Sleep Disruption, Fatigue, and Altered Neurobehavioral Performance Among Flight Controllers During Spaceflight Operations

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In spaceflight operations, flight controllers manage technical aspects of spaceflight control and spacecraft systems. The flight control team is a group subjected to shift work. Acute and chronic exposure to shift work has been associated with circadian misalignment, sleep impairment, and a negative impact on cognitive performance. This study aims to review the effects of shift work on sleep, circadian rhythms, mood, and cognitive performance of flight controllers during real and simulated spaceflight operations. Shift work during low-Earth orbit spaceflight missions is associated with a reduction in alertness, motivation, processing speed, and working memory performance efficiency. Flight controllers also report excessive insomnia and insufficient total sleep time. The development of shift work sleep disorder may be present in up to 40% of workers, especially among night and evening shift workers. Mars operations and Mars-simulated missions are associated with an impairment of visual-motor performance, working memory efficiency, and reaction time. Between 50%–87% of controllers can synchronize their circadian rhythm to a Mars day (24.65 hours), although this adaptation is not reflected in improved neurobehavioral performance.

Keywords: Circadian rhythm; Sleep; Sleep deprivation; Aerospace medicine

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INTRODUCTION

Spaceflight operations present unique demands on human performance and shift workloads. Among ground personnel, a group particularly subjected to shift work is the flight control team. Flight controllers and flight directors are highly qualified professionals who manage the technical aspects of flight control and spacecraft systems (e.g., flight dynamics, guidance, navigation) [1]. This specialized staff works in a high-stress environment, and their skills include fast-paced decision-making, situational awareness, conflict management, and team care [2,3].

Shift work is known to negatively affect the normal circadian rhythm of workers [4]. Circadian misalignment has a negative impact on sustained attention, information processing, and visual-motor performance [5,6]. In addition, working memory capacity, cognitive flexibility, perceptual reasoning, and processing speed all worsen acutely during shift work [7,8]. Working shifts during the night or in the early morning leads to disrupted and shortened sleep [9]. Insufficient sleep quality and/or quantity causes a decrease in subjective alertness [10], mood disturbances [11], and can lead to judgment errors [12].

Shift work not only has acute effects, but chronic exposure to shift work has also been associated with chronic impairment of cognitive performance [13]. Chronic insufficient sleep, even without extended wakefulness, has been shown to inhibit optimal neurobehavioural performance, regardless of the time of day [14]. The acute and chronic effects of shift work are of concern, as they are associated with an increase in human operational errors. Remarkably, the report of the Presidential Commission on the Space Shuttle Challenger Accident cites the contribution of poor judgment related to irregular and extended working hours and insufficient sleep [15].

Due to the high-pressure and specialized technical requirements of spaceflight operations, maintaining a high level of individual and team performance during shifts is critical to the safety and success of the missions. Sleep loss and circadian desynchro-
nization in ground personnel is also a major concern for future deep space exploration plans, including long-term missions to the Moon and Mars.

To our knowledge, no prior review has synthesized the effects of shift work schedules on controllers during spaceflight operations. The aim of this article is to review all the evidence available of circadian disruption, sleep disturbances, fatigue, and altered performance in flight controllers in the last three decades, and to delve into the challenges of shift work schedules for future missions, especially to Mars. The efficacy of the countermeasures applied during the experiences will also be reviewed.

**METHODOLOGY**

A literature search was conducted between December 2022 and September 2023 using PubMed and Scopus. A broad search was performed using the MeSH string: (("controller"[tiab] OR "flight controller"[tiab] OR "ground personnel"[tiab]) AND ("sleep" OR "sleep, REM"[tiab] OR "Circadian Rhythm"[tiab] OR "Psychomotor Performance"[tiab] AND ("shiftwork"[tiab] OR "shiftworker"[tiab]) OR "shift"[tiab])). Free terms were introduced while searching digital archives from space agencies. Following a review of the title and abstract of the articles retrieved, 12 were chosen. After a complete reading of the articles, 8 were selected based on the following eligibility criteria: study design (observational or experimental), use of quantitative and/or qualitative methodology, reported outcomes (functional status, symptoms, perceived value of treatment), subjects (human participants exclusively), and setting of the study (real or ground-based space missions).

