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Original Article

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Sleep deficiency in spaceflight is associated with degraded neurobehavioral functions and elevated stress in astronauts on six-month missions aboard the International Space Station

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Abstract

Astronauts are required to maintain optimal neurobehavioral functioning despite chronic exposure to the stressors and challenges of spaceflight. Sleep of adequate quality and duration is fundamental to neurobehavioral functioning, however astronauts commonly experience short sleep durations in spaceflight (<6 h). As humans embark on long-duration space exploration missions, there is an outstanding need to identify the consequences of sleep deficiency in spaceflight on neurobehavioral functions. Therefore, we conducted a longitudinal study that examined the sleep-wake behaviors, neurobehavioral functions, and ratings of stress and workload of $N = 24$ astronauts before, during, and after 6-month missions aboard the International Space Station (ISS). The computerized, Reaction SelfTest (RST), gathered astronaut report of sleep–wake behaviors, stress, workload, and somatic behavioral states; the RST also objectively assessed vigilant attention (i.e. Psychomotor Vigilance Test-Brief). Data collection began 180 days before launch, continued every 4 days in-flight aboard the ISS, and up to 90 days post-landing, which produced $N = 2{,}856$ RSTs. Consistent with previous ISS studies, astronauts reported sleeping ~6.5 h in-flight. The adverse consequences of short sleep were observed across neurobehavioral functions, where sleep durations <6 h were associated with significant reductions in psychomotor response speed, elevated stress, and higher workload. Sleep durations <5 h were associated with elevated negative somatic behavioral states. Furthermore, longer sleep durations had beneficial effects on astronaut neurobehavioral functions. Taken together, our findings highlight the importance of sleep for the maintenance of neurobehavioral functioning and as with humans on Earth, astronauts would likely benefit from interventions that promote sleep duration and quality.

Statement of Significance

Successful spaceflight missions depend on the capability of astronauts to maintain high levels of neurobehavioral functioning. Sleep of adequate duration and quality is fundamental to neurobehavioral functioning, however astronauts commonly sleep short durations (≤6 h) in spaceflight. To examine the consequences of this sleep deficiency, we prospectively evaluated the sleep-wake behaviors and neurobehavioral functions of $N = 24$ astronauts before, during, and after 6-month missions aboard the International Space Station. Our results demonstrate that sleep durations of 6 h or less are associated with slower psychomotor speed, increased negative somatic behavioral states, and elevated stress. As with humans on Earth, our findings highlight the importance of adequate sleep in spaceflight and suggest that longer sleep durations can promote neurobehavioral functioning.

Key words: spaceflight; sleep; sleep loss; vigilant attention; stress; astronaut

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Introduction

International space agencies anticipate sending humans to Mars in the 2030 decade, which includes the development and habitation of a lunar station. The trip to Mars will be the most ambitious human exploration of space to date [1]. The estimated 7-month spaceflight from Earth to Mars will challenge both the physical and psychological endurance of the astronauts undertaking the journey. Mission success will rely on the extent to which astronauts can maintain high levels of neurobehavioral coping to minimize and tolerate the chronic physical and psychosocial stressors of the mission [2], which include prolonged confinement and exposure to microgravity in the spacecraft, as well as exposure to ionizing radiation [3–5].

Adequate sleep is critical for maintaining physical and behavioral health. Extensive evidence indicates that regular nightly sleep of 7–8 h is sufficient to maintain health [6]. However, short sleep durations (i.e. ≤6 h per night) are more common in astronauts on spaceflight missions than the average US adult on Earth [7–9]. Earth-based laboratory studies demonstrate that chronic exposure to the average nightly sleep duration of 6 h on ISS missions cumulatively degrades neurobehavioral functions, with pronounced deficits in vigilant attention and disturbances in mood [10, 11]. Despite the prevalence of short sleep duration in spaceflight, the consequences of astronaut sleep deficiency on neurobehavioral functions during spaceflight are unknown.

To address this gap, this longitudinal observational study evaluated the sleep–wake behaviors, neurobehavioral functions, and ratings of stress and workload of $N = 24$ astronauts, before, during, and after 6-month ISS missions. This was achieved via the Reaction SelfTest (RST), a software developed for astronauts, that captured astronaut self-report of sleep timing and sleep duration, astronaut ratings of stress, workload, and somatic behavioral states using visual analog scales, and objectively assessed vigilant attention via the Psychomotor Vigilance Test-Brief (PVT-B) [12]. The study had three primary objectives, which were: (1) to evaluate the impact of spaceflight on astronaut sleep-wake dynamics, vigilant attention performance, and self-report of stress, workload, and somatic behavioral states; (2) to replicate previous studies of astronaut sleep duration of 6–6.5 h per night on 6-month ISS missions [7]; and (3) to evaluate the relationships between sleep duration and vigilant attention performance, as well as sleep duration and stress, workload, and somatic behavioral states.

