi et al., 2008). This early awakening decrement can be partially reduced with a 30-min nap in the afternoon (Waterhouse, Atkinson, Edwards, & Reilly, 2007), although performance decrements may occur for 15-20 minutes after awakening from the nap (Naitoh & Angus, 1987; Dinges, Orne, & Orne, 1985). If the early awakening sleep restriction is implemented for three successive days then those tasks requiring larger muscle groups show the most performance decrement (Thun et al., 2015) but only if the exercise protocol is implemented in the evening (Souissi et al., 2008; Reilly & Deykin, 1983; Reilly & Piercy, 1994) rather than the morning or afternoon (Symons, VanHelder, & Myles, 1988; Blumert et al., 2007; Symons et al., 1988; Bulbulian, Heaney, Leake, Sucec, & Sjoholm, 1996). The reduced evening performance may be a result of circadian rhythm asynchronies after sleep deprivation (Souissi et al., 2003; Bougard & Davenne, 2012) therefore the individual’s peak biological time must be considered (Thun et al., 2015). Interestingly, regularly exercising in the morning can improve morning performance relative to evening performance (Souissi, Gauthier, Sesboüé, Larue, & Davenne, 2002; Sedliak, Finni, Cheng, Kraemer, & Häkkinen, 2007).

3.3. Cognitive Performance after Sleep Deprivation

Kanki (2018) presented an information-processing framework to discuss current knowledge about crewmember cognition that is useful to the current discussion (see Figure 4). The framework combines aspects from five established models of human cognition (Baddeley & Hitch, 1974; Ericsson & Kintsch, 1995; Cowan, 2012; Zsambok & Klein, 2014 and Wickens, Hollands, Banbury, & Parasuraman, 2015).

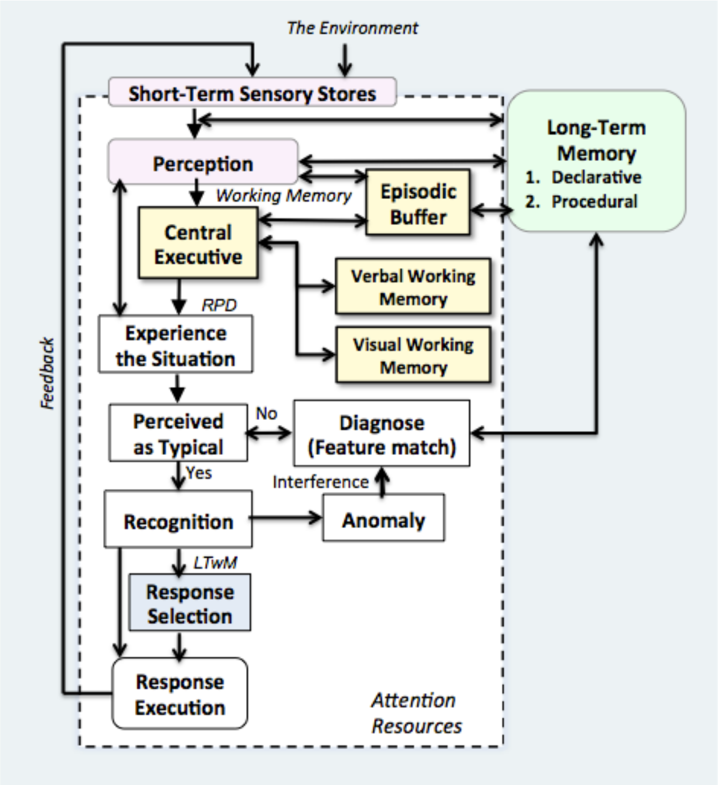

Figure 4. Information processing framework (Kanki, 2018) combining human cognition models developed by Baddeley & Hitch (1974), Ericsson & Kintsch (1995), Cowan (2012), Zsambok & Klein (2014) and Wickens et al. (2015). RPD refers to Recognition-Primed Decision Making as described in the text.

As shown in Figure 4, cognitive performance entails a number of component processes. Researchers and clinicians now recognize that to clearly understand what cognitive processes are affected by stressors, and to what degree, they must select tasks that allow dissociation of the cognitive processes (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010). Emerging evidence suggests that the component processes are differentially affected by sleep loss.

Information from the environment enters through the senses (e.g., vision, audition, vestibular) and is temporarily stored in Short-term Sensory Stores (see Figure 4). Those items that are attended to are Perceived and transferred to Working Memory (yellow boxes) where they will be encoded and consolidated into chunks of information. Working memory is controlled by a central executive function. The central executive is critical to our ability to plan, set goals, inhibit responses and monitor our own performance. Sleep deprivation impairs central executive functions (Drummond & Brown, 2001). Performance decrements appear to result from deficits in both attention processes (e.g., Lim & Dinges, 2008) and self-performance monitoring, particularly error monitoring including error detection, error correction, and post error speed and accuracy adjustments (Danielmeier & Ullsperger, 2011).

When crewmembers are first exposed to gravity transitions (e.g., 1 G to microgravity, microgravity to 1 G), they experience perceptual distortions while their vestibular, visual and proprioceptive systems are recalibrating (Prsa, Gale, & Blanke, 2012). In terrestrial studies, degraded perceptual processing, possibly related to an impaired capacity to sustain attention (e.g., Lim & Dinges, 2008), results in a percept that is harder to maintain in working memory, leading to a drop in Short-term Sensory Store capacity (Chee & Chuah, 2008). Such a mechanism may link deficits in attention with those affecting memory and learning (Mu, Mishory, Johnson, Nahas, Kozel, Yamanaka, Bohning, & George, 2005). It would be interesting to know if spaceflight stressors affect the Short-term Sensory Store capacity. To date, this has not been empirically examined.

Vigilance, or monitoring tasks, requires a constant readiness to react (Mackworth, 1968). Subjects show a progressive drop in the number of correct detections and/or increased reaction times that are exacerbated by environmental stressors. In a meta-analysis of the literature, cognitive performance was more affected by the time awake than motor performance (Pilcher & Huffcutt, 1996). On the ISS, as part of a research payload, crewmembers completed the psychomotor vigilance test (PVT) (Lim & Dinges, 2008) to measure their vigilance and attention relative to fatigue. Tests of vigilance are particularly sensitive to the effects of sleep disruption (Angus & Heslegrave, 1985; Mullaney, Fleck, Daira, & Kripke, 1985; Krueger, 1989) and boredom (O'Hanlon, 1981).

