Repeated long-duration space missions facilitate brain plasticity at night and psychological resilience during daytime

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Abstract

Repeated long-duration spaceflights of a healthy astronaut, 4 years apart, facilitated microgravity-induced brain-plasticity and psychological-resilience, observed about 20 days after launch (ISS01) during the second mission. Sleep duration lengthened, sleep quality improved, and spectral power of heart rate variability indices (HRV, $msec^2$), co-varying with activity of the salience network (SN), increased at night: HF-component (0.15–0.50 Hz) from 345.1 to 557.5 (P = 0.0580), and HF-band (0.30–0.40 Hz) from 52.7 to 101.5 (P = 0.0417). Spectral power of HRV indices during daytime, which correlate negatively with psychological-resilience, decreased: HF-component from 321.0 to 249.8 (P = 0.0240), and HF-band from 58.5 to 36.7 (P = 0.00002). LF-component and LF-band, reflecting activity of the default mode network, did not change significantly. Contrary to the first mission, no significant changes in 24-hour acrophases of HRV endpoints were observed about 20 days after launch during the second mission, but the 12-hour acrophase of TF-HRV underwent a remarkable phase delay from − 216° to -52° (P < 0.0001). The 12-hour component could thus consolidate the circadian system and contribute to a better adaptation in space by taking advantage of brain plasticity at night and psychological resilience during daytime.

Introduction

Magnetic resonance imaging (MRI) studies showed narrowing of the central sulcus, upward shift of the brain, and narrowing of cerebrospinal fluid spaces at the vertex in most astronauts examined [1, 2]. Impaired cerebrovascular circulation in microgravity may induce cortical reorganization. Understanding the effects of spaceflight on the human central nervous system is pivotal for the development of adequate countermeasures. Maximizing crew performance and health is crucial for the success and safety of future prolonged space missions, including missions to the moon or Mars.

The central nervous system seems capable of adaptation to microgravity by the process of neuroplasticity, as previously shown in animals [3]. Yet, little is known about the effects of microgravity and gravity transitions on the human brain [4]. After exposure to microgravity, significant differences in resting-state functional connectivity between motor cortex and cerebellum, and changes within the default mode network (DMN) have been reported [2, 4]. Changes in brain function could account for the fact that second-time flyers are less prone to some microgravity-related problems than first-time flyers, given the process of neural adaptation. It is thus important to learn how long physiological adaptation processes last. Research investigating space travelers at different intervals post-flight could answer this question.

The intimate brain-heart connection enunciated by Claude Bernard can be studied by analyzing heart rate variability (HRV) [5]. HRV may reflect the activity of the coordinating system [6, 7], notably brain functional connectivity, including the DMN and the salience network (SN), which integrates the brainstem nuclei that directly regulate the heart. The heart and brain are connected bi-directionally, and HRV varies in concert with changes in brain functional connectivity. As we reported earlier [7], HRV may serve as a proxy for ‘vertical integration’ of the brain in association with DMN and SN functions. HRV may provide

information on how the brain coordinates with the periphery, and may thus inform about the extent of adaptive adjustment.

Many investigations recently showed how psychological resilience, including subjective well-being and life satisfaction, can be assessed using imaging modalities within the brain, such as low-frequency fluctuations in the anterior cingulate cortex (ACC), orbitofrontal cortex (OFC), posterior cingulate cortex (PCC) and thalamus, largely comprising the brain functional networks of the DMN and SN [8, 9]. Astronauts aboard the International Space Station (ISS) must be filled with a strong vocation, which is reflected on the mission. In the case of repeated space missions, astronauts must have an even stronger commitment for a better accomplishment.

Herein, we investigate one astronaut's brain plasticity by assessing how sleep performance and HRV (gauging activity of intrinsic networks of the brain, particularly the DMN and SN) changed from first-time to second-time long-duration spaceflight four years later. We also examine how repeated spaceflights affect the well-being or life satisfaction of this astronaut, gauged by changes in HRV associated with changes in brain functional connectivity, for a better adaptation to microgravity.

Subject And Methods

Subject

A healthy astronaut participated in the ISS Japan Aerospace Exploration Agency (JAXA) investigation named "Biological Rhythms 24 Hrs & 48 Hrs". Stays in space lasted approximately 4.5 and 6 months on the first and second flights, respectively. The astronaut had passed class III physical examinations from the National Aeronautics and Space Administration (NASA). The study was approved by the Institutional Review Boards of NASA, ESA (European Space Agency), Pro0406 (MODCR940) - Amd-10, and JAXA, JX-IRBA-20-084 Amd-10. Informed consent was obtained from the astronaut. A detailed explanation of the study protocol was given to the astronaut before obtaining written, informed consent, according to the Declaration of Helsinki Principles. All methods were performed in accordance with the JAXA/ESA/NASA guidelines and regulations.