**RESULTS**

Operations during low-Earth orbit crewed spaceflight missions

Chronobiological effects of work shift operations among flight controllers

A study conducted during the Space Transport System (STS) 53rd mission obtained data from 17 flight controllers at National Aeronautics and Space Administration’s (NASA’s) Mission Control Center across three shifts: day (“Orbit 1”), evening (“Orbit 2”), and night (“Orbit 3”) shift. The shift duration varied among the three groups as Orbit 3 and Orbit 1 personnel worked for 9.8–10.0 hours, and Orbit 2 controllers averaged 8.7 hours at work. Breaks also showed variability (1.0 vs. 0.1 break per shift for Orbit 1 and 3, respectively). Regarding the effects of shift work during the mission, subjective measures showed that flight controllers during the midway and final phase of night shifts presented a marked elevation of sleepiness and fatigue, with a reduction in alertness and energy. Orbit 3 subjects were also less motivated and felt they did worse in performance probes. Objective assessment of memory, arithmetic speed, and word fluency showed trends toward lower performance efficiency near the end of Orbit 3, compared to Orbit 1 and 2. Regarding sleep/wake patterns, flight controllers reported during the mission an average of 6.5 hours of total sleep time, with differences between shifts; Orbit 3 personnel averaged 6.1 hours while Orbit 1 and 2 controllers averaged 6.6 and 6.7 hours, respectively [16].

Stewart et al. [17] published a study based on a survey answered by 28 workers of the Payload Operations Control Center (POCC) at the Marshall Space Flight Center. These controllers were subjected to shift work schedules during Space Shuttle missions and simulations. Twenty-four volunteers worked 9-hour shifts, and 4 worked 13-hour shifts. In the survey, 75% reported not feeling rested after sleeping, 54% felt that their performance was degraded during mission shiftwork and 45% declared taking days off from work after each mission to recover from their shiftwork schedules. In addition, 32% of staff experienced illnesses that they claimed were a consequence of their shiftwork schedules. Mizuno et al. [18] examined the sleep patterns of 52 shift workers at the Flight Control Team of the Japan Aerospace Exploration Agency (JAXA). Data analysis revealed that 30 controllers were identified as night shift workers (NW); among them, 46.7% (14/30) subjects declared experiencing “almost always” symptoms related to insomnia or excessive wake time sleepiness. Among flight controllers who were occasional night and/or evening shift workers (ONEW), 50% (7/14) reported experiencing the same symptoms. No day workers (DW; 8) reported suffering from insomnia. Thus, 40.4% (21/52) of shift workers were classified as having a “shift work sleep disorder” (SWSD). Among the SWSD NW group, the most frequent insomnia symptoms reported were “feeling unrestored after sleep” (71%; 10/14) and “waking up earlier than one’s intention” (64%; 9/14). Moreover, the SWSD group presented a higher perceived risk of human error and a tendency to be subjectively unadapted, compared to the non-SWSD group. The SWSD subjects presented a decreased working competency, which was observed mainly in the case of night shifts. Although insomnia symptoms are common among flight controllers, taking sleeping pills or using alcohol to help induce sleep is an uncommon practice.

Countermeasures strategies applied on controllers working overnight shifts

A study conducted by Barger et al. [19] enrolled 20 NASA flight controllers working at the International Space Station (ISS) Mission Control. Subjects were randomized to either the countermeasure or control condition. The countermeasure consisted of short work breaks with intermittent exposure to blue-enriched polychromatic light (179±59 lux) and exercise, before and during two blocks of night shifts. A questionnaire and the psychomotor vigilance task (PVT) were applied. Results showed that the lowest 10% reaction times on the PVT in the experimental condition was significantly faster than the control (543.7±311.4 ms vs. 611.0±376.9 ms; p=0.031) although there were no significant differences in PVT mean reaction time (p=0.11). In addition, controllers
that were subjected to the countermeasures rated themselves significantly more alert (p<0.0001), interested (p<0.0001), energetic (p<0.0001), motivated (p<0.0001), and happier (p=0.0031) compared to the control group.

