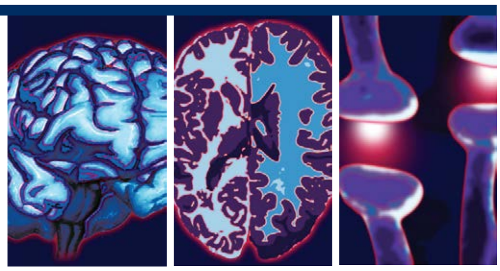
Research



Effects of Sleep Deprivation under Social Isolation Environment on Individual Working Memory

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Abstract

Aim

Spaceflight puts human into an extreme environment which has the specific and non-specifc factors like changes of circadian rhythms and interpersonal issues because of social isolation. Few studies investigated both the specific and non-specific factors of spaceflight on individual performance. Therefore, the present study used the sleep deprivation technique under social isolation environment to investigate its effects on individual cognition.

Methods

We compared the WM performances of 12 healthy males exposed to 72h social isolation and 72h sleep deprivation as separate conditions at four time points: one day before the experiment (pre-test), 12h and 36h into the experiment (test 1 and test 2) and one day after the experiment (post-test). A 2-back task and a resting state task were performed by the participants in the pre-test and post-test measurements, during which their galvanic skin response (GSR), heart rate (HR), and heart rate variability (HRV) were assessed.

Results

Decrease of reaction accuracy (ACC) and increase of reaction time (RT) after 12h SD revealed WM impairments under social isolation environment. Compared to the pre-test, the participants' GSR showed a significant decrease under both conditions. Compared to the resting state, the participants' GSR, HR and HRV increased significantly during 2-back task under both conditions.

Conclusions

Results provided further evidence for impaired working memory after sleep deprivation. Our results elucidate part of the effects of sleep deprivation on the complex interactions between cognitive performance, behavior, and the autonomic nervous system under social isolation environment.

Keywords

Social Isolation, Sleep Deprivation, Working Memory, Physiology

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Introduction

Recent research emphasized the importance of pilot fatigue during flight, crew members usually experience sleep disturbances and the phenomena of circadian rhythm desynchronization, which influences the pilots' alertness and performance. In other words, spaceflight has unique physical characteristics like the changes of circadian rhythms which lead to disruptions of individual sleep. On the other hand, non-specific factors of spaceflight like the interpersonal issues because of social isolation also posed challenges for individuals to adapt to [1]. However, few studies concentrated on both of the specific and non-specific factors.

The changes of circadian rhythm day-night cycles provide disruptions to individuals' sleep cycle and the sleep deprivation experiment was used to mimic the effects of circadian rhythm variation on earth. Sleep deprivation (SD) is a common technique which can be used to evaluate the effects of sleep deprivation on individual health and performance [2]. Acute total sleep deprivation (ATSD) and chronic partial sleep restraint (CPSR) are two types of sleep deprivation techniques. Research suggests that the effects on individual cognitive performance after one to three nights of ATSD is equal to the effects of chronic sleep deprivation [3], while this is a particular case and differences may occur considering the protocols used and the test used to measure the cognitive performance. For example, the study of Tassi et al. was in accordance with the above suggestion that the effects of ATSD on cognition was equal to the effects of chronic sleep deprivation on cognition [4], while the study of Lo et al and Ogawa et al showed different results [5,6].

Individuals experience a reduction in performance as well as changes in physiology after sleep deprivation [7]. Specifically, sleep deprivation influences individual cognitive performance [8]. Restriction of sleep time below the level of an individuals' optimal sleep time can cause a series of cognitive and behavioral deficits, including attention and working memory deficits and mood changes [9-11]. The reason for chosing working memory as the cognitive variable had two aspects as follows: firstly, neuropsychological research using electroencephalography (EEG) revealed that physiological variations in the prefrontal cortex (PFC) after sleep deprivation explain the decrease of cognition to a high relative degree [12,13], while WM performance mainly depends on PFC function; secondly, research suggests that sleep deprivation mainly affects the activity of the hippocampus [14], which is an integral part of the neural memory circuit, together with the prefrontal cortex [15]. Working memory turned to be a possible target for measuring cognitive deficits after sleep deprivation.