Experimental protocols

Ambulatory around-the-clock ECG records were obtained over 24 hours on the first flight and over 48 hours on the second flight by a two-channel Holter recorder (FM-180; Fukuda Denshi, Tokyo, Japan). Measurements were taken four times during each mission: once before flight (Pre: 189 and 50 days before launch); twice during flight on the ISS: ISS01 (day 18 and day 21 after launch), and ISS02 (day 67 and day 181 after launch); and once after the mission (Post: 138 and 188 days after return to Earth).

For assessing microgravity-induced brain plasticity, we focused only on ISS01 because measurements were obtained at about the same time after launch in both missions, on days 18 and 21 on the ISS, respectively. Because the second session on the ISS took place much later on the second than on the first

spaceflight (on day 181 versus day 67), data collected during ISS02 were not suitable for evaluating brain plasticity.

Analysis of HRV

Data collection and measurement procedures were conducted as previously reported [7, 10, 11, 12, 13]. Briefly, for HRV measurements, the RR intervals between normal QRS waveforms were extracted as normal-to-normal (NN) intervals, which were A/D converted (125-Hz) with 8-ms time resolution. The authors first confirmed that all artifacts were actually removed and that the data excluded supraventricular or ventricular arrhythmia. Next, time-domain measures (CVRR, r-MSSD and pNN50), Lorenz plot (Length, Width and Length/Width ratio), and frequency-domain measures (TF-, ULF-, VLF-, LF- and HF-HRV, LF/HF ratio and β, reflecting the intrinsic cardiovascular regulatory system) were obtained with the Maximum Entropy Method (MEM) software (MemCalc/CHIRAM, Suwa Trust GMS, Tokyo, Japan) [14]. Time series of NN intervals covering 5-min intervals were analyzed by the MEM to compute the spectral power in different frequency regions. Frequency regions examined were 0.05–0.15 Hz (LF-component) and 0.15–0.50 Hz (HF-component), according to Chang et al. [6]; 0.01–0.05 Hz (LF-band), 0.05–0.10 Hz (MF1-band), 0.10–0.15 Hz (MF2-band), and 0.15–0.20 Hz (HF01-band), according to Baria et al. [15]; 0.20–0.30 Hz (HF02-band), 0.30–0.40 Hz (HF03-band), and 0.40–0.50 Hz (HF04-band), according to Chen and Glover [16].

A positive response in these bands is thought to indicate how astronauts adapt to the space environment. The LF- and MF1-bands reflect an activation of the DMN's medial prefrontal cortex (mPFC), posterior parietal cortex, posterior portion of precuneus and posterior cingulate cortex. The MF2- and HF01-, HF02-, HF03-, and HF04-bands show dynamic interactions among the DMN and SN, i.e., the alerted DMN involved in the adaptation to a novel environment [7, 15, 16].

Cosine curve fitting for estimating amplitude and phase by cosinor

The MEM software (MemCalc/Win, Suwa Trust GMS, Tokyo, Japan) [14] was used to fit a single 24-hour or 12-hour cosine curve individually to each of the HRV measures by cosinor [17, 18, 19]. The 24-hour and 12-hour amplitudes and acrophases together with the MESOR (Midline Estimating Statistic Of Rhythm, a rhythm-adjusted mean) were thereby estimated. Changes in biological rhythm amplitude and acrophase assessed the response in rhythmicity of each biological rhythmic component to the space environment.

Sleep duration and sleep quality

Sleep duration at night was estimated by using circadian profiles of RR-intervals and 5-min HF endpoints of HRV [10, 13, 20]. Sleep duration on the second spaceflight was estimated as the average of the two consecutive sleep spans of the 48-hour ECG record. Sleep quality was determined based on whether a sleep-related increase in RR-interval and in HF of HRV could be observed or not, as shown in Fig. 1.

Statistical analyses

Data were expressed as mean ± standard deviation (SD). For comparison of HRV indices, statistical analyses were applied on hourly averages of the 5-minute estimates in order to minimize serial correlation. Paired hourly HRV indices were compared between the two spaceflights, focusing on ISS01 (days 18 and 21 after launch, respectively), using the paired t-test. The Stat Flex (Ver. 6) software (Artec Co., Ltd., Osaka, Japan) was used. P-values less than 0.05 were considered to indicate statistical significance.

Results

Change in sleep performance

Sleep duration around day 20 after launch during ISS01 was longer on the second (374 min) than on the first (300 min) spaceflight. Sleep duration before flight, during ISS02 and after return to Earth on the second versus first mission was 297 vs. 289 min, 365 vs. 295 min, and 330 vs. 360 min, respectively. Sleep quality was improved on the second compared to the first spaceflight, as suggested by a clear increase in spectral power of the HF-HRV, Fig. 1.