A previous experience tested a light-treatment protocol with NASA controllers working during Space Shuttle missions. Countermeasures consisted of intense light (approximately 10,000 lux) exposure schedules, avoidance of sunlight, and sleep. Thus, large circadian phase delays were induced (e.g., subjective day occurred during night shifts and subjective night occurred during daytime). Additionally, subjects were exposed to overhead illumination (80 to 250 lux) during night shifts. Daily sleep logs, daily symptom ratings, and the Stanford Sleepiness Scale at the beginning and end of each work shift were applied. A post-mission survey was also conducted. Results showed that the treatment group reported improved alertness, concentration, and speed of work. Scores on the Stanford Sleepiness Scale indicated that the control subjects were sleepier than volunteers subjected to countermeasures. Controllers in the treatment group rated their speed of work, concentration, and alertness while on duty significantly higher than the control group [17].

**Operations during real and simulated Mars missions**

**Chronobiological effects of work shift operations among mission controllers**

One main challenge for mission control personnel on Earth is to synchronize their circadian rhythm to a Martian day, which lasts 24.65 hours, 39 minutes longer than an Earth day. Working on Mars time optimizes the work of rovers and landers but requires the implementation of special shift schedules (e.g., a participant who starts his shift at 13:00 one day would start at 13:39 the next day, and so on).

In 2004, NASA’s Mars Exploration Rovers (MER) Project successfully landed two rovers on the surface of Mars. Mission planners chose to adopt the Mars time to optimize the work of both rovers. Mission control personnel worked on Mars time for 90 days [20]. A study regarding sleep quality and circadian rhythmicity was performed during the mission (n=30 volunteers). During operations, the number of consecutive workdays ranged from 1–31 (mean=6.8), with 9% of participants working ≥17 consecutive days, while the number of consecutive days off ranged from 1–11 (mean=3.0). Work shifts ranged from 1.3–23 hours, with 58% lasting >10 hours. Regarding sleep, the average time in bed was 7.81±0.67 hours, with a significant (p=0.000004) reduction in sleep time compared to the pre-mission period. Actigraphy-based sleep/wake period increased from 24.08 hours during a 2-week baseline Earth schedule to 24.84 hours during the mission, with about half of the participants exhibiting entrainment to the 24.65-hour schedule, and the rest showing circadian periods of about 25 hours. Circadian acrophase (223±61 degrees rise in phase angle during operations) and relative amplitude (0.673) both increased (p<0.01) during the MER regimes. Despite the apparent entrainment, controllers reported an 82% increase in fatigue, 64% in sleepiness, and 59% in irritability, while levels of concentration and energy decreased by 55% and 59%, respectively [21]. Additionally, 50% of participants found it difficult to work on Mars time, while 27% were neutral and 23% found it easy. Analysis of this experience showed that causes for maladaptation included the absence of environmental cues to help track Mars time, and the difficulty of isolating people from their broader responsibilities and personal commitments. Additionally, personal stress and conflict lead to a greater level of fatigue, which resulted in high-risk events (e.g., one member falling asleep while driving on a freeway) [20].