As the experimental parameters of chronic sleep restriction are problematic to control, and consistency of the results vary between individuals [16], the present study used 72 hours social isolation without sleep deprivation and 72 hours social isolation with sleep deprivation to investigate the effects of sleep deprivation under social isolation environment. Our aim is to confirm the effects of sleep deprivation on working memory under social isolation environment.

Methods

■ Participants

12 Male undergraduates between the ages of 18 and 30 were recruited via flyers in the University and through the campus network. The recruitment process was performed in accordance with the Declaration of Helsinki. Participants were required to be physically healthy, meaning cardiovascular or, endocrine, mental disorders were all exclusion criteria, as well as insomnia. Mental or neural disorders (such as epilepsy) in the family medical history were also exclusion criteria. Participants were required to have good sleep habits and experiencing good sleeping patterns and were to be generally well-rested after sleep. In the week before the experiment, participants were not allowed to use alcoholic or caffeine-containing drinks (such as coffee or tea), and were not allowed to smoke. 12 physically and mentally healthy participants were randomly selected. The 12 participants (24.6±2.9 years old) were randomly divided into four equal groups. All participants were required to perform a series of psychological tests before, during, and after the experiment. All participants filled in an informed consent before the experiment started, and got a monetary reward upon its conclusion. One participant was missing some data, and was therefore excluded, resulting in a final sample of the remaining 11 participants. Experimental procedures were approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning of Beijing Normal University.

Measurements

The present study adopted the classic 2-back task to test (spatial) working memory [17]. This task shows a stream of numbers, ranging from 1 to 9, around (above, below, left and right) a fixation cross. There was no order to the numbers, and the numbers appeared at random locations. The color scheme was set to white-on-black, with the numbers being shown in Times New Roman with font size 60. The 2-back task asked the participants to compare whether the current stimulus was the same as the stimulus that appeared two trials before. A single trial would last 4500ms; after presenting an "X" (to prompt the subject), a 1300ms delay followed. The numbers were then presented for 200ms, which allowed the participants 2500ms to respond. The 2-back task included 84 trials in 2 blocks. The first two stimuli of each block were discarded. Participants were to indicate if the location of a number matched with the location of the number two trials before, using two buttons on a keyboard. Participants were instructed to ignore the value of the number. Response buttons were counterbalanced between subjects. The task was programmed by using E-Prime 1.2.

Procedure

The experiment was conducted in the Social Isolation and Sleep Deprivation experiment laboratory of the Astronaut Center of China. The laboratory was 8m^2 and well-ventilated, and included a washroom. The experiment room had a table and a bed and was isolated from the monitor room by a gate comprised of two doors. The participant in the experiment room could communicate with the monitor room by a computer. The experimenter and the participant had no direct contact during the social isolation and sleep deprivation experiment; food and other necessities were delivered through the isolated gate. The participant was not allowed to use a phone or browse the internet during the experiment. The participant can freely control their behavior during an appointed time (half of an hour in the morning and night).

The experiment duration of both the social isolation and sleep deprivation conditions was six days. The specific timeline was as follows:

Day1: The participants were provided with experiment materials to be familar with the experiment which was called the "Practice" part. (The test time was set at 15:00 pm)

Day2: The participants were asked to conduct the baseline test (Pretest) at 08:00 am which included the 2-back working memory task (the physiological data was recorded while performing the working memory task using a a 16-lead polygraph).

Day3, Day4 and Day5: the participants were under 72 hours social isolation setting or 72 hours sleep deprivation setting. The participants should finish the 2-back working memory task at 12 hours of the 72 hours test (Test 1) and the 36 hours of the 72 hours test (Test 2).

Day6: The participants were asked to conduct the Posttest (the same contents as the pretest, working memory task with physiological indices recorded) at 08:00 am.

The twelve participants were divided into four teams with three in each. All participants performed both conditions (social isolation and sleep deprivation). Two teams firstly did the 72-hour social isolation condition and then did the 72-hour sleep deprivation condition while the other two teams firstly did the 72-hour sleep deprivation condition and then the 72-hour social isolation condition. In the 72-hour social isolation condition, the participants had normal sleep every day while in the 72-hour sleep deprivation condition, the participants were kept awake for 72 hours under social isolation environment.