Dynamic response of the autonomic nervous system

As shown in Table 1 (right), nighttime HR was lower on the second than on the first mission during ISS01 (56.5 vs. 58.3 bpm, P = 0.0220 by paired t-test), as was the intrinsic cardiovascular regulatory function |β| (0.5400 vs. 0.7533, P = 0.0137). Parasympathetic activity was increased on the second mission, as shown by the Width of Lorenz plot (159.3 vs. 119.3, P = 0.0466) and by HF-HRV (510.7 vs. 317.4 $msec^2$, P = 0.0939). No significant changes were found during nighttime in sympathetic activity, gauged by the LF/HF ratio and Lorenz plot's Length/Width .

During daytime (Table 1, left), parasympathetic activity was lower on the second than on the first mission during ISS01, gauged by r-MSSD (32.2 vs. 41.8, P = 0.0002), pNN50 (9.2 vs. 17.7, P = 0.0001), Length of Lorenz plot (263.6 vs. 300.2, P = 0.0378), Width of Lorenz plot (81.9 vs. 138.2, P = 0.0087), and HF-HRV (227.7 vs. 283.1, P = 0.0501). Sympathetic activity increased during daytime, gauged by the LF/HF ratio (4.85 vs. 3.63, P = 0.0005) and Lorenz plot's Length/Width (3.69 vs. 2.62, P = 0.0004). No statistically significant changes were found in HR and NN-intervals.

Effects of spaceflight on brain functional networks estimated by heart rate variability

Activity of brain functional networks is reflected in several indices of HRV [6, 7]. Although not statistically significant, HRV indices reflecting SN activity tended to increase on the second compared to the first spaceflight during nighttime (Table 1, right) [5, 15, 21, 22]. The HF-component increased from 345.1 to 557.5 $msec^2$ (P = 0.0903) (Fig. 2, top of right), HF01-band from 102.5 to 138.3 $msec^2$ (P = 0.0737), HF02-band from 162.2 to 270.9 $msec^2$ (P = 0.1392), HF03-band from 52.7 to 101.5 $msec^2$ (P = 0.0665) (Fig. 2,

bottom of right), and HF04-band from 27.7 to 46.8 msec^2 (P = 0.0788). As shown in Table 1, left, these HRV indices reflecting SN activity changed statistically significant during daytime during ISS01. The HF-component decreased on the second versus first spaceflight during daytime (P = 0.0240) (Fig. 2, top of left), HF03-band and HF04-band decreased from 58.5 to 36.7 (P = 0.0002) (Fig. 2, bottom of left) and from 37.9 to 22.1 (P = 0.0003), respectively.

The LF-component, LF- and MF1-bands, reflecting DMN activity [6, 15, 21], showed no significant changes between the two spaceflights, during daytime or nighttime (Table 1).

Circadian desynchrony in space favorably modified by amplified circasemidian rhythm: difference between the two spaceflights

Changes in circadian and circasemidian amplitudes of HRV endpoints in response to the novel microgravity environment and the long-duration spaceflight are shown in Table 2. On the first spaceflight, the circadian amplitude of HR increased more than two-fold during both during ISS01 (255%) and ISS02 (271%) compared to pre-flight, as observed previously [13]. This was not the case on the second spaceflight. On the first mission, the circadian amplitude of the intrinsic cardiovascular regulatory system function (β) also increased during both ISS01 (303%) and ISS02 (233%), compared to pre-flight. The adaptation behavior of the 12-hour component of HRV endpoints was remarkably larger than that of the 24-hour rhythm, particularly for TF-HRV, seen in both amplitude and phase. The 12-hour amplitude of TF-HRV increased up to 574% and 473% during ISS01 and ISS02, respectively, on the first spaceflight, although similar changes were not clear on the second spaceflight.

An apparent phase shift of the 24-hour and 12-hour components of HRV endpoints in response to spaceflight was observed after fitting a single 24-hour or 12-hour cosine curve separately to the 20 HRV measures by cosinor. Results are summarized in Table 3, where misaligned circadian phases occurring at unusual times (such as day-night reversals), are shaded. On the first but not on the second spaceflight, quite a few HRV endpoints show circadian misalignment pre-flight (Table 3, left), suggesting that circadian desynchrony due to social jetlag was larger on the first than on the second mission.

The recovery process of such internal desynchrony of the 20 HRV indices during spaceflight is shown in Fig. 3. It depicts the time course of the circadian (Fig. 3, top) and circasemidian (Fig. 3, bottom) acrophases during the first (Fig. 3, left) and second (Fig. 3, right) missions. On the first mission, circadian acrophases advanced on average by about 8 hours, from 14:37 (pre-flight) to 6:26 (ISS01) (P < 0.0001). Any misalignment of these circadian acrophases improved during ISS01, maintaining a similar timing of 8:59 during ISS02 (Fig. 3, top left). Circasemidian acrophases showed an average phase-delay of 165 degrees (5.5 hours) from − 155° (05:10 and 17:10) to -320° (10:40 and 22:40) (P < 0.0001) during ISS01, and were maintained at -247° (08:14 and 20:14) during ISS02 (Fig. 3, bottom left). The 5-time amplified 12-hour component may thus help restore internal synchrony to the 24-hour clock. Presumably, circadian

acrophases may have over-adjusted to 06:26 during ISS01 and were readjusted to 08:59 during ISS02 (Fig. 3, top left).