It is currently thought by many scientists that sleep is critical for memory consolidation into Long-Term Memory and that this consolidation occurs during specific sleep stages (Frank & Benington, 2006; Rasch & Born, 2013). Certain medications taken by the crew can affect sleep architecture (Uchimura, Nakajima, Hayash et al., 2006). It is therefore critical to determine memory consolidation in crewmembers since many suffer from sleep loss of some sort.

Rehearsal helps transfer the information into Long-Term Memory where the chunks of information are converted into a network of schemas. Nader & Hardt (2009) found that active retrieval leads to a re-consolidation of the information—helping to cement the memory trace. If a Decision and Response are required, experts will rapidly link the information to a similar situation through a process referred to as recognition-primed decision-making followed by response execution. Spaceflight cognitive tests should include a measure of recognition-primed decision making.

3.4. Cognitive Performance after Partial Sleep Deprivation

Although crewmembers sometimes experience entire nights without sleep, sleep restriction (partial loss of sleep) is much more typical. In a meta-analysis of the literature, Pilcher & Huffcut (1996) reported that partial sleep deprivation (<5 hours sleep in a 24-hour period) was more cognitively debilitating than full sleep deprivation (entire night spent awake). Possible reasons discussed by Pilcher & Huffcut included the effects of partial sleep deprivation on circadian rhythms and other physiological changes. After delayed bedtimes (i.e., being awake for approximately 17 hours), both speed and accuracy are compromised, mimicking the effects of a 0.05% blood alcohol concentration (Williamson & Feyer, 2000).

Banks and Dinges (2007) describe three types of partial sleep deprivation; sleep fragmentation, one of the types, refers to a disruption of the normal progression of sleep stages. Crewmember interviews revealed that sleep was often fragmented due to alarms sounding (often false alarms) during the sleep period. In one interview the crewmember recounted a sleep period that was disrupted because the ground was remotely repositioning a camera view angle outside of his sleep quarters.

In some cases, workload precluded nominal sleep hours. Several crewmembers recounted that mild pain (back pain, headache) disturbed their sleep. Some crewmembers said that their bedtime was later because they were enjoying Earth observations out of the cupola. Several crewmembers conceded that they sleep shorter hours (~6 hours/night) terrestrially also, so without these control data it is unclear whether shorter sleep periods are normal for these high achievers. There is evidence for a genetic contribution to sleep behavior, some individuals being short- and others long-sleepers (Hamet & Tremblay, 2006).

Caffeine has been shown to have beneficial effects on cognitive performance when individuals are either partially or totally sleep deprived (Patat, Rosenzweig, Enslen, Tocherie, et al., 2000; Penetar, McCann, Thorne, Kamimori, et al., 1993; Reyner & Horne 2000). Lieberman, Tharion, Shukitt-Hale, Speckman, & Tulley (2002) examined the effects of caffeine in the stressful environment of U.S. Navy SEAL operations. They found that caffeine, in moderation (200-300 mg), improved vigilance, choice reaction time and alertness particularly one hour after being consumed—and that positive performance effects persisted for eight hours.

In summary, evidence demonstrates that extended wakefulness affects cognitive performance more than physical performance, and partial sleep deprivation can be more cognitively debilitating than full sleep deprivation. Total sleep deprivation significantly affects attention processes, self-performance monitoring and possibly the short-term sensory store as well as endurance exercise performance. Early awakenings affect physical performance while delayed bedtimes affect speed and accuracy performance on cognitive tests.

4. ISS Work Characteristics that may Disrupt Sleep and Subsequent Performance

To advance an understanding of how the workload on ISS contributes to sleep loss and circadian de-synchronization, the discussion will now turn toward examining the published literature on how the workplace can contribute to sleep loss.

To say that the ISS is understaffed is an understatement. In present ISS operations, long-term (i.e., ~6 month) resident crew size is limited to about a half dozen people. Hiring practices and years of training ensure that each crewmember possesses the knowledge, skills, abilities and other characteristics (KSAOs) needed to succeed. However, these qualities only provide the potential for success (Wright & McMahan, 2011). To capitalize on crew time, common human capital leveraging strategies are employed by NASA including the use of extended shifts, deadlines, rigorous schedules, and slam shifts. Although these leveraging strategies can initially bring more human capital to bear, recent evidence suggests that human capital leveraging strategies can undermine sleep and recovery time and ultimately weaken performance (Barnes, Jiang, & Lepak, 2015). So, although NASA may have been able to successfully use these strategies on short duration missions, human capital leveraging strategies could gradually weaken performance on long duration missions. The literature supporting this statement will now be presented.

4.1. Extended Shifts

The first human capital leveraging strategy, extending the workday into time intended for relaxation or sleep, has two main effects: those relating to circadian rhythms and those resulting from lack of recovery time.

One of the most obvious consequences of extended work-shifts is that time spent working deducts from time spent sleeping (Barnes, Wagner, & Ghumman, 2012). Crewmember interviews and Crew Comments reveal that extended shifts were often used before an EVA or to ready the station for an arriving vehicle. Evidence of work impinging on sleep time is seen in Astronaut Journals (Stuster, 2010).

> *"...tonight I thought I had a good chance of being in bed by 2200, it's almost 2300 and I am not yet there."* Astronaut Journal entry (Stuster, 2010).

Occasionally, crew members will be permitted to sleep-in the next morning, but when this is not allowed, or if circadian regulation inhibits the ability to sleep (Czeisler, Weitzman, Moore-Ede, Zimmerman, & Knauer, 1980), terrestrial research suggests that the next days' work will be more effortful with poorer sustained attention (Doran, Van Dongen, & Dinges, 2001) and less creativity and innovation (Killgore, 2010). The crewmember may also feel sleepy. Sleepiness is thought to be due to the accumulation of extracellular adenosine, a potent sleep inducer (Porkka-Heiskanen, 1999). The thalamus starts inducing sleep through the hypothalamic adenosine receptors and the reticular activating system. Theta activity increases, the eyelids are forced to close, and the eyeballs are rotated upward (Saper, Chou, & Scammell, 2001).

> *"I just need sleep."* Astronaut Journal entry (Stuster, 2010).
>
> *"I fell asleep while typing."* Astronaut Journal entry (Stuster, 2010).