Data Recording

Physiological activity was recorded using a 16-lead polygraph (BIOPAC MP150). The response electrodes of the galvanic skin response (GSR) were connected to the tip of the index and middle fingers of the left hand. The gain of the amplifier was set at 5. A high pass DC filter and low pass 1 Hz filter was applied during recording. The sample frequency was set to 250 Hz. The unit of GSR was μhmo. The heart rate (HR) was computed directly from the interval between two heartbeats (R-R interval) from the electrocardiogram (ECG), and is defined as beats per minute (BPM). The ECG was recorded using four electrodes; one positive connected to the lower left limb, one negative connected to the upper left limb, and a ground electrode connected to the lower right limb. The gain of the amplifier was set to 500, and the sampling rate was set to 500Hz. The recording was subject to a 0.5Hz high pass and a 35Hz low pass filter.

The GSR is a measure of the electrical resistance of the skin which is proportional to sweat secretion. The sweat glands are controlled by the sympathetic nervous system (SNS), therefore GSR acts as an indicator for SNS activation due to the stress reactivity [18]. HRV reflects the continuous interplay between both the sympathetic and the parasympathetic nervous systems and is regarded as a measure of autonomic flexibility and even as a biological marker of stress [19]. Associated with these reactions is a frequently reported increase in low frequency (LF, centered around 0.1Hz) heart rate variability, a decrease in high frequency (HF, 0.12 or 0.15–0.4Hz) power, and/or an increase in the LF/HF ratio [20]. Concluding, under stress, the GSR increases, as do the LF and the LF/HF ratio of the HRV, while the HF of the HRV decreases.

Data Analysis

SPSS16.0 was used for data processing and statistical analysis. A repeated-measures ANOVA was employed for analysis. All data points that existed outside of three standard deviations from the mean were removed from the analysis. A 2×4×2 repeated measures ANOVA was conducted with TEST CONDITION (social isolation and sleep deprivation), TEST TIME (pre-test, test 1, test 2 and post-test) and TEST TASK (resting state and working memory test). All statistical analyses were subject to double-tailed significance (p<0.05), and the effect size was represented as the n^2_p. The paired sample *t-test* was used to analyze any significant main effects. Significant interactions were followed up using post-hoc testing. Due to non-normality of the data, the Greenhouse-Geisser method was used to correct the relevant values. All the results are presented in *M±S.D.*

Results

▪ Behavior results of the working memory task under social isolation and sleep deprivation

Two-way 2×4 repeated-measures ANOVA' were performed on individual working memory performance (accuracy, **ACC** and reaction time, **RT**) to test for possible effects. The independent variables were TEST TIME (pre-test, test 1, test 2 and post-test) and TEST CONDITION (social isolation and sleep deprivation). The ACC and RT of the 2-back task under social isolation and sleep deprivation in the pre-test, test 1, test 2 and post-test are shown in **Table 1**.

The results showed that the main effect of TEST TIME on working memory ACC was significant, $F_{(1,10)}$=10.885, p=0.008, $\eta 2$=0.521. A further paired-sample t-test found that, in test 2 (36h), the participants' ACC decreased significantly under sleep deprivation when compared with social isolation, $t_{(10)}$=2.839, p=0.018, d=0.848. The main effect of TEST TIME on working memory RT was significant, $F_{(1,10)}$=2.979, p=0.047, $\eta 2$=0.230. In addition, the interaction of TEST CONDITION and TEST TIME on working memory RT was also significant, $F_{(3,30)}$=4.462, p=0.010, $\eta 2$=0.309. A further simple effects test showed that, at test 1 (12h), the participants' RT decreased under sleep deprivation compared with social isolation, $F_{(1,10)}$=4.88, p=0.052. In the test 2 (36h), the participants' ACC decreased significantly under sleep deprivation compared with social isolation, $t_{(10)}$=2.839, p=0.018, d=0.848 and their RTs were significantly higher, $F_{(1,10)}$= 4.26, p=0.066.