During the second mission, circadian acrophases, on average, showed no significant changes from pre-flight (05:15) to ISS01 (05:22) and ISS02 (04:24) (Fig. 3, top right). Circasemidian acrophases, by contrast, advanced on average by 164 degrees (5.5 hours) from − 216° (07:12 and 19:12) to -52° (01:44 and 13:44) ($P < 0.0001$), returning to their original phase of -244° (08:08 and 20:08) during ISS02 (Fig. 3, bottom right). However, when examining results in Table 3, TF-HRV, ULF-HRV and MF2-band showed some phase misalignment during the second mission, with advanced circadian acrophases occurring at 10:21, 11:11 and 05:20, respectively. In this case, it seems that the 12-hour component was sufficient to repair the small 24-hour internal desynchrony without any amplification.

Discussion

The comparison of HRV behavior of a healthy astronaut monitored on two long-duration space missions indicates improvement in the process of neural adaptation on the second spaceflight. Results assessed around day 20 after launch indicate that microgravity-induced brain-plasticity or well-being, including life satisfaction, may have contributed to the improved adaptation. During nighttime, sleep improved, and HRV activity co-varying with brain neural activity in the SN accelerated, while decelerating during daytime. HRV endpoints reflecting DMN activity showed no differences between the 2 space missions.

Stimulating environment and brain plasticity

Brain plasticity refers to the capacity of neurons and of neural circuits in the brain to change, structurally and functionally, in response to experience. This property is fundamental for the adaptability of behavior, for learning and memory processes, brain development, and brain repair. The environment can greatly affect brain function. Exposure to stimulating environments has repeatedly been shown to strongly influence brain plasticity. Thus, it is a crucial underlying component of the enormous challenge of space adaptation for astronauts. Neural plasticity can take place at several levels, from synaptic plasticity at the (sub)cellular level to plasticity at the system and network levels [23, 24]. Brain plasticity can be studied with a number of methods, such as electroencephalography (EEG)/evoked potentials (ERPs), structural and functional MRI and transcranial magnetic stimulation (TMS). Herein, it was assessed in a healthy astronaut as changes in sleep performance and HRV behavior in specific frequency regions for interpretation in terms of functional brain networks, as done in previous studies [10, 20, 11, 13].

Our observation of improved sleep should show beneficial consequences of brain adaptation. Indeed, previous investigations reported shorter sleep duration and inadequate sleep quality of astronauts during spaceflight aboard the ISS. These results were attributed to environmental factors, including exposure to microgravity, the 90-min light-dark cycle from the skylight, weightlessness itself, excitement, and workload scheduled by operational demands [25, 26].

Effect of nighttime HRV changes on brain plasticity in space

Despite increased interest in the effect of spaceflight on the human central nervous system (CNS) [27], not much is known thus far about the functional and morphological effects of microgravity on the human CNS. Previous studies have shown that CNS changes occur during and after spaceflight in the form of neuro-vestibular problems, alterations in cognitive function and sensory perception, problems with motor function, cephalic fluid shift, and psychological disturbances [28, 29]. In the past few years, advances in structural and functional neuroimaging techniques have shown spaceflight-induced neuroplasticity in humans in several brain regions, including the insular cortex, the temporo-parietal junction, and the thalamus, in relation to short- and long-duration spaceflight [1, 2, 4]. However, this investigation did not show any accelerated DMN activity, reflected by Baria's LF-band [15] or Chang's LF-component [6] between the two spaceflights, either during daytime or nighttime.

We did observe a statistically significant increase in HRV indices that co-vary with SN activity. The SN is linked to the autonomic nervous system function in that both are sensitive to environmental challenges. The SN is mainly centered on the dorsal anterior cingulate, extending into the perigenual anterior cingulate cortex, and orbital fronto-insular cortices, but it also encompasses the limbic and brainstem areas. Relevance to HF-HRV is suggested by the inclusion of known autonomic nervous system control areas in the SN, and by this vagal marker's putative role in switching between rest and activity and between internal and external focus of attention.

Acceleration of SN activity started with nighttime sleep, suggesting that brain plasticity may have been initiated at night. The sensitivity of vagally-induced heart rate reactions to event salience might further suggest relationships between the SN and HF-HRV, as might the apparent overlap between nodes of the SN and areas related to autonomic control.