Methods

Study design and participants

Twenty-four astronauts from multiple international space agencies (majority from NASA) scheduled for 6-month ISS missions from 2009 to 2014 participated in the observational study. This longitudinal study assessed astronauts before, during, and after spaceflight to capture the dynamics of astronaut sleep-wake behaviors, neurobehavioral performance, and behavioral states across ISS missions. The Reaction SelfTest (RST) was sampled twice on each testing day, in the morning after getting up and in the evening in the 2 h pre-bed, with the following frequency: pre-mission data collection began 180 days prior to launch and repeated every 30 days until one week prior to launch, during which astronauts completed testing. In-flight on the ISS, astronauts were scheduled to perform testing every fourth day. Post-mission testing was conducted daily for the first week upon return to Earth and then conducted 30, 60, and 90 days thereafter. The study was approved by the Institutional Review Board of NASA Johnson Space Center. Astronauts gave written informed consent before the start of the study.

Reaction SelfTest (RST)

The RST is a computerized test that was deployed on astronaut and ISS support computers to assess the following three behavioral domains: (1) sleep timing, duration, and quality; (2) visual analog scale (VAS) ratings of behavioral states; and (3) neurobehavioral performance (i.e. PVT-B). Sleep timing and duration were assessed via self-report on each morning RST. Astronauts reported on the time to bed and time out of bed, along with the amount of time it took to fall asleep, time spent awake due to sleep disturbances, and time spent in bed after awakening (Table S1). Caffeine consumption was reported in the evening RST.

The RST assessed astronaut behavioral alertness using the 3-min Psychomotor Vigilance Test-Brief (PVT-B; see supplementary material) [12]. The PVT-B is free of aptitude and learning, which contaminate most other cognitive tests [13]. The primary PVT-B outcome was response speed, which is the reciprocal of reaction time (RT) and is the most sensitive neurobehavioral metric to sleep loss [13]. Other PVT-B outcomes included lapses of attention (i.e. RT ≥ 355 ms) and errors of commission (false starts, i.e. reactions without a stimulus or RT < 130 ms).

Visual analog scales (VAS) were used to assess astronaut report of behavioral states, as previously used in long-duration spaceflight analog environments on Earth [14]. Immediately before each PVT-B, astronauts completed computerized scales prompting them to report on their current behavioral state on 11-point VASs in the following domains: sleep quality (morning only), workload (evening only), stress, mental fatigue, physical exhaustion, tiredness, and sleepiness (see Supplementary Table S2 for binary VAS anchors).

Astronaut sleep–wake schedules and identification of sleep shifts

The daily sleep–wake schedule for each astronaut throughout their ISS mission was obtained from NASA (www.nasa.gov/mission_pages/station/timelines). Sleep–wake schedules were downloaded and matched with RST assessments. The standard sleep opportunity on the ISS was scheduled from 9:30 pm to 6:00 am. A sleep-shift day was classified as any day with a differently scheduled sleep period. A total of 537 sleep periods that were different from the scheduled sleep period were identified; there were a total of $N = 207$ sleep shift periods that averaged 2.6 ± 2.9 days (range 1–17 days). The RST was sampled more frequently than the every fourth mission day in the days proximal to sleep shifts (daily during two sleep shifts) and before, as well as after extravehicular activities (EVA, e.g. spacewalk).

Statistical analyses

ISS missions are not exclusive to the time in-flight on the ISS, but also include pre-flight preparation and post-flight re-acclimation to Earth, and as such, two general analytic time periods were examined. The first evaluated relationships across *mission phases* that included comparisons between pre-flight, in-flight, and post-flight, and the second was exclusive to astronaut profiles across time in-flight on the ISS by *ISS mission quarters*.

Sleep duration was calculated by subtracting sleep onset latency, duration awake during the sleep period, and the duration spent in bed after waking from the time in bed (TIB) estimate (i.e. TIB = "time out of bed" – "time went to bed"). The standard sleep period on the ISS was scheduled from 9:30 PM to 6:00 AM GMT. An astronaut's in-flight days were counted relative to the date of ISS docking (i.e. day of docking = 0 days in mission). Mission quarters were based on the average mission duration of 160 days, which yielded the following ranges for mission quarters (MQ): first mission quarter (MQ1; days 0–40); second mission quarter (MQ2; days 41–80); third mission quarter (MQ3; days 81–120); and fourth mission quarter (MQ4; ≥121 days).

Mixed effects models with a random subject intercept were used to analyze the data (SAS, Version 9.3, SAS Institute, Carey, NC). Degrees of freedom were adjusted with the Satterthwaite method. For mission quarter analysis, data were averaged across multiple test bouts within subjects for each mission quarter. Test III effects were reported for analyses with > 2 time periods. Post-hoc paired *t*-tests compared groups and/or time-points where appropriate. The time period factor was usually the only independent variable in the model. Models with outcome variables acquired in the morning and in the evening had a binary variable adjusting for time of day. For statistical significance reporting, unadjusted *p*-values are presented and post hoc comparisons were adjusted based on the false discovery rate method with significance at $p \leq 0.05$ [15]. For analyses assessing the relationship between sleep duration and astronaut ratings of stress, workload, sleep quality, and somatic behavioral states, mixed effects models adjusted for age, sex, and RST administration time of day were conducted by specifying the 7–8 h sleep duration group as the referent. To evaluate the association of increasing stress ratings in-flight with other astronaut outcomes, the Bland-Altman method for correlations in repeated measures designs was used [16].