▪ The physiology results of working memory task under social isolation and sleep deprivation

Three-way repeated-measures ANOVAs were conducted on the individual physiological values (galvanic skin response, **GSR**; heart rate, **HR**;

Table 1: The accuracy (%) and reaction time (ms) of participants' working memory 2-back task at different-test time (pre-test, 12h, 36h and post-test) and test conditions (social isolation and sleep deprivation).

		Test Time			
		pre-test	12h	36h	post-test
Index	Conditions	M SD	M SD	M SD	M SD
ACC	Sleep Deprivation	89.66(9.78)	87.39(12.03)	81.14(18.78)**	83.86(18.57)
	Social Isolation	92.95(10.55)	93.86(7.04)	93.41(8.14)	92.05(11.00)
RT	Sleep Deprivation	884.85(154.79)	807.53(110.09)**	899.86 (147.49)**	800.98(165.68)
	Social Isolation	972.34(219.14)	887.13(139.13)	800.38(93.59)	783.06(107.46)

Note: *p<0.05, **p<0.01. ACC, accuracy (%); RT, reaction time (ms) heart rate variability, **HRV**; low frequency of HRV, **LF**; high frequency of HRV, **HF**; the **LF/HF** ratio) to test the effects of social isolation and sleep deprivation. The analysis included THREE independent variables, TEST TIME (pre-test, post-test), TEST CONDITION (social isolation, sleep deprivation) and TASK (resting state, working memory task). The participants' physiological data under the resting state and the working memory task in the pre-test and post-test for the social isolation and sleep deprivation conditions are shown in **Table 2.**

The results showed that the main effect of TEST TIME on GSR was significant, $F_{(1,10)}$=10.053, p=0.010, $\eta 2$=0.501, which meant that in the post-test, for both social isolation condition and sleep deprivation, the participants' GSR under resting state and working memory task was lower than the pre-test. The main effects of TASK on GSR ($F_{(1,10)}$=36.122, p<0.001, $\eta 2$=0.783), HR ($F_{(1,10)}$=7.899, p=0.018, $\eta 2$=0.441), LF ($F_{(1,10)}$=5.369, p=0.043, $\eta 2$=0.349) and LF/HF ($F_{(1,10)}$=7.364, p=0.022, $\eta 2$=0.424) were also significant.

■ The correlations of the behavior and physiology results of the working memory task under social isolation and sleep deprivation

Pearson correlation tests were conducted between the working memory task performance (ACC and RT) and the physiological data (GSR, HR, LF, HF and LF/HF), at the different time points (pre-test and post-test). These results are listed in **Table 3 a,b**. The correlation results showed that, under the social isolation condition, in the pre-test, the participants' RT of working memory was negatively correlated with the HRV under resting state and working memory task in the post-test. Under sleep deprivation, in the pre-test, the LF/HF ratio was negatively correlated with the ACC of post-test.

Table 2: In the pre-test and post-test, the galvanic skin response (GSR), heart rate (HR) and heart rate variability (HRV) of participants in resting state and working memory test under different conditions (sleep deprivation and social isolation).

			Physiological Index				
			GSR	HR	HR	LF	LF/HF
Time	Task	Condition	M SD	M SD	M SD	M SD	M SD
Pre-test	Resting	Sleep Deprivation	6.65(3.86)	75.90(9.53)	3.06(0.23)	2.51(0.17)	0.82(0.04)
		Social Isolation	6.58(5.38)	70.63(7.28)	2.83(0.50)	2.26(0.48)	0.79(0.04)
	WM	Sleep Deprivation	8.87(4.07)	80.68(8.18)	3.07(0.39)	2.56(0.27)	0.84(0.06)
		Social Isolation	9.74(6.08)	76.02(11.06)	3.03(0.41)	2.53(0.30)	0.84(0.04)
Post-test	Resting	Sleep Deprivation	3.87(3.52)*	78.64(16.02)	2.77(0.62)	2.18(0.58)	0.77(0.10)
		Social Isolation	5.04(3.59)*	71.44(7.50)	3.04(0.10)	2.46(0.09)	0.81(0.02)
	WM	Sleep Deprivation	5.08(3.71)*	80.61(14.07)	2.99(0.43)	2.49(0.32)	0.84(0.04)
		Social Isolation	7.90(3.14)*	76.33(10.08)	3.01(0.33)	2.49(0.19)	0.83(0.06)

Note: *p<0.05, GSR= galvanic skin response (μhmo), HR= heart rate (beats per minute, bpm), HF= high frequency of heart rate variability (nu), LF= low frequency of heart rate variability (nu), LF/HF, the ratio of LF and HF; SD= sleep deprivation, SI= social isolation. WM= working memory.