Identified as related to HF-HRV, the mPFC is important both as a node in the DMN and in the SN [30]. Anatomically, the mPFC is known to connect to pre-autonomic cell groups in the hypothalamus, periaqueductal gray, and brainstem [31, 32]. If diffuse attention is a major aspect of the functionality of the DMN, then the overlapping membership of the mPFC in the two networks would provide an anatomical site for shifting from DMN activation to SN activation. Some evidence supports the view that DMN activation is switched to SN activation when an interoceptive or environmental stimulus is encoded as significant [33].

Daytime HRV fluctuations associated with brain resilience in space

Because HRV may be associated with neural structures that are involved in the appraisal of threat and safety, HRV can be considered a potential marker of stress. HRV reflects the status of one's ongoing adjustment to constantly changing environmental demands. Previously, under stressful environments,

such as performing tasks during a spaceflight mission, HRV was found to be decreased [5]. Increased HF-HRV is considered to be associated with a positive mood, absence of negative affect, and an alert readiness to engage with the physical and social environment [34, 35].

Much recent research has found that psychological resilience, including subjective well-being and life satisfaction, is mediated by spontaneous brain activity measured with resting-state functional MRI. Although Waugh et al. [36] found that when facing with a threat, participants had prolonged changed activity in the insula in response to aversive stimuli, psychological resilience is a complex construct that likely involves different brain functions. Other studies provided evidence that brain resilience is related not only to the insula, but also to the mPFC, OFC, PCC, ACC, and thalamus [37, 38, 39, 40, 41, 42, 43]. In the extant literature, the most consistent brain area related to psychological resilience is the ACC, perhaps because the ACC is associated with many important emotional functions, including motivation, emotion regulation, and attention or adaptation to a novel environment, such as space [44, 45, 46, 47]. Previous investigations on resilience speculated that local activity in the ACC (such as fractional amplitude of low-frequency fluctuations measured by fMRI) would be negatively associated with psychological resilience [8, 47, 48].

The bi-directional connections between heart and brain enunciated by Claude Bernard can be studied by analyzing HRV [5, 49]. Over the past several years, many neuroimaging studies examined the association of HRV endpoints with fluctuations in brain functional connectivity [6, 7, 22, 50, 51]. They confirmed the existence of intimate connections between the different brain regions and HRV endpoints. They also posited that any changes in brain functional networks, which dynamically adjust the structure of their global and local network connectivity, should affect and change HRV activities in their respective frequency bands. “HRV is like a mirror reflecting the strength of activities of humans’ brain and mind” [5].

Astronauts’ vocation aboard the ISS is also expected to reflect changed activities in the respective HRV frequency bands. Several investigations reported a relation between levels of psychological well-being and HRV [52, 53], which confirmed a statistically significant negative correlation between life satisfaction and HF-HRV activities [52]. Our observation of decreased spectral power of HF-HRV, HF-component, and the series of the HF-band groups, and of lowered r-MSSD, pNN50 and Lorenz plot’s measures (Table 1, left and Fig. 2, left) thus suggests psychological resilience of the astronaut during the second space mission. It likely reflects increased well-being, a feeling of satisfaction or fulfillment during daytime on second compared to the first spaceflight.

Role of biological rhythms in the adaptation to the space environment

Whereas the circadian system plays a key role in the adaptation to a novel environment, such as microgravity in space [7, 10, 11, 12, 13], ultradian components provided an evolutionary advantage for almost all life forms, from bacteria to humans [54, 55, 56, 57, 58].

These ultradian rhythms can be expected to be important for the rapid adaptation to microgravity in space. The 12-hour (circasemidian) component in particular may be involved [59, 60, 61, 62, 63, 64]. It may reflect the function of two stress response pathways reacting to unfolded protein in the endogenous endoplasmic reticulum (ER) and mitochondria. A 12-hour (circasemidian) component characterizes the ER- and mitochondria-associated “unfolded protein response (UPR) cycle” [62, 63, 64, 65, 66, 67]. Several potential roles of the circasemidian clock in coordinating human health have been proposed, such as maintaining metabolic homeostasis [61], coordinating sleep quality of slow wave sleep [68, 69], and mediating aging, especially in the prevention of aging-related metabolic decline [61, 62, 70, 71].

Based on our observations herein, the following hypothesis comes to mind. First, when faced with a new environment in space, the 12-hour response appeared faster and was larger than the circadian response (Table 2). Second, strong 12-hour clock regulation might help repair circadian desynchrony (Table 3 and Fig. 3). The more severe internal desynchrony is (Table 3, Flight 1), the larger is the activation of the 12-hour component (Table 2 and Fig. 3, Flight 1). Third, the circasemidian response was milder during the second than during the first mission, suggesting that spaceflight-induced neuroplasticity was present in the astronaut’s brain during the second mission.

In conclusion, harmonic oscillations of 24 and 12 hours likely provide evolutionarily adaptive advantages. The 12-hour (circasemidian) component contributes to consolidating a strong circadian system in space, and may contribute to the better adaptation in space by taking advantage of brain plasticity at night and psychological resilience during daytime.