Extended work shifts also hinder sleep quality. Subjective reports of fragmented sleep (arousals per hour) are associated with long work hours (Åkerstedt, Knutsson, Westerholm, Theorell, Alfredsson, & Kecklund, 2004; Åkerstedt, Fredlund, Gillberg, & Jansson, 2002). Although the exact mechanism has not been established, fragmented sleep hinders sleep's restorative effects.

Extended work shifts conflict with the daily biological clock. Earlier it was mentioned that crewmembers are sometimes required to work into their pre-sleep and sleep time. Not only does this disrupt their circadian clock, but because cognition and performance are regulated by a circadian timekeeper, the crew may be working during a time of decreased executive functioning (Killgore, Kahn-Greene, Grugle, Killgore, & Balkin, 2009), worse psychomotor vigilance (Kubo, Takeyama, Matsumoto, Ebara, Murata, Tachi, & Itani, 2007), with poorer memory (Smith, 1995) and poorer visual search (Santhi, Horowitz, Duffy, & Czeisler, 2007), all of which could increase the effort required to perform the job. These cognitive and perceptual declines are observed in real-world settings. For example, Lockley, Barger, Ayas, Rothschild, Czeisler, & Landrigan (2007) reported increased risk of occupational injury or making a medical error when nurses worked shifts greater than 12.5 hours.

Performance decrements have been observed in space operations due to fatigue. Two cosmonauts on the space station Mir were so tired that the Soviet ground control placed them on 4.5-hour work shifts/day leaving ample time for relaxation and sleep. When the crewmembers continued to complain about fatigue, they were then given two days off after which the crew was still tired. The ground had safety concerns for the crew's return and therefore flew an escort to bring the two travelers home (Covault, 1988).

An example of how extended work shifts can create stress and undermine efficiency is shown in the Astronaut Journal entry:

> *"Had an uneventful rendezvous and docking, but then had to work quite a few hours that day in order to unpack the Soyuz and ready it for an emergency landing if necessary. I found myself getting pretty inefficient; by the time I got to bed tonight my work day will have been about 27 hours, and that's on top of 2 nights with pretty minimal sleep."* Astronaut Journal Entry (Stuster, 2010).

Schedule-driven experiments, extended EVAs and intricate station maintenance subject the crew to extended periods of cognitive overload. Hockey (1986) found that prolonged cognitive overload results in an aversion to further effort requirements. This can lead to a change in strategy, typically short-cuts, that can be mistaken for task efficiency. An interview with one crewmember revealed that skipping seemingly unnecessary steps in payload procedures was a common tactic used to stay on schedule.

The cognitive performance of sleep-deprived subjects on an extended shift improved when they were told that a nap will soon be permitted (Haslam, 1985). It is likely that any type of break from the prolonged effort will re-invigorate a person—on ISS this may be scheduling time to email family, enter tweets or observe the Earth through the cupola.

4.2. Ambitious Deadlines and Rigorous Schedules

A very common strategic human capital strategy is the adoption of deadlines. Deadlines can be a very effective tool for enhancing efficiency by providing a guide for the precise synchronization of tasks. The OSTP has many interesting characteristics as a managerial coordination device. Not only is it extremely ambitious, it is also highly specific. Because planners and procedure writers do not always anticipate difficulties that may arise in the ISS environment, schedule over-runs are common. Research shows that ambitious deadlines can exacerbate the negative effects of temporal uncertainty, rather than alleviate them (Blount, Waller, Leroy, Starbuck, & Farjoun, 2005). Evidence of schedule over-runs can be seen in the Crew Notes:

> *"Again—this set of procedures just requires more time in microgravity."* Crew Note entry.

Deadlines can vary in their degree of specificity and that choice sends a message to workers (McGrath & Rotchford, 1983). Specific deadlines create a culture that promotes a high sense of time urgency, heightens the experience of time pressure and constrains decision-making (Starbuck & Farjoun, 2009). Particularly in contexts containing many complex, tightly linked tasks and processes, rigid deadlines allow little room to manipulate the timing of specific tasks or in transitioning activities across tasks. This suggests that the OSTP may not be the most effective tool for coping with the temporal uncertainty that is inherent to performance on ISS.

Highly specific deadlines emphasize accountability and the need to minimize wasted time, particularly when they are set ambitiously. The OSTP places high symbolic value on the timeline between crew and ground personnel especially when deadlines are shared. The OSTP viewer contains a color scheme for indicating the status of an activity: Active, Completed, Modified, Enabled, Deferred, Aborted, Time Critical, Expired, etc. The ground team continuously monitors the activities as the crew performs them. Figure 5 shows an example of the OSTPV being followed by a Flight Director in June of 2015. Frequently, the crew is too busy with the activity to update the color scheme, so the MCC controllers verify their status through voice communication in order to keep the viewer up to date. Not only does this shared visibility communicate a commitment to the timeline, it also raises stakes associated with the deadlines. Meeting the deadlines become a measure against which performance may be evaluated (Starbuck & Farjoun, 2009; crew interview, 2016). This public linking of the deadlines with success can lead workers to be reluctant to shift the deadline back as unexpected events occur (Barnes et al., 2015).

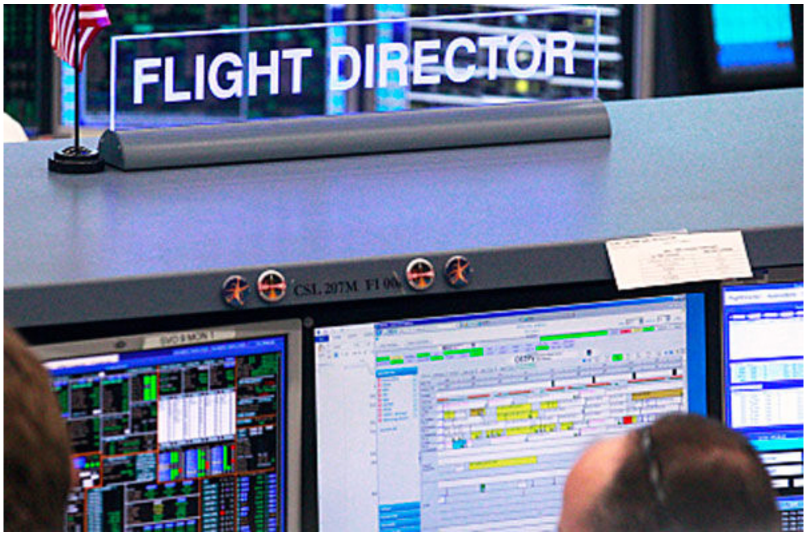

Figure 5. Photo of a flight director's workstation including the OSTPV. Almost every workstation in the MCC displays the OSTPV timeline.