In 2008, mission personnel were required to work on Mars time for 78 days to control the Phoenix Mars Lander. A voluntary fatigue management program was offered, and 19 subjects agreed to join. Subjects (n=19) were generally required to work 4-days on/2-days off, with an average reported work shift duration of 8.6±2.6 hours, with approximately 30% of shifts lasting ≥10 hours. Photic exposure, napping, and caffeine intake were applied as countermeasures. Most of them (87%) exhibited circadian rhythms in urinary 6-sulfatoxymelatonin that were synchronized to a Mars day. Regarding sleep, subjects exhibited chronic sleep deficiency, with 50% of sleep episodes lasting ≤6 hours, and only 23% lasting ≥7 hours. When participants’ circadian rhythm was synchronized with Mars time, the main sleep duration was 5.98±0.94 hours but fell to 4.91±1.22 hours when misaligned (p<0.001). Increased time awake was found to be detrimental, as performance on the nonverbal memory and serial reaction time tasks deteriorated, and self-reported ratings for anxiety, sleepiness, and vigor also worsened (p<0.001). Self-reported levels of sleepiness and fatigue also increased significantly when work was scheduled at an inappropriate circadian phase (p<0.001). Although 64% of participants reported that working on a Mars day was “somewhat easy” or “very easy,” fatigue was reported as “strongly increased” or “moderately increased” for 64% of respondents. Twenty-eight additional controllers who did not volunteer for the full study also completed the questionnaire. In this cohort of 28 people, 75% reported that during Mars day operations, fatigue “strongly increased” or “moderately increased” [22].

The Institute of Biomedical Problems of the Russian Academy of Sciences conducted a 105-day study, that simulated a Mars mission in 2009. Nineteen mission controllers participated in this experience and were scheduled to work periodic 24-hour shifts in support of the mission simulation. Photic exposure, napping, and caffeine intake were applied as countermeasures. Controllers worked on average 19.9±7.1 hours during 24-hour shifts during the mission and slept 5.63±0.95 hours the day prior to their extended duration work shift. Cognitive functions significantly worsened as evidenced by a reduction in the number of correct mathematical calculations (p<0.01), the number of correct symbol-number matches (p<0.05), and the inhibitory control component of executive function (p<0.05). Subjective sleepiness significantly increased (p<0.001) compared to pre-mission values. In addition,
controllers became less alert (p<0.001), energetic (p=0.0001), interested (p<0.01), and well (p<0.01). Self-reported motivation also decreased (p<0.01). There was no significant gender difference in the amount of sleep obtained, performance, visual analog scales, but performance on the digit-symbol substitution task worsened significantly more in men than women during night shifts (p<0.01) [23].

Countermeasures strategies applied during mission operations
During the 3 Mars missions revised, different countermeasures were applied to prevent fatigue and performance related issues. The type and implementation of them were diverse. Figure 1 shows a summary and description of these strategies across the experiences.

<table>
<thead>
<tr>
<th>Experiences</th>
<th>Caffeine</th>
<th>Napping</th>
<th>Photic exposure</th>
<th>Exercise</th>
<th>Days off</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 MER</td>
<td>N=15</td>
<td>N=11</td>
<td></td>
<td>N=7</td>
<td>N=5</td>
</tr>
<tr>
<td>2008 Lander</td>
<td>N=19</td>
<td>N=17</td>
<td>N=16</td>
<td></td>
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**DISCUSSION**

This review synthesizes the available evidence from real and simulated spaceflight operations related to the effects of shiftwork on sleep, mood, and cognitive performance of flight controllers, as well as fatigue management countermeasures applied during the experiences. To our knowledge, this is the first review that synthesizes the available data on circadian rhythm and neurobehavioral performance of spaceflight controllers.

Across missions, both objective and subjective measurements were found to worsen. Controllers performed worse in cognitive tasks, while subjective reports of sleepiness, fatigue, and a reduction in alertness and energy were present when surveys were applied. During missions, flight controllers slept less, with up to 50% of subjects developing chronic insufficient sleep (2008 Phoenix

Figure 1. Characterization of countermeasures applied on mission controllers during real and simulated Mars operations. A: A summary of the different countermeasures strategies applied during the 3 Mars missions reviewed in the text, and the number of subjects exposed to them. The presence of color bars indicates that a specific countermeasure was applied. The number of subjects exposed to each strategy is shown in each bar. The symbol “?” indicates that the reference does not reveal the exact number of controllers subjected to a specific countermeasure. B: Description of each countermeasure strategy adopted in every Mars operation (real or simulated). Each color box details how countermeasures were implemented (duration, pattern, type, or regime as applicable). MER, Mars Exploration Rovers; Lander, Phoenix Mars Lander Mission; Simulation, Simulated 105-day spaceflight mission.
Mars Lander mission); evidence also shows the development of shift work sleep disorder among shift workers, as this diagnosis was performed during operations (40.3% of controllers at JAXA). Of concern is the association between SWDS and impaired vigilance, performance, and increased rate of accidents reported in the literature [24-26]. Literature also reports reversed daily cortisol secretion, as well as metabolic, cardiovascular, and mood disturbances related to SWSD [27-31]. Social isolation and reduced social participation due to shift work might have deleterious effects on cognitive performance too, which may help to explain the results exposed.