Limitations

This investigation has several limitations. First, the study is limited to a single astronaut, and space adaptation of human neural cardiovascular coordination remains a challenge, as mechanisms are diverse and complex. Second, brain oscillatory activity data are lacking. Several studies, however, showed that HRV is associated with structures and functions of the neural network, and HRV is a biomarker reflecting activities of the brain integration system. These associations are extremely complex, however, and have not yet been fully confirmed. Future investigations are needed to directly assess the brain’s oscillatory activity in space.

Conclusion

We examined the hypothesis proposed by Demertzi et al. [4] that second-time flyers adapt more quickly and are less prone to microgravity-induced problems [4, 72]. We confirmed that sleep duration lengthened and sleep quality improved. HRV behavior, which estimates the process of neural adaptation, displayed changes interpreted in terms of brain functional networks, which showed brain plasticity during nighttime and psychological resilience during daytime. Underlying factors for these adaptations are the contribution of the 12-hour component, which undergoes larger changes than the 24-hour component in response to the space environment, as assessed around day 20 on the ISS. HRV in the HF spectral region may be critical to assess microgravity-induced brain plasticity and psychological resilience, because HF-HRV

reflects the adaptation process. Adaptation to the microgravity environment in space studied herein pointed to functionally integrating the SN, consisting of neural centers (ACC, OFC, Amygdala and Insula), which involves and responds in a task-dependent manner to interoceptive-autonomic and reward processes in a task-independent manner to emotional and homeostatic stimuli of personal salience [8, 43, 44, 47, 52, 73, 74, 75].

Declarations

Data availability

Restrictions from Japan's Aerospace Exploration Agency apply to the availability of the data supporting the findings of this study. The data were used under license for the current study. As such, they are not publicly available. Thus, readers have been unable to obtain necessary materials to replicate the findings.

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Tables

Tables 1 to 3 are available in the Supplementary Files section.

Figures

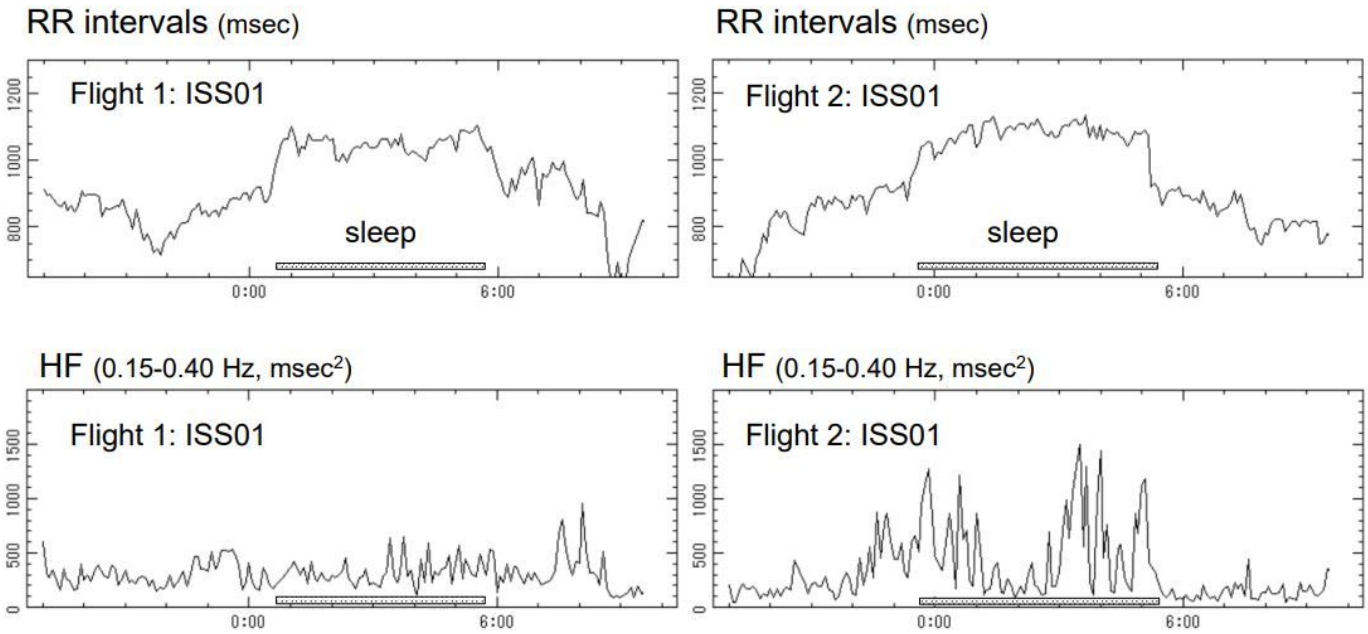

Figure 1

Estimation of sleep span and assessment of sleep quality.