Results

Twenty-four astronauts ($n = 19$ males; $n = 5$ females) participated in the study and were on average 48.2 ± 4.8 years of age at ISS docking. Astronauts spent an average of 160 ± 18.9 days aboard the ISS (range: 123–192 days). RST data were acquired from all $N = 24$ astronauts across mission phases, yielding a total of $N = 2{,}856$ RSTs (Supplementary Table S4; 78.9% of scheduled 3,620 RSTs), of which $n = 394$ were pre-flight, $n = 2{,}109$ were in-flight, and $n = 353$ were post-flight. A total $N = 537$ sleep shift nights were identified across all ISS sleep periods (15.7%; $N = 3{,}429$ total sleep periods on ISS) and there were $n = 367$ RST administrations on sleep shift days ($n = 207$ unique days).

Sleep timing and duration across mission phases

Twenty-three astronauts provided $N = 1{,}418$ sleep estimates, of which $n = 987$ were in-flight on the ISS. Astronauts reported an average nightly sleep duration of 6.5 ± 1.4 h in-flight and slept the NASA scheduled 8.5 h sleep opportunity on 5.9% of nights. Sleep duration was stable over time in-flight across ISS mission quarters (Figure 1B), but changed across mission phase (Figure 1A; $F = 5.64$; $p = 0.0005$), which was due to longer sleep durations after returning to Earth. Given that the ISS is an operational work environment, differences in sleep duration and timing between weekdays and weekends were examined. The short sleep duration observed on weekdays was followed by significantly longer sleep durations on the weekend (Figure 1C; $F = 27.56$; $p < 0.0001$) and the prevalence of nights with ≤6 h of sleep was lower on weekends (40.0% of weekdays vs. 22.5% of weekends; Supplementary Figure S2B, C; Table S5). Furthermore, the truncated sleep periods of astronauts relative to the NASA scheduled sleep opportunity was due to astronauts going to sleep later, where bedtimes on weekdays were >2 h later than the scheduled start of the sleep period (i.e. 23:33 vs. 21:30), while their wake times were similar to the scheduled times (Supplementary Figure S1F; 06:19 vs. 06:00). Although astronaut weekend bedtimes were also later (Supplementary Figure S1C; 0:27), astronauts remained in bed longer on weekends and had substantially later wake times (Supplementary Figure S1F; 08:09). Sleep efficiency averaged 91.8% and remained stable across all mission phases (Supplementary Figures S4A, B), yet was lower when sleep was shifted (89.2%; Supplementary Figure S4C).

The dynamics of neurobehavioral functions and ratings of stress, workload, and sleep quality across mission phases

The primary outcome for vigilant attention was PVT-B response speed, due to its sensitivity to sleep loss [13]. Astronaut PVT-B response speed changed across mission phase (Figure 1D; $F = 10.10$; $p < 0.0001$), which was driven by slower PVT-B response speed during the week prior to launch. In-flight, PVT-B response speed exhibited a significant, albeit modest, increase across ISS mission quarters (Figure 1E; $F = 3.04$; $p = 0.031$). PVT-B response speed in MQ4 was faster than both MQ2 ($\beta = -0.079$, 95% CI [–0.136, –0.022]; $p = 0.007$; adjusted $p < 0.05$) and MQ3 ($\beta = -0.070$, 95% CI [–0.127, –0.014]; $p = 0.015$; adjusted $p < 0.05$). PVT-B lapses of attention (Supplementary Figure S5A) and errors of commission (Supplementary Figure S5D) exhibited variability by mission phase, but were stable across ISS mission quarters, weekdays vs. weekends, and sleep shifts.

Twenty-one astronauts rated their levels of stress, workload, sleep quality, and somatic behavioral state across mission phases; somatic behavioral states included physical exhaustion, mental fatigue, sleepiness, and tiredness. Astronaut ratings of stress changed across mission phase (Figure 1G; $F = 5.38$; $p = 0.0004$), with peak stress ratings occurring 1 week prior to flight, as astronauts prepared for departure from Earth. In-flight stress ratings increased across ISS mission quarters (Figure 1H; $F = 4.20$; $p = 0.007$), where stress was higher in MQ4 than both MQ1 ($\beta = -3.627$, 95% CI [–6.055, –1.199]; $p = 0.0037$; adjusted $p < 0.05$) and MQ2 ($\beta = -3.64$, 95% CI [–6.082, –1.194]; $P = 0.0038$; adjusted $p < 0.05$). Stress ratings were lower on weekends relative to weekdays (Figure 1I; $F = 13.96$; $p = 0.0004$). Ratings of workload were highest during the pre-flight period (Supplementary Figure S8A), however workload was not different between other mission phases. Workload did not change across ISS mission quarters, but was lower on weekends relative to weekdays. Astronaut ratings of sleep quality and somatic behavioral states