Currently, payload schedule planners pad the time for each task to alleviate the time pressure. This is likely not an effective strategy alone for several reasons. People tend to systematically underestimate how much time tasks and projects are likely to take to complete (Kahneman & Tversky, 1979; Buehler, Griffin, & Ross, 1994; Byram, 1997). Adding to this tendency is a tendency to estimate a task or project's time to completion based on beliefs about how long that task or project "should" take to accomplish, rather than drawing from past experiences with similar tasks. Finally, there is a tendency to not learn from one's own past mistakes on estimating how long a task will take. This final tendency occurs because people focus on unique elements of the reason the task took so long rather than generalizing the lesson about mis-estimation. Byram (1997) showed that it is very hard to de-bias these tendencies.

Could the schedule planners reduce the use of prescribed deadlines in the face of evidence suggesting that these schedules are stressful? In the early 1970s research surrounding a construct called "escalation of commitment" and more recently "plan continuation errors" can explain this behavior. Both constructs refer to the tendency to continue to commit to a previously chosen course of action even in the face of negative feedback regarding the fallibility of those decisions (Staw, 1976; Staw & Fox, 1977; Orasanu, Martin, & Burian, 2000). These types of errors occur because people use prior investments to justify further investment (Staw & Hoang, 1995). The ISS crewmember's schedule began planning five years prior to the increment. It is hard to justify changing the strategy when this would involve International cooperation. In addition, people do not seek negative feedback about their plan and when they receive it, tend to interpret it in ways that support past decisions (Caldwell & O'Reilly, 1982). Finally, people have a completion bias, that is, they like to follow through on commitments (Conlon & Garland, 1993).

Could NASA stop using the current human capital leveraging strategies such as the use of ambitious deadlines? The answer is yes, with the stipulation that the period of time that a crew has worked under a given set of human capital leveraging strategies can play a role in outcomes from changing those strategies. If the crew changes from high levels of human capital leveraging strategies to low levels, this moves in a direction that will be likely to help their performance. However, how rapidly these gains occur will depend on how long the crew used high levels of human capital leveraging strategies. If the crew has used high-leveraging strategies for a long time, they will be chronically sleep deprived and thus slow to gain the benefit of switching to a low-leveraging strategy (Rupp, Wesensten, & Balkin, 2010; Rupp, Wesensten, Bliese, et al., 2009). In contrast, for crews that have not been using the leveraging strategies for long, it takes a lesser amount of time to gain the benefits of switching to a low-leveraging strategy.

4.3. Worktime Control

Another factor that can create stress leading to sleep loss is having little control over one's own worktime. Examples of control include starting and ending times of the workday (flextime), when to take a break, when to take vacation or a day off, the distribution of the workdays over the work week, schedule development, schedule re-arrangement and what tasks are being performed. As discussed, ISS crewmembers have some control over re-arranging their schedules, however when they work, when they rest and what they do is predominantly defined by ground schedulers and cultural norms.

For the past 30 years research has examined the relationship between high-demand jobs and worktime control factors. Much of this research attempts to test and expand Karasek's (1979) seminal model of *Job Strain*. The *Job Strain Model* suggests that jobs are stressful when demands (e.g., workload) exceed the worker's resources and that control can serve as a buffer or protective factor. This model was expanded into the demand-control-support model that suggests that a combination of high control and high social support at work can buffer the effects of high demands (Johnson & Hall, 1988). In a 2013 review of this literature, high job demands and low job control were found to be related to poor sleep quality (van Laethem, Beckers, Kompier, Dijksterhuis, & Geurts, 2013). As discussed in Section 3, there is a direct link between sleep quality, fatigue and performance.

Research supporting Karasek's *Job Strain Model* (Bongers, de Winter, Kompier, & Hildebrandt, 1993) also supports studies showing that the combination of extended workshifts, high job demands (workload and pace) and individual control contribute to an increased risk of ischaemic heart disease and increased mortality (Habibi, Poorabdian, & Shakerian, 2015). In combination with other factors, high workload has also been associated with other forms of ill health. Musculoskeletal disease, for example, has been found to be associated with high-perceived workload, time pressure, and low control on the job, monotonous work, and lack of social support by colleagues (Habibi et al., 2015).

Could NASA maintain the rigid schedule for those things that must be accomplished at a certain time, but leave the rest of the schedule up to the discretion of the crew? The answer to this is—perhaps. Currently, some flexibility is permitted on ISS. This would entail extending the concept of the Task List to include those things that should be done within the day (i.e., a daily Task List), but with no time constraint. Estimates of the time the task will take could be provided to help the crew with tasking decisions, but the hard deadline and regimented order could be loosened. The effectiveness of this strategy would need to be assessed empirically.

4.4. Interruptions/Intrusions

“Workflow” refers to the continuous engagement in a primary work task or series of tasks. Assuming that the crewmember enjoys the set of tasks assigned to them, maintaining a continuous engagement in these tasks should be pleasurable. Crewmembers report enjoying mealtime, exercise, photography and science—depending on the experiment. However, station cleaning and station maintenance can sometimes be frustrating, particularly when an area is difficult to reach or maintain.

Interruptions, specifically intrusions (Jett & George, 2003) refer to unexpected, temporary halts in a task due to the onset of a secondary task or demand brought upon by another individual (e.g., email, instant messages, co-worker asking a question, phone calls, MCC call-ups). The applied research shows that interruptions are not just an inconvenience but can be disruptive to safety and primary task performance (Monk, Trafton, & Boehm-Davis, 2008). In the medical field, beeper call interruptions have been found to result in use of the wrong syringe (O’Shea, 1999; Westbrook, Woods, Rob, Dunsmuir, & Day, 2010). In aviation, nearly half of all aviation accidents are a result of concentration-lapses due to interruptions (Dismukes, Young, Sumwalt, & Null, 1998). Workplace interruptions have been found to consume an average of 2.1 hours per day (Spira & Feintuch, 2005).

Intruding on a smooth workflow can trigger negative emotional responses such as frustration (Berkowitz, 1989).

> *“In EY they have scheduled us to 120% and that causes huge problems when unexpected issues arise. And guess what, something arises almost every single day. It is very demanding and not enjoyable.”* Astronaut Journal entry (Stuster, 2016).