The circadian phase is one of the four components of major physiologic determinants of alertness and performance in healthy subjects [24]. For flight controllers participating in Mars missions, the challenge extends beyond typical shiftwork, by having to entrain to a different circadian rhythm that diverges from the evolutionary pattern of human physiology. Circadian rhythm entrainment has been assessed utilizing biomarkers and actigraphy-based sleep/wake periods across the Mars experiences reviewed. Remarkably, most subjects exhibited synchronized circadian rhythms with the Martian day, which highlights the adaptive capacity of the circadian clock system to novel environments. Nevertheless, despite this circadian adaptation, individuals experienced negative results in performance and subjective well-being. Consequently, routine analysis of circadian entrainment alone seems inadequate as a predictive tool for assessing performance and genuine adaptation to a Mars-day regime.

Furthermore, this review uncovers the need to develop more effective countermeasure strategies for flight controllers to efficiently mitigate the negative impact of shift work regimes and ensure successful future space missions, expected to increase in complexity in future years. Photic exposure (blue-enriched light intervention) is the only countermeasure capable of improving alone subjective and objective parameters in low-Earth orbit operations, although the objective improvement is just modest [32]. Of concern are the results obtained in the Mars real and simulated missions, where despite applying a combination of countermeasures, both objective and subjective measurements were found to worsen across all experiences. Fatigue is a complex phenomenon with large inter-individual differences, with even highly trained military pilots displaying up to 66% variation in performance under similar sleep-deprivation conditions [33]. Adequate and high-quality sleep is the most effective preventive measure against fatigue. In literature, napping stands out as the most effective nonpharmacological technique for restoring alertness and psychomotor performance [34]. The Aerospace Medical Association recommends naps/controlled rest, no longer than 40 minutes, to prevent sleep inertia [34]; this contrasts with the naps applied during Mars operations, which lasted for several hours. Paradoxically, by sleep inertia, prolonged naps might have contributed to increase fatigue in controllers, rather than mitigating it. Besides naps, exercise has been shown to be an effective fatigue countermeasure in both laboratory and aviation environments in the short term, as it can also induce phase shifts in the melatonin circadian rhythm and can improve the quality of a subsequent sleep period [34-36]. Controllers during Mars operations had a positive subjective appreciation of exercise, although the effect of this countermeasure alone was not objectively evaluated. However, exercising during a work shift is difficult to apply during critical space operations. Alternatively, the use of stimulants such as dextroamphetamine, caffeine, and modafinil only temporarily diminish the effects of fatigue but do not alleviate its effects, hence representing a last-resort countermeasure when preventive strategies have failed [33].

Some limitations should be considered when interpreting the results of the articles included in this review. First, the articles included were heterogeneous in terms of study design, number of subjects, sociocultural backgrounds, and outcomes assessed. Second, there were limited spaceflight studies, which were generally underpowered. Third, it should be noted that other factors that may interfere with performance and fatigue results, such as stress, were not studied in the articles reviewed.

In conclusion, shift work among flight controllers during low-Earth orbit spaceflight operations is associated with a reduction in motivation, alertness, processing speed, and working memory performance efficiency. Flight controllers also report excessive insomnia and insufficient total sleep time, especially among night shift workers. Mars operations and Mars-simulated missions are associated with an impairment of reaction time and working memory efficiency. Notably, between 50%-87% of controllers can synchronize their circadian rhythm to a Mars day (24.65 hours), although this adaptation is not reflected in improved neurobehavioural performance.

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Conflicts of Interest
The authors have no potential conflicts of interest to disclose.

Availability of Data and Material
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