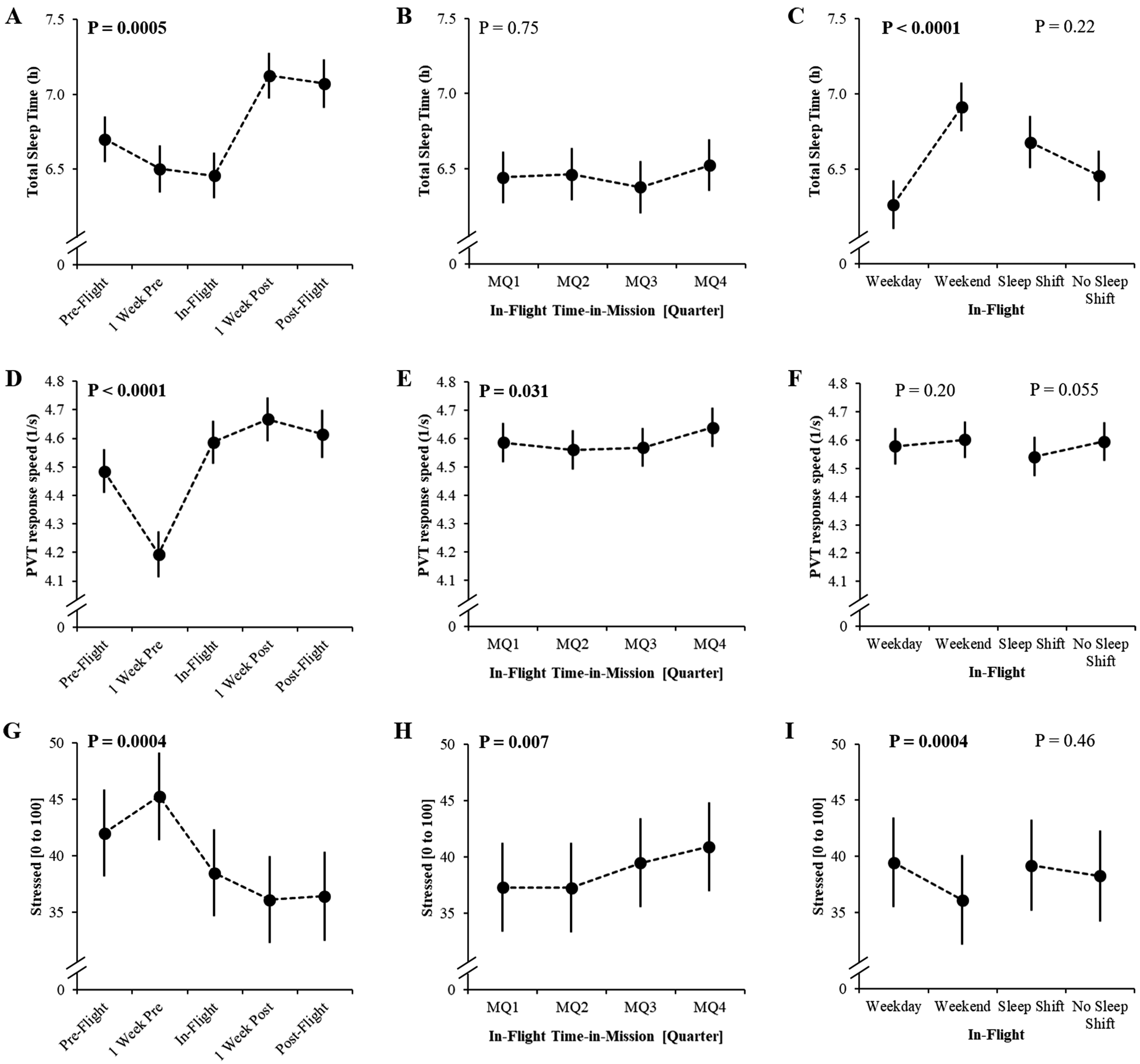

Figure 1. The dynamics of sleep duration, PVT-B response speed, and astronaut stress ratings across mission phases. Means (± SEM) are presented for sleep duration (total sleep time [TST]; *N* = 1,418 TST measurements) in panels A–C, PVT-B response speed in panels D–F (*N* = 2,856 PVT-B measurements; a lower score on PVT response speed is slower), and ratings of stress in panels G–I (*N* = 2,541 stress measurements; VAS anchors: 100 = very stressed; 0 = not stressed). Given that ISS missions include both the pre-flight preparation and post-flight readjustment to Earth, as well as in-flight on the ISS, profiles of the three outcomes are first separated by mission phase (Panels A, D, G). In-flight profiles of TST, PVT-B response speed, and stress ratings are then presented across time-in-mission, by ISS mission quarter (Panels B, E, H). Data from these outcomes are also presented for in-flight weekdays and weekends, as well as sleep-shift vs. no sleep-shift (Panels C, F, I). Mixed-model analyses for statistical significance ($p \leq 0.05$) for each data domain and mission time period are shown in the upper left-hand corner for mission phase and ISS mission quarter analyses (Panels A–B, D–E, G–H) and for Panels C, F, and I the left *p*-value refers to the weekday vs. weekend comparison and the right *p*-value refers to sleep shift vs. no sleep shift comparison (bolded *p*-values denote significance).

(i.e. physical exhaustion, mental fatigue, sleepiness, tiredness) did not exhibit differences between mission phases or changes across ISS mission quarters, with the exception of physical exhaustion, which exhibited a significant increase in the first week post-flight (Supplementary Figure S13A). Astronaut report of caffeine use changed across mission phase and increased across ISS mission quarters (Supplementary Figure S9).