RR-intervals (top) and HF-HRV (bottom) of the first (left) and second (right) spaceflight assess sleep duration and sleep quality. HF-HRV spectral power is clearly larger on the second than on the first spaceflight. Sleep-related increase in RR-intervals also appears to be larger on the second than on the first spaceflight.

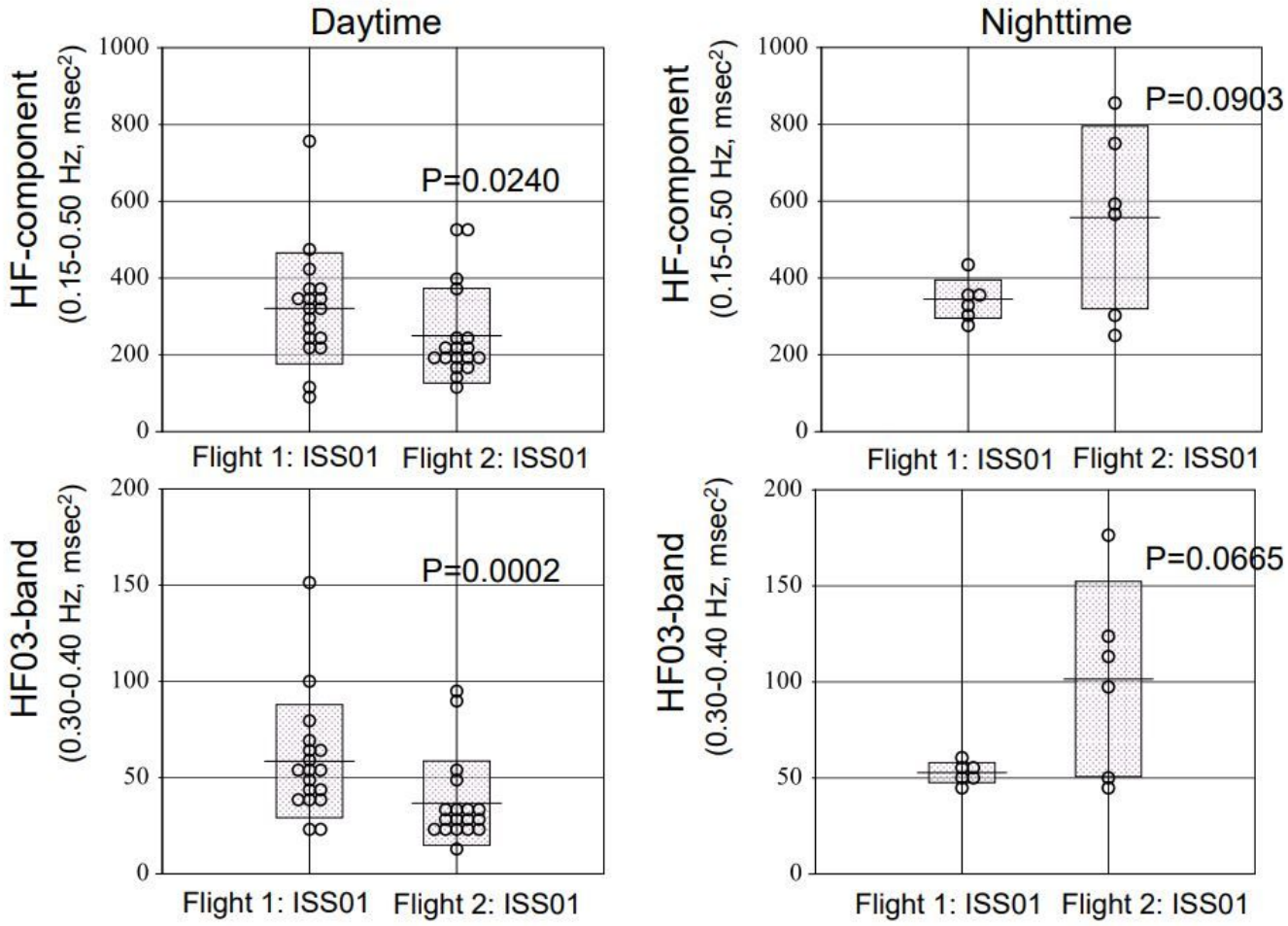

Figure 2

Brain plasticity at night and psychological resilience during daytime took place on the second mission.

HRV indices reflecting SN activity, HF-component and HF03-band, decreased during daytime (left), but increased during nighttime (right). These changes are in agreement with previous investigations showing that brain plasticity takes place at night while psychological resilience takes place during the daytime (see text).