Because workplace display of emotional expression is discouraged, the display of frustrated affect may often be suppressed (Ekman & Friesen, 1975). This suppression can consume executive control resources (see Figure 4) since the intrusion requires an appraisal of the time that will be taken from the scheduled primary task, task-switching, forming an appropriate response to the intruder (information encoding in working memory, decision-making which involves working and long term memory and response execution which includes a motor component), tuning out the incomplete primary task and trying to remember that you still have the primary task to finish (i.e., prospective memory). As a result, repeated exposure to uncontrollable, unpredictable intrusions result in elevated levels of cognitive fatigue. Attending to intrusions requires a conscious decision to engage in a task that evokes frustration.

Research has delved into strategies to mitigate the disruptive effects of interruptions. Mitigation strategies include training how to resume an interrupted task (Cades, Trafton, & Boehm-Davis, 2006), guidelines on the use of memory aids (McDaniel, Einstein, Graham, & Rall, 2004), preventing interruptions on certain tasks (Oulasvirta & Saariluoma, 2006) and providing the user with control over when they are interrupted (McFarlane, 2002).

Crewmembers often need to perform complex tasks that demand undivided attention. Interviews revealed that the ground does intrude on crew workflow. The extent to which interruptions and distractions are affecting crew workload and performance has not been determined. Currently ISS crewmembers have near constant connectivity. The literature suggests that this constant connectivity may necessitate the development of guidelines. Jackson, Dawson, & Wilson (2001) examined how employees allow themselves to be interrupted by the arrival of an email and provided a set of recommendations for email usage to reduce the incidence of interruptions. This suggests that field research may be in order to capture the actual frequency with which intrusions occur on ISS and in the mission control room. The need to study intrusions is exacerbated given the rapid introduction of new technologies creating new media through which the ground and flight crew can intrude upon each other.

4.5. Cultural Norms

NASA and crew office culture set the basic assumptions about how the crewmember's work is arranged and how they will be managed and thus can determine the extent to which schedules are used to undermine sleep (Bowen & Ostroff, 2004; Schneider, Ehrhart, & Macey, 2013). If the crew perceives that they will be rewarded for sacrificing sleep for work, they are more likely to exert greater discretionary effort to do so. This is consistent with research highlighting the tradeoff between time spent working and time spent on other activities such as sleeping (Barnes et al., 2012).

Similar to the norms for prioritizing work over sleep, the norms for "constant connectivity" (i.e., constant email or internet access) is another cultural strategy used to utilize employees' human capital more effectively (Barnes et al., 2015). First, constant connectivity norms extend the time individual members spend on work. Second, keeping employees constantly connected with work enables NASA to utilize the crewmember human capital when and where it is needed, in a timely manner. Astronaut Journals provide examples of how cultural norms influence the crew.

> *"The fatigue that develops from working here comes from the time pressure. The ground says 'don't chase the red line' on OSTPV, but the fact is we crewmembers simply cannot ignore that. What is scheduled is what is expected, and another astronaut probably got all this work done on-time on some past mission. No one wants to be seen as a slacker or as incapable."* Astronaut Journal entry (Stuster, 2016).
>
> *"I'm feeling less time pressure—mostly due to [the realization] that the ground is actually guessing when they decide how long a task should take. I'm astounded at times by how much they can underestimate how long a task will take. Even if I were maximally efficient, accomplishing a task can take twice as long, or more, than the time given."* Astronaut Journal entry (Stuster, 2016).

4.6. Teamwork

Although many of the activities performed by ISS crew are done individually, some tasks require teamwork. Researchers have likened teamwork to a dual-task paradigm, where two tasks must be accomplished concurrently. That is, team performance requires team members to concurrently engage in task work and teamwork activities (Glickman, Zimmer, Montero, Guerette, & Campbell, 1987; Morgan, Salas, & Glickman, 1994). Teamwork includes time-sharing the requirements for exchanging information, developing and maintaining communication patterns, coordinating actions, maintaining social order, and so on, with the demands imposed by performing their specifically assigned tasks.

ISS crewmembers must shift from autonomous tasks to tasks performed interdependently with other crewmembers (Smith-Jentsch, Sierra, Weaver et al., 2011). The workload associated with these demands could decrease as a function of training, experience and/or practice with the combined workload requirements (Smith-Jentsch, 2015). To balance workload among crewmembers, software could be developed that will help guide role assignments dynamically.

Alliger, Cerasoli, Tannenbaum, & Vessey (2015) discuss team resilience. Of particular interest here is their discussion of team resilience during chronic and acute stressors. In terms of workload, crewmembers are not only exposed to chronically busy schedules but are sometimes challenged by sudden, radical increases in workload. Examples of ISS crewmember resilience are seen when the crew vocalize concerns to one another or when they help each other during high-demand periods. On the rare occasions when one crewmember has completed a task early, they may look to see if another crewmember is too busy and will offload some of their work. Although ISS crewmembers have highly prescribed roles during nominal operations as well as anticipated off-nominals, there is no automated support to help them balance their workload or identify and locate needed resources in an emergency. Currently, emergencies of this sort are handled by immediate evacuation to a Soyuz spacecraft for possible return to Earth.

4.7. Perseverative Cognition (aka Rumination)

Highly constrained, ambitious and public deadlines in a temporally uncertain work environment can lead to work stress. Work stress can impair sleep (Åkerstedt et al., 2002; Burgard & Ailshire, 2009; de Lange, Kompier, Taris, Geurts, Beckers, Houtman, & Bongers, 2009; Geiger-Brown, Trinkoff, & Rogers, 2011; Åkerstedt, Nordin, Alfredsson, Westerholm, & Kecklund, 2012) and as discussed in Section 3, impaired sleep can directly affect task performance. To understand the work stress-sleep relationship, researchers have investigated the association between work stress and work-related rumination (Åkerstedt et al., 2002; Brosschot, Peiper, & Thayer, 2005). Rumination is the tendency to think and ponder about work outside of the workplace, typically when faced with problems or following intense work. In fact, the more stressful the day, the more likely a person is to think about it outside of work (Cropley & Millward-Purvis, 2003; Cropley, Dijk, & Stanley, 2006; Elfering, Grebner, Semmer, Kaiser-Freiburghaus, Ponte, & Witschi, 2005; Querstret & Cropley, 2012). Sometimes rumination can be beneficial to problem solving. At other times, rumination, or perseverative cognition, that is emotionally intrusive, pervasive and recurring can have a negative effect on the recovery process.