Sleep duration and neurobehavioral functions during spaceflight

Mixed-models evaluated the relationship between sleep duration and PVT-B outcomes, adjusting for RST administration time of day (i.e. morning/evening), age, sex, and astronauts' report of distractions during the PVT-B. Sleep duration was associated with PVT-B response speed (Figure 2A; $F = 40.76$; $p < 0.0001$); neither age nor sex accounted for a significant portion of variance in the model. PVT-B response speed was significantly slower when sleep duration was ≤6 h (34.9% of nights) than when sleep duration was >6 h (Supplementary Table S6). Conversely, more than 9 h of sleep was associated with faster PVT-B response speed relative to sleep durations ≤7 h. Although, sleep duration was associated with both PVT-B lapses of attention (Supplementary Figure S6) and PVT-B errors of commission (Supplementary Figure S7), pair-wise comparisons were not significant after correction for multiple testing.

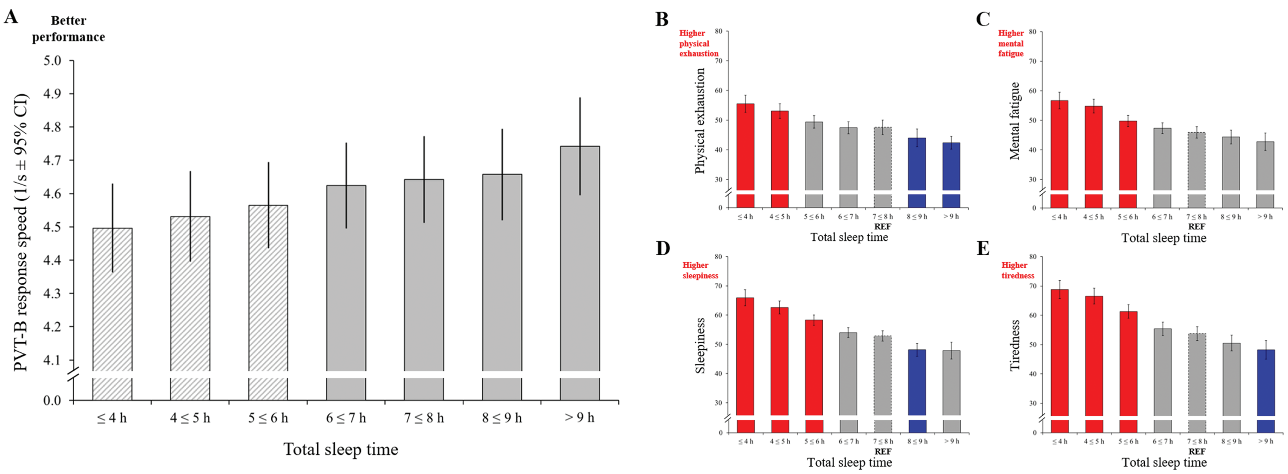

Figure 2. The impact of sleep duration on neurobehavioral functions during ISS missions. For all figure panels, sleep duration is binned into 1 h periods between ≤4 h and >9 h total sleep time (TST). In panel A, mean PVT-B response speed (N = 1,774 independent PVT-B assessments) is presented with 95% confidence intervals where larger numbers represent better performance. Sleep durations < 6 h were associated with slower PVT-B response speed; this is visualized using the gray diagonally lined bars (i.e. ≤4 h, 4 ≤ 5 h, and 5 ≤ 6 h TST), which represent significant pairwise differences from all dark gray bars (Supplementary Table S6). Conversely, longer sleep duration of TST > 9 h was associated with faster (i.e. higher) PVT-B response speeds relative to all groups with TST ≤ 7 h. Panels B–E present the least squares means ± SEM (adjusted for age, sex, and RST administration time of day) for astronaut ratings of somatic behavioral states, including physical exhaustion (B), mental fatigue (C), sleepiness (D), and tiredness (E) as a function of sleep duration (N = 1,703 independent ratings in each panel). For Panels B–E, the recommended sleep amount for healthy adults of 7–8 h (6) was used as the reference group ("REF") and significantly higher astronaut ratings relative to the reference are colored red and significantly lower ratings are colored blue. Sleep durations < 5 h were associated with higher ratings of all somatic behavioral states, while longer sleep durations were associated with reductions in negative ratings of some somatic behavioral states (i.e. physical exhaustion [B], sleepiness [D], and tiredness [E]).

Given that the ISS is an operational work environment and that the recommended nightly sleep duration for healthy adults is 7–8 h [6], mixed-models evaluated the relationship between sleep duration and astronaut ratings of stress, workload, sleep quality, and somatic behavioral states, adjusting for age, sex, and RST administration time of day (i.e. morning/evening) specifying the 7–8 h sleep duration group as the referent. Significant relationships between sleep duration and astronaut ratings of somatic behavioral states were observed for physical exhaustion (Figure 2B; $F = 6.49$; $p < 0.0001$), mental fatigue (Figure 2C; $F = 8.22$; $p < 0.0001$), sleepiness (Figure 2D; $F = 13.27$; $p < 0.0001$), and tiredness (Figure 2E; $F = 22.62$; $p < 0.0001$). Less than 5 h of sleep was associated with higher ratings of all somatic behavioral states and sleep durations less than 6 h were associated with higher ratings of mental fatigue, sleepiness, and tiredness (Table 1). Six or more hours of sleep was not associated with differences in astronaut ratings of somatic behavioral states and longer sleep durations (e.g. >8 h) were associated with lower ratings of physical exhaustion, sleepiness, and tiredness (Figure 2B–E; Table 1).