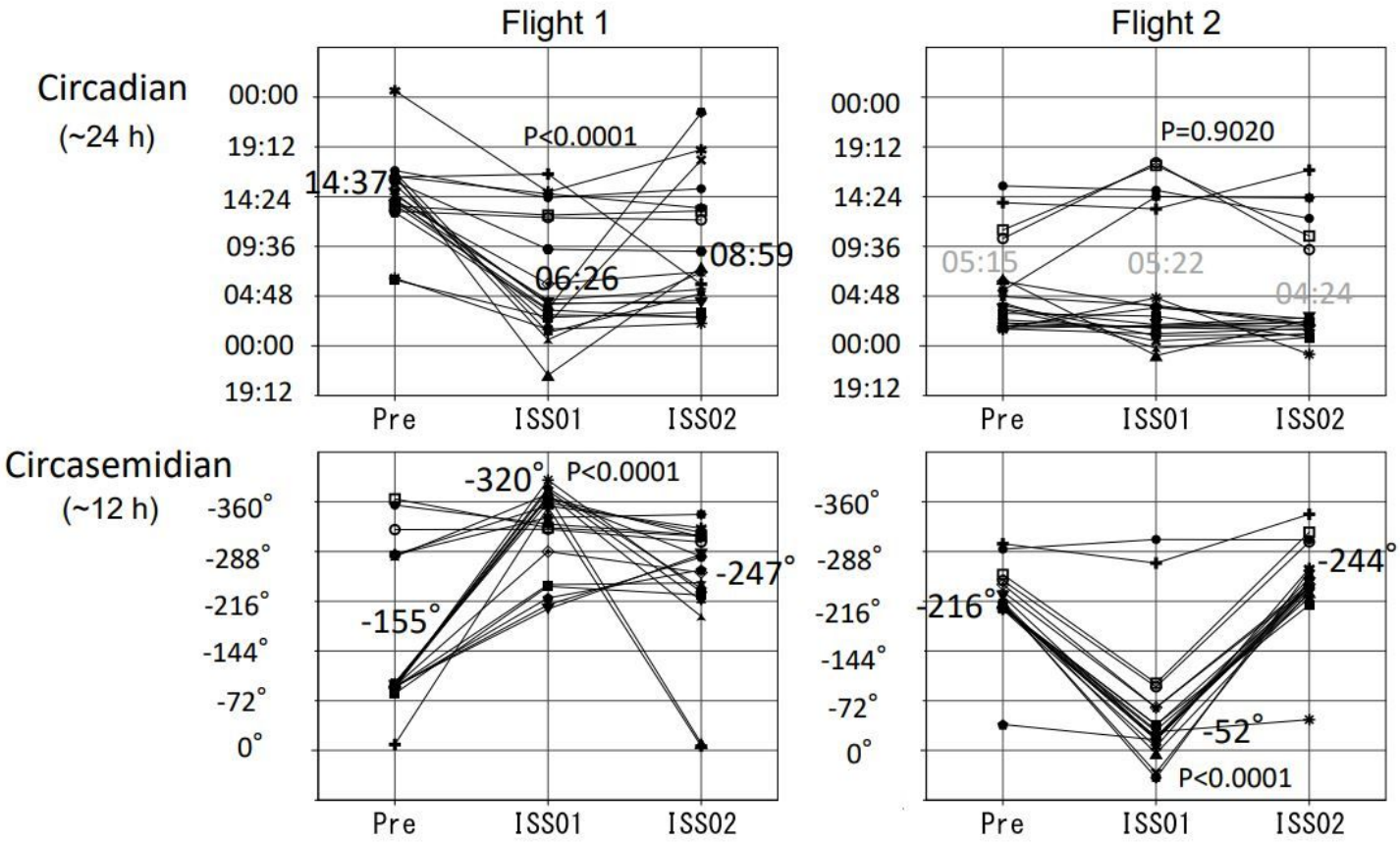

Figure 3

Changes in 24-hour and 12-hour acrophases of HRV endpoints during two space missions.

On the first mission (Flight 1, left), circadian acrophases advanced on average by about 8 hours from pre-flight to ISS01 (from 14:37 to 06:26, P<0.0001). Circadian acrophases were mostly restored during ISS01 and ISS02, when they averaged 08:59 (top left). Circasemidian acrophases were delayed on average by 165 degrees (5.5 hours) from -155° (05:10 and 17:10) to -320° (10:40 and 22:40) (P<0.0001) between pre-flight and ISS01 (bottom left).

On the second spaceflight (Flight 2, right), circadian acrophases showed no significant changes on average from Pre (05:15) to ISS01 (05:22) and ISS02 (04:24). Circasemidian acrophases were phase-advanced on average by164 degrees (about 5.5 hours) from -216° (07:12 and 19:12) to -52° (01:44 and 13:44) (P<0.0001), returning to their original acrophase of -244° (08:08 and 20:08) during ISS02 (bottom right).

Acrophases of 12-hour component expressed in (negative) degrees, with 360°≡12 hours, 0°=00:00.

Supplementary Files

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- Table1..pdf
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