Crewmembers subjectively report that a “thinking/active mind” and “mission-related work issues” make it more difficult to fall asleep (Whitmire, Slack, Locke, & Leveton, 2013). “Not being able to stop thinking about work” is part of the work over-commitment (WOC) index developed by Siegrist, Wege, Pühlhofer, & Wahrendorf (2009). The results of several studies suggest that it is not the perception of work demand that impairs sleep, rather the inability to stop thinking about work during off-work hours (Åkerstedt et al., 2002; Fahlén, Knutsson, Richard, et al., 2006). When the work-related thoughts are essentially rehearsing the past day's events, then sleep onset can be delayed (Wicklow & Espie, 2000; Zoccola, Dickerson, & Lam, 2009). Relevant to ISS crewmembers, there is a direct relationship between time pressure and rumination (Berset, Elfering, Lüthy, Lüthi, & Semmer, 2011).

Evidence of emotionally intrusive thoughts at bedtime can be seen in crewmember journal entries which are often written just before bedtime (Stuster, 2010).

> *"I am a little apprehensive about this EVA…I would like for it to be successful, of course. Not only for the good of the program, but also for professional and personal satisfaction. If all goes well it will be unremarkable to folks on the ground (which is good, the best result that one can hope for!). However, if we have problems, we will be remembered poorly, since it is human nature to remember the latest events."* Astronaut Journal entry (Stuster, 2010).
>
> *"I am ready, but a bit nervous. Lots of connections have to go right tomorrow—and be on time. We have several 'bingo' points where we might have to back out if we are not far enough along. Hopefully, it won't come to that."* Astronaut Journal entry (Stuster, 2010).
>
> *"I had trouble sleeping for the last week just due to over active brain. Our schedule was beyond slammed and everything was breaking down."* Astronaut Journal entry (Stuster, 2010).

Rumination can also affect sleep quality (Thomsen, Mehlsen, Christensen, & Zachariae, 2003; Cropley et al., 2006; Guastella & Moulds, 2007) by playing a mediating role in the direct relationship between work stress and sleep quality (Berset et al., 2011; Zawadzki, Graham, & Gerin, 2012; Vahle-Hinz, Bamberg, Dettmers, Friedrich, & Keller, 2014).

What can be done about work stress/rumination? Martin & Tesser (1996) proposed distraction, disengagement from goals, and goal attainment as three mechanisms to stop ruminative thinking. If goal attainment on a stressful workday is not possible because there is simply too much to do, autonomy and time control might help employees to adjust work demands to individual needs and to recover on weekends. There were reports of weekends being adequate to recover from cumulative fatigue in the Crew Comments database. But there were also entries indicating that the weekends are sometimes busy times. Therefore, a job aid that tracks workload and thus time pressure or provides resources that enable crew to reach or postpone work-related goals (e.g., autonomy or social support) might be beneficial to reduce ruminative thinking after a stressful workday (Sonnentag & Zijlstra, 2006).

There is a body of research examining strategies to reduce sleep destructive rumination (see Hiller, Johnston, Dohnt, Lovato, & Gradisar, 2015 for a review). For example, Cognitive Behavioral Therapy for Insomnia (CBT-I) has typically been found to have long-term benefits (Riemann & Perlis, 2009). CBT-I focuses on improving sleep habits for sleep onset latency, waking after sleep onset, total sleep time and sleep efficiency. It teaches how to control negative thoughts and worries that affect sleep. Another strategy used by clinicians is "mindfulness meditation." This is a technique of meditation where, rather than pushing the negative thoughts out of your mind, these thoughts are acknowledged and observed as they arise. Ong, Shapiro, &

Manber (2008) found that the best treatment was to combine CBT-I and mindfulness meditation. These mitigations may also be helpful for ISS crewmembers; a psychiatrist who supports crew members on missions currently offers Cognitive Behavioral Therapy strategies for insomnia.

4.8. Effort-Reward Imbalance

Research in the occupational health domain has focused on the Effort-Reward Imbalance (ERI) model developed by Siegrist, Siegrist, & Weber (1986). The model proposes that work-related stress is induced when there is high effort with low rewards. The model also posits that employees reporting an extrinsic ERI (working hard on a low salary with few promotions and little job security) along with over-commitment are at the highest risk of poor health. The ERI model is quite popular in Europe and has considerable empirical support (see van Vegchel, De Jonge, Bosma, & Schaufeli, 2005 for a review). The model focuses more on physical health outcomes such as cardiovascular disease, rather than behavioral impacts such as sleep disruption. Nonetheless, it would be wise to include the assumptions of this well-researched model in any model of ISS crewmember workload.

4.9. Recovery from Work Overload

Recovery may be defined as psychological and physiological replenishment after a period of work effort (Geurts & Sonnentag, 2006). There is a cognitive component to the recovery process that is largely influenced by the extent to which people can disengage from work demands and related thoughts (Cropley et al., 2006; Sonnentag, Mojza, Binnewies, & Scholl, 2008; Sonnentag & Zijlstra, 2006; Rook, & Zijlstra, 2006). Rumination (discussed in Section 4.7) is an example of a mechanism that impairs recovery.

Non-work time on ISS refers to time spent taking care of other responsibilities and commitments than work, such as sleep, personal hygiene, straightening personal belongings, eating or viewing earth from the cupola. The activities that people undertake during non-work time can have a significant impact on sleep and recovery (Fritz & Sonnentag, 2005; Rook & Zijlstra, 2006; Sonnentag, 2001; Sonnentag & Zijlstra, 2006; Westman & Eden, 1997; Zijlstra & Cropley, 2006). In short, activities that require active engagement help people take their minds off of work.

> *"Something that Houston has continued to do that is a little irritating, is cancel events for me because of a perception that I am too busy. Yes, I do have a full work schedule, but Houston is canceling fun events..."* Astronaut Journal entry (Stuster, 2010).

Several crewmembers report that they may call friends or family at the end of their day. Research has shown that positive interactions after work with family members and friends are helpful in detaching oneself from work (Sonnentag & Kruel, 2006). Particularly after a stressful work week, it might be important to engage in positive social contacts.