Sleep duration was also associated with astronaut ratings of stress (Figure 3A; $F = 5.94$; $p < 0.0001$), where less than 6 h of sleep was associated with higher ratings of stress relative to 7–8 h of total sleep time (Table 1). The amount of sleep was associated with astronaut ratings of workload (Figure 1B; $F = 16.48$; $p < 0.0001$), where sleep durations less than 7 h were associated with higher ratings of workload, while sleep durations longer than 8 h were associated with lower ratings of workload (Table 1). Ratings of sleep quality were also associated with sleep duration (Figure 3C; $F = 29.56$; $p < 0.0001$), where sleep durations less than 7 h were associated with ratings of worse sleep quality and 9 h or more of sleep was associated with better ratings of sleep quality (Table 1).

The effect of increasing in-flight stress ratings on the relationships between sleep and astronaut ratings of stress, sleep quality, and somatic behavioral states

Given the importance of stress responses to astronaut behavioral health and that stress ratings significantly increased across mission duration (Figure 1H), we examined whether astronauts who reported increasing stress ratings exhibited other changes in sleep–wake behaviors and neurobehavioral functions. To achieve this, the study sample was limited to astronauts with significantly increasing stress ratings ($n = 15$ astronauts) and between subjects correlations were evaluated. In these astronauts, increasing stress ratings were associated with shorter sleep duration (Supplementary Table S10; rho = −0.69; $p = 0.004$) and higher physical exhaustion (rho = 0.55; $p = 0.028$). Furthermore, increasing physical exhaustion ratings were also associated with worse sleep quality (rho = −0.80; $p = 0.0002$) and greater tiredness (rho = 0.81; $p = 0.0002$).

Discussion

In the largest study to date of astronaut sleep and neurobehavioral functions during spaceflight missions on the ISS, this study found that when sleep was 6 h or less, astronauts exhibited significant decrements in neurobehavioral functions, including vigilant attention and somatic behavioral states, consistent with laboratory studies on Earth [11, 17]. Although astronauts exhibited faster mean PVT response speed in the fourth mission quarter, the effect was moderate and less than the differences observed between sleep durations. Despite a scheduled sleep opportunity of 8.5 h per night, astronauts reported an average of ~6.5 h of nightly sleep and astronauts slept the scheduled 8.5 h on only 5.9% of nights, consistent with previous

Table 1. The association between sleep duration and astronaut ratings of behavioral state

	Stressed		Workload		Sleep quality		Physical exhaustion		Mental fatigue		Sleepiness		Tiredness	
Variable	β	*P* value	β	*P* value	β	*P* value	β	*P* value	β	*P* value	β	*P* value	β	*P* value
Total sleep time														
≤4 h	**7.652**	**<0.0001**	**9.953**	**0.019**	**21.137**	**<0.0001**	**7.751**	**0.0002**	**10.578**	**<0.0001**	**12.793**	**<0.0001**	**15.594**	**<0.0001**
4 ≤ 5 h	**3.765**	**0.0040**	**13.084**	**0.0001**	**21.493**	**<0.0001**	**5.522**	**0.0009**	**8.508**	**<0.0001**	**9.542**	**<0.0001**	**12.733**	**<0.0001**
5 ≤ 6 h	**2.633**	**0.0025**	**14.239**	**<0.0001**	**9.154**	**<0.0001**	**2.406**	**0.032**	**4.012**	**0.0009**	**5.265**	**<0.0001**	**7.804**	**<0.0001**
6 ≤ 7 h	0.545	0.48	**6.341**	**0.0014**	**3.656**	**0.0066**	0.403	0.69	1.676	0.12	1.424	0.19	1.963	0.060
7 ≤ 8 h	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
8 ≤ 9 h	−1.064	0.39	**−10.495**	**0.001**	−3.581	0.093	**−2.929**	**0.065**	−1.326	0.44	**−3.772**	**0.029**	−2.438	0.14
> 9 h	−0.516	0.76	**−16.547**	**0.0002**	**−10.016**	**0.0006**	**−5.319**	**0.015**	−3.920	0.096	**−4.909**	**0.040**	**−5.722**	**0.013**
Age	0.506	0.59	−0.041	0.94	−0.662	0.27	0.141	0.77	−0.137	0.74	−0.317	0.41	0.284	0.60
Sex	−3.360	0.74	−0.978	0.87	1.260	0.84	3.788	0.46	**11.581**	**0.009**	1.156	0.77	−5.807	0.30
Evening RST	0.452	0.40	.	.	.	.	**16.840**	**<0.0001**	**14.553**	**<0.0001**	**22.035**	**<0.0001**	**24.293**	**<0.0001**

Bolded values identify significant associations at $p < 0.05$. RST administration time of day was not included in mixed-models for both astronaut ratings of workload and sleep quality as these ratings were collected exclusively in evening and morning RSTs, respectively.