There are large individual differences in how crewmembers attempt to recover from their high workload. One crewmember reported that he "protected his sleep"—not permitting work to interfere with scheduled sleep time. Some crewmembers take naps to compensate for the fatigue they were feeling. Others report that they attempt to "catch-up" on their sleep during the weekends, sometimes sleeping until 10:00 a.m., telling the ground their preference was not to place tasks on the schedule early in the morning.

Most sleep occurs outside of the workplace. ISS crewmembers are in the unique position of living where they work. In fact, their sleeping quarters are filled with work-related artifacts. In Figure 6 below, Dr. Wakata is using an Internet capable personal computer in his sleeping quarters. Crewmembers often email friends and family and twitter on their personal computer. Just behind Dr. Wakata's personal computer is the government computer where he accesses the OSTP to prepare for the next day's work. Working from their sleeping quarters may have some advantages, such as privacy, but there are also some negative aspects (Lundberg & Lindfors, 2002). People need to cognitively switch-off from work in order to recover. Because ISS crewmembers live where they work, they don't have a physical distance to travel that would permit "leaving work behind." Moen, Lam, Ammons, & Kelly (2013) tested four strategies to ameliorate the negative effects of stress resulting from long schedules and blurred boundaries between work and non-work times and places: *prioritizing* time, *scaling back* obligations, *blocking out* time, and *time shifting* of obligations. Blocking out time for relaxation and time-shifting to enhance the schedule were found to be the most effective. It may be critical to implement these strategies on an exploration mission to Mars since crewmembers will have even less room to set up their work and sleep stations.

Figure 6. Commander Koichi Wakata, a Japan Aerospace Exploration Agency (JAXA) astronaut, is providing a tour of his sleeping quarters on the ISS in 2014.

4.10. Work Underload

This report focuses on work overload on ISS. Work underload refers to a state of low arousal and dissatisfaction due to an unchallenging work situation that fails to use a worker's capabilities. Astronaut Journal entries provide evidence for lack of stimulation from meaningful work:

> *"The frustration is that so much more meaningful work could be done."* Astronaut Journal entry (Stuster, 2010).
>
> *"Most of the work has been menial labor. I feel like a part time janitor."* Astronaut Journal entry (Stuster, 2010).
>
> *"Another slow day, which makes me think how over qualified and over trained I am. Basically, I am a part time janitor and handy man here. I came up with a motto: 'No one has ever trained so hard and done so little with it."* Astronaut Journal entry (Stuster, 2010).

Entries in the Crew Notes database suggest that such tasks as downloading data or photos, cleaning filters and certain maintenance tasks also fall into this category. Crewmembers spend a huge amount of time performing inspections and routine maintenance. It is in this area that automation could improve not just crewmember frustration, but also decrease the number of tasks on the daily schedule. In addition, well-designed automation could provide more accurate predictions about how long a task will take and when it could be completed.

The most relevant research identified on the topic of work underload pertains to Perceived Overqualification (POQ - Fine, 2007). POQ refers to the situation where the individual has qualifications such as education and skills that exceed the job requirements. Discussions with several crewmembers as well as Crew Notes have revealed that some tasks are viewed as wasting valuable time on orbit, particularly when the task has been called-out as an issue but has not been resolved. This is not a universal perception but does exist in some crewmembers. Lobene, Meade, & Pond (2015) found that work conditions (e.g., repetitive tasks) were most strongly associated with POQ. Higher POQ was related to lower job satisfaction and organizational commitment but was not related to withdrawal behaviors such as truancy, absenteeism, and turnover intentions. Variables such as empowerment (Erdogan & Bauer, 2009) and personal initiative (Agut, Piero, & Grau, 2009) have been explored as moderators of POQ. Further exploration of moderators is the next important theoretical step for the POQ literature (Erdogan & Bauer, 2009; Erdogan, Bauer, Peiro, & Truxillo, 2011).

5. Discussion

Missions on ISS have all the ingredients for work stress: an ever-increasing workload with extended shifts, shifting schedules, deadlines, routine and unsatisfying work, rigorous schedules with little control over their own schedule. Terrestrially-based research provides an understanding of the potential impact on sleep quantity and quality and how sleep loss can affect physical and cognitive performance. Human capital-leveraging strategies may have immediately apparent benefits, but over time can undermine sleep and therefore can have a cumulatively negative effect on performance. Coupled with this finding is evidence from the psycho-medical literature, that sleep is disturbed by stress, among other primary causes. Together these findings suggest a possible role for workplace policies that can reduce work-related stress on the ISS, which in turn may be able to reduce sleep difficulties. The work of Spreitzer (Barnes & Spreitzer, 2015; Spreitzer, Fritz, & Lam, 2016) on employee sleep management suggests a change in how we view crewmember sleep. NASA and the ISS crew can engage in activities that influence their sleep and recovery from high workloads in a positive direction.

5.1. The Role of Automation

Automation will play an interestingly important role, particularly on Exploration Class Missions. While the currently published Design Reference Architecture to Mars (v 5.0) is being updated, the publicly available concept outlines a mission with little crew involvement. Transit time to Mars would be approximately 180 days (0.5 years) with up to two weeks provided for the deconditioned crew to acclimate to the 3/8 G force of the Mars surface. During the acclimation period, all assembly operations would either be conducted robotically by the crew or remotely from Earth. In the Long-stay Mission scenario, the stay time could be as long as 550 days (or 1.5 years). All data collection plans revolve around geology, either of the Martian moons or the Mars surface with crew either directly exploring the surface or by driving a remote robot.

A small deep-space habitat will enhouse crewmembers on a long duration mission to Mars. Advances in vehicle automation could significantly contribute to safety and crew performance and facilitate self-sufficiency on a lengthy voyage to Mars. If techniques such as artificial gravity during the transit are not applied, then the crew will require several days, perhaps several weeks, to adapt to the Mars gravity environment. This introduces additional schedule pressure as well as lander design features. Changes in the ways that crewmembers perform their duties—from manually performing vehicle maintenance or diagnostics to spending a majority of their time performing scientific research and self-fulfillment activities—can, and should, be used to safely improve efficiency and balance workload.

Ample evidence shows that the introduction of automation does not necessarily mean that workload will be reduced (Edwards, 1976; Wiener & Curry, 1980; Woods, 1994). In fact, automation can increase workload, decrease workload or leave it unaffected. “Clumsy” automation, for example, may increase the chance of mode errors, where recovering from these errors will increase workload (Nof, 2009, p. 422). When air traffic controllers were outfitted with automatic updating of aircraft expected times, workload during high traffic times was reduced. However, because the automation could not totally replace the human controller, its calculations of a previously routine task for controllers can impact the controller’s situation awareness (Hopkin, 1995) making him ill-equipped to take over in an emergency or off-nominal event.

Automation tools should be designed to support the optimal allocation of tasks between the system and the crew. Function allocation (FA) strategies can be either static or dynamic. Static FA assumes that the automation and human will maintain unchanging roles and responsibilities. Dynamic FA strategies adjust seamlessly and appropriately as required to balance workload and capitalize on the human and automation’s strengths. Attempts to develop dynamic FA strategies have applied artificial intelligence research, multi-agent systems and task scheduling (Schurr, Good, Alexander, Picciano, Ganberg, Therrien, Beard, & Holbrook, 2010). Results show a marked qualitative improvement in using dynamic FA optimization versus static FA. This suggests that rather than having automation take over all repetitive tasks on an exploration class mission, that at times of low workload, it may be beneficial to turn over these responsibilities to the crew.

Dynamic function allocation strategies must consider a balanced workload between people as well as between people and automation. There are quite a few Crew Comments about poor distribution of workload between the crewmembers.

5.2. Individual Differences

Although the Crew Notes and Astronaut Journal entries supported the notion that the human capital leveraging strategies and cultural norms at NASA are stressful to crewmembers, there is evidence that not all crew are negatively affected all the time.

Individual differences are pervasive throughout all areas of the research discussed in this review. There are key individual differences in reactivity to stress and vulnerability to insomnia. Individual differences in work stress-related rumination and disrupted sleep have been found (Morin et al., 2003; Hall et al., 2000). Individual differences in the effects of long work hours and poor social support on sleep disruption have also been reported (Nordin et al., 2012; Salo et al., 2014). Finally, individual differences have been reported in the need for sleep and in tolerance to circadian disruption due to shift work (Costa, 1996; Knauth, & Hornberger, 2003). Future studies could identify the specific factors that reliably predict crewmembers' predisposition to sleep disturbance in response to commonly experienced work stressors.

5.3. Sleep Disruption and Workload: A Reciprocal Relationship

While observational and experimental studies suggest that psychological stress can disrupt sleep, there is an emerging literature that suggests that disturbed sleep may also contribute to psychological stress. For example, short sleep duration and sleep deprivation are associated with increased physiological reactions to stress and emotion dysregulation. Further, Åkerstedt et al. (2015) found a reciprocal association between disturbed sleep and job strain (workload + control + social support).

5.4. Limitations of this Review

There are four key limitations that should be mentioned regarding the current review. First, most of the research data discussed is terrestrially based. Although anecdotal reports from crewmembers and MCC support the research findings, how these findings extend to low earth orbit and further to exploration is an empirical question. Second, the terrestrial samples range from college students to nuclear submariners. These same studies performed on an ISS crew population may show quite different patterns. Third, self-reports and questionnaire data comprise some of the findings. Although they offer many advantages, self-ratings may be subject to distortions in retrospective recall and may also be influenced by social desirability and other response biases. Behavioral and biological measures of sleep may play an important role in clarifying the nature of the relations among workload and fatigue. Fourth, this review focuses on the interaction of workload, sleep and circadian de-synchronization, however, other variables are relevant and may mediate the interaction. For example, headaches and back pain are common crew complaints as more time is spent on ISS. Research indicates that pain significantly affects cognitive encoding time and memory retrieval (Kuhajda, Thorn, Klinger, & Rubin, 2002; Register-Mihalik, Guskiewicz, Mann, & Shields, 2007; Moriarty, McGuire, & Finn, 2011). Both of these would increase task difficulty and therefore workload. Other variables of interest include working in a dangerous environment, isolation and confinement.

5.5. Future Work

Throughout this report, suggestions of future research or training were provided. Table 1 summarizes major proposals.

Table 1. Summary of Major Proposals

Do spaceflight stressors affect the Short-term Sensory Store capacity?
Could an effective motivator reduce the deficit observed with sleep deprivation on the ISS?
Does the speed/accuracy trade-off curve slope differ during space flight?
Is recognition-primed decision making affected by spaceflight? Cognitive tests should include a measure of recognition-primed decision making since sleep is critical for memory consolidation into Long-Term Memory.
How do interruptions and distractions affect crew workload and performance?
Develop dynamic FA strategies between crew and between crew and automation.
Identify the specific factors that reliably predict crewmembers' predisposition to sleep disturbance in response to commonly experienced work stressors.

Two other research ideas that were not discussed in the text are provided below.

1. *Develop a predictive capability.*

Wickens, Santamaria, & Sebok (2013) developed a model of work overload that simulates workload transitions, task shedding and task switching for multiple (more than two) tasks. More recently, Wickens and his colleagues expanded this model to include sleep restriction, sleep inertia, sleep deprivation and circadian cycle (Wickens, Laux, Hutchins, & Sebok, 2014; Wickens, Hutchins, Laux, & Sebok, 2015).

It is recommended that this model be augmented to include some of the stressors discussed in this review—e.g., long work hours, worktime control, the salience of distractors, rumination and recovery time.

Harvey (2002) has developed a model of insomnia that predicts sleep disturbances resulting from rumination and worry. Because this model has a clinical origin, it is based on a different definition of rumination. In the model, the term “worry” best describes what the work and organizational psychology literature call rumination. It is possible that this model may inform the Wickens model as to how to include aspects of rumination.

2. *Examine the norms within ground and crew cultures regarding work versus sleep/restoration and develop tailored interventions for crewmembers.*

Occupational psychologists are well aware of western sleep practices and the overprescribed schedules of workers. Some occupational therapists will begin therapy with the identification of an individual’s sleep architecture (i.e., sleep onset time, time spent in each stage, total sleep time, number and length of awakenings). They will also administer tests that assess daytime sleepiness, job strain (workload, control and social support) and off-work activities. Based on these findings they will develop a tailored therapeutic intervention for that individual that includes such things as goal setting and action planning. As therapy progresses there are re-assessments and the interventions are adjusted. Here it is proposed that we extend this therapeutic regimen with actigraphy, a sleep/wake diary to capture work-related rumination and physical pain (headache, back ache) and enhance the intervention with Cognitive Behavioral Therapy for Insomnia (CBT-I) and mindfulness meditation which are effective in decreasing thoughts that disrupt sleep.

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