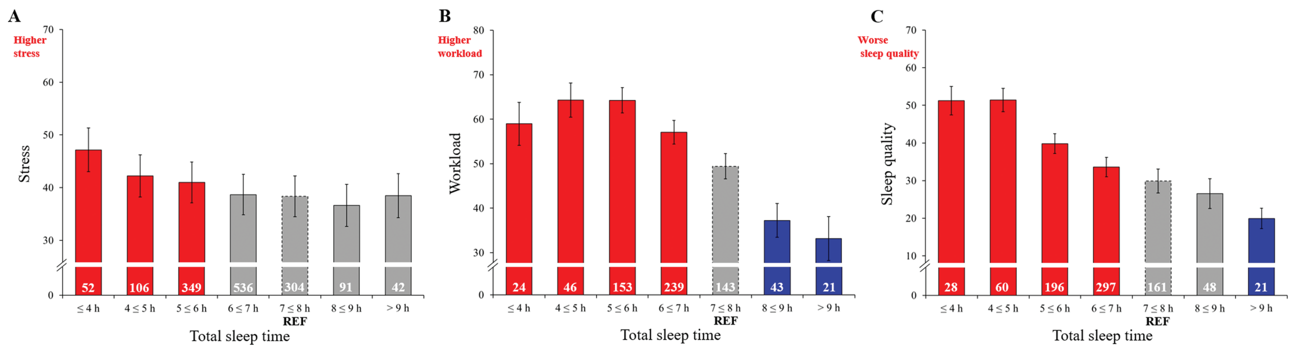

Figure 3. The impact of sleep duration on astronaut ratings of stress, workload, and sleep quality. Sleep duration is binned into 1 h periods between ≤4 h and >9 h total sleep time (TST). Least squares means ± SEM (adjusted for age, sex, and RST administration time of day) are presented for astronaut ratings of stress (A; N = 1,703 measurements), workload (B; N = 764 measurements), and sleep quality (C; N = 939 measurements) for each sleep duration grouping. The number of ratings within each sleep duration grouping is shown in white at the bottom of each bar; ratings of stress were collected in both morning and evening RST administrations, while workload (evening RST) and sleep quality (morning RST) were collected once on an RST testing day. The recommended sleep amount for healthy adults of 7–8 h (6) was used as the reference group ("REF"), and significantly higher astronaut ratings relative to the reference are colored red and significantly lower ratings are colored blue. Sleep durations < 6 h were associated with higher ratings of stress (A) while longer sleep durations were not associated with lower ratings of stress. Higher astronaut ratings of both workload (B) and worse sleep quality (C) were observed for sleep durations < 7 h, while longer sleep durations were associated with lower ratings of workload (B; > 8 h TST) and better sleep quality (C; > 9 h).

reports of astronaut sleep-wake behaviors on ISS missions [7]. Astronaut ratings of stress increased across ISS mission quarters and in astronauts that reported increasing stress ratings, sleep duration was shorter. Furthermore, short sleep durations were associated with elevated ratings of stress and workload, negative somatic behavioral states, as well as ratings of worse sleep quality. These findings demonstrate the importance of achieving sleep of adequate duration and quality in astronauts in the operational environment of the ISS. Sleep of 7 h or more can also have beneficial effects on astronaut neurobehavioral functions, highlighting the need to ensure astronauts achieve sufficient sleep durations during spaceflight.

Many factors can contribute to sleep-wake dynamics during spaceflight, including both environmental factors and operational demands. Barger et al. [7] posit that the sleep deficiency of astronauts is behaviorally induced and the findings of this study, to some extent, provide support for this assertion and suggest that operational demands are also substantive contributors to the observed sleep deficiency. In this study, short sleep duration in-flight was primarily due to a shift in sleep timing that resulted in truncated sleep opportunities; astronauts went to sleep later than the NASA scheduled start of the sleep period and awoke close to the scheduled wake time (Supplementary Figure S1). The sleep opportunity of astronauts (i.e. time in bed) was stable across ISS mission quarters, however higher workload was significantly associated with shorter time in bed (Supplementary Figure S14), suggesting that shorter sleep duration on the ISS is, to some extent, a function of truncated sleep opportunities. Also, astronauts did not exhibit changes in wake after sleep onset (a crude metric of sleep disruption) or changes in sleep efficiency while on the ISS (Supplementary Figures S3 and S4), suggesting that astronaut sleep was not necessarily disrupted in spaceflight. Although self-reported sleep disturbance on the ISS is relatively common (35% of nights) [7], one PSG study in cosmonauts did not find significantly disturbed sleep during long-duration spaceflight on MIR relative to Earth, but found alterations in sleep architecture [9]. Moreover, the associations between sleep duration and astronaut ratings of workload suggest that the operational demands on astronauts may be drivers of the observed sleep deficiency. Short sleep durations were associated with significantly higher ratings of workload and relative to shorter sleep durations, longer sleep durations were associated with substantially lower ratings of workload. Astronaut sleep duration in-flight was also significantly longer on weekends (6.9 h) relative to weekdays (6.3 h) and although causality cannot be delineated from these observational data, it appears that astronauts can sleep longer when the work demand is lower, if provided the opportunity. However, the longer sleep durations observed on weekends, when workload was lower, did not result in sleep durations commensurate with the scheduled sleep period, suggesting that although a strong contributor to sleep duration, workload is not the only contributor to the observed sleep deficiency. These findings highlight the importance of optimizing astronaut work-rest schedules to allow for operational and personal/social demands while also providing adequate opportunities for sleep. This is consistent with epidemiological findings of work-rest schedules on Earth and suggests that maintaining Earth-based rhythms may help to promote healthy sleep-wake behaviors of astronauts on long-duration spaceflight missions [18, 19].

Given the differences between the spaceflight environment from that of Earth, the pathways through which spaceflight impacts human biology and influences behavior may vary from those established on Earth. Furthermore, the potential for both independent and interactive effects of the chronic stressors of spaceflight, such as exposure to microgravity and ionizing radiation, as well as prolonged isolation and confinement, suggest that examining factors together may provide an understanding of the consequences of spaceflight on human biology. A prominent candidate through which spaceflight may impact neurobehavioral performance as a function of sleep and stress is through changes in brain structure and functional connectivity [20–26]. Widespread reductions in gray matter volume, notably in the orbitofrontal cortex (OFC) and the medial temporal lobe (MTL), as well as reductions in white matter, have been observed in astronauts and cosmonauts after completing long-duration spaceflight missions [20, 21, 25]. Convergent evidence from neurobiological studies position sleep, and the loss of sleep, as a central and potentially modifiable factor connecting spaceflight-associated brain changes, neurobehavioral performance, and chronic stress [27–29]. Sleep loss is associated with inhibited functional connectivity in the frontal lobe [29] and the neurobehavioral deficits resulting from sleep deprivation are preceded by increased neuronal response latencies in the MTL [28]. Sleep loss also elevates stress [30–32] and chronic stress induces neural remodeling in both the OFC and MTL in rodents [27]. A recent ground-based simulation of the prolonged confinement and isolation characteristic of long-duration spaceflight found volumetric reductions in both the OFC and MTL, with greater reductions in the dentate gyrus associating with greater neurocognitive impairment [33]. In this study, decrements in vigilant attention and higher ratings of stress were observed when sleep durations were short (<6 h) and future studies that integrate neuroimaging with measures of astronaut sleep and neurobehavioral functions are needed. Taken together, the potential for independent, interactive, and additive effects between sleep loss, chronic stress, and changes in brain structure and function suggest that countermeasures aimed at promoting sleep and stress management should be informed by neuroscientific approaches. Examining factors, such as sleep and stress, together may provide a more comprehensive view of these relationships, which is highlighted by the independent and interactive effects of radiation exposure (a substantial risk for astronauts on a Mars mission) and sleep restriction on neurobehavioral performance decrements in rodents [34, 35].

Although the study has strengths, it is not without limitations. The study relied on self-reported sleep-wake behaviors, however the study findings are consistent with previous objective and self-reported sleep measurements of astronauts on the ISS [7]. Furthermore, circadian misalignment has negative effects on astronaut sleep in spaceflight; where sleep periods at an adverse circadian phase have been reported on 19% of nights and on these nights, sleep duration was significantly shorter (i.e. 5.4 h adverse circadian phase vs. 6.4 h aligned circadian phase) [36]. In this study, we found that sleep shifts occurred on 15.7% of nights ($n = 537$ sleep periods) and although we assessed the impact of shifted sleep on study outcomes, the study design limited the ability to evaluate circadian misalignment effects on neurobehavioral function due to the lack of continuous sleep-wake measurements and RST evaluations. Also, astronaut PVT-B response speed increased across mission quarters with the highest performance in ISS mission quarter four, despite unchanging sleep duration across ISS mission quarters. This increase in PVT-B response speed may have been influenced by increased caffeine consumption [37], which was also highest in ISS mission quarter four (Supplementary Figure S9), even though caffeine consumption did not vary by sleep amount. Moreover, indeed sleep is an integral factor, it is not the sole factor that influences vigilant attention [38]. The sample size of the study was modest for Earth-based studies, yet large for studies of astronauts during spaceflight[5] and the repeated measures within individuals mitigates concerns of inadequate statistical power. There were missing data and although data imputation was not conducted, the use of mixed-models accommodates missing data and the averaging of data within a pre-selected time period (e.g. pre-flight, in-flight, post-flight, or ISS mission quarters) to some extent, reduces contributions of missing data between astronauts. The low number of female astronauts precludes the examination of sex differences, although the study sample demographics are representative of the NASA Astronaut Corps [39, 40]; future studies with adequate female representation are needed to examine sex differences. Although the study had repeated measurements, the observational nature of the data prevent examining the causality of relationships.

The association of reduced sleep duration and worse sleep quality with astronauts' ratings of negative somatic behavioral states and stress in spaceflight suggests that sleep deficiencies may have a sustained and possibly cumulative adverse effect on astronauts in-flight as mission duration increases. The consequences of shortened sleep duration are not limited to neurobehavioral functions, but include impacts on immune regulation and autonomic nervous system functioning [41, 42]. Recent strategies employed on the ISS to mitigate the spaceflight-induced impacts on immune regulation hold promise [43, 44]. If successful, they may support the examination of integrative strategies that target the underlying biological systems influencing neurobehavioral functions essential for astronaut behavioral resilience and health during exploration class missions to Mars [45].

Supplementary Material

Supplementary material is available at *SLEEP* online.

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C.W.J., D.F.D., and M.B. declare no competing interest. D.J.M. and C.M. are principals of Pulsar Informatics; Pulsar Informatics was responsible for software implementation of RST. D.J.M. and C.M. declare no conflict of interest. This manuscript has not appeared in any preprint repository.

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Data Availability

Data have been uploaded to NASA's Life Sciences Data Archive (LSDA) per funding agency requirements and are available through request from NASA.

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