Table 3a: In the pretest and posttest, under the social isolation condition, the correlation of working memory performance (ACC and RT) and physiological indices (GSR, HR, HF, LF, LF/HF) under different tasks (resting and working memory).

	PreACC	ACC1	ACC2	PostACC	PreRT	PostRT
		r (p)	*r (p)*	*r (p)*	*r (p)*	*r (p)*
PreLF-WM			0.683(0.021)			
PreHF-WM		0.635(0.036)	0.739(0.009)			
PreLF/HF-WM	-0.606(0.048)	-0.702(0.016)				
PostLF/HF-R				-0.710(0.014)		
PostHR-R					-0.680(0.021)	-0.769(0.006)
PostLF-R						-0.629(0.038)
PostHF-R					-0.645(0.032)	-0.797(0.003)
PostHR-WM					-0.778(0.004)	
PostLF-WM					-0.610(0.046)	
PostHF-WM						-0.687(0.019)
PostLF/HF-WM					0.603(0.049)	

Note: Pre-ACC and post-ACC were the accuracy for participants of working memory task in pre-test and post-test. Pre-RT and post-RT were the reaction time for participants of working memory task in the pre-test and post-test. PreLF-WM, preHF-WM and preLF/HF-WM were the LF, HF and LF/HF under working memory task in the pre-test. PostLF-WM, postHF-WM and postLF/HF-WM were the LF, HF and LF/HF under working memory test in the post-test. PostLF-R, postHF-R and postLF/HF-R were the LF, HF and LF/HF under resting state in the post-test.

Table 3b: In the pretest and posttest, under the sleep deprivation condition, the correlation of working memory performance (ACC and RT) and physiological indices (GSR, HR, LF, HF, LF/HF) under different tasks (resting and working memory).

	PreACC *r (p)*	PostACC *r (p)*	PostRT *r (p)*
PreLF/HF-R		-0.687(0.020)	
PostLF-WM	-0.616(0.043)		0.734(0.010)

Note: PreGSR-R, preLF-R and preLF/HF-R were the participants' GSR, LF and LF/HF under resting state in the pre-test of sleep deprivation. PreGSR-WM was the GSR under working memory task in the pre-test. postLF/HF-R was the ratio of LF and HF under resting state in the post-test. PostLF-WM was the LF under working memory task in the post-test.

Discussion

The present study found that the individual working memory was significantly impacted after 72h social isolation and after 72h sleep deprivation. As sleep deprivation continued, the working memory accuracy decreased and reaction time increased. This can be seen in the significant decrease of the participants' 2-back accuracy after 36h of sleep deprivation, which represents evident fatigue effects. The participants had a decreased reaction time on working memory 2-back task after 12h sleep deprivation compared to social isolation, which means that participants sacrifice cognitive resources to maintain proper responses, which translates to lower performance, which was the expected effect of sleep deprivation.

The participants' GSR decreased both after social isolation and sleep deprivation. Compared with the pre-test, the GSR decreased significantly in the post-test in both the resting state as well as the working memory task under both social isolation and sleep deprivation. This result indicated that physiological indices like GSR was sensitive to the variation of environment. Finally, correlations of working memory task performance (ACC and RT) and physiological data suggest that there was a connection between individual cognitive performance and physiological activation under social isolation and sleep deprivation condition.

The decline in task performance as sleep deprivation progressed, was in accordance with the study of Teran-Perez and his colleagues, they found that participants' task accuracy in a working memory task declined after 24-hour sleep deprivation, and their reaction times increased after 30-hour sleep deprivation [21]. In our study, compared the social isolation, participants' reaction times of the working memory task decreased after 12-hour sleep deprivation. We thought this was caused by the anticipation effect of the sleep deprivation condition, and can be seen as coping behavior of sleep deprivation. As the sleep deprivation condition continued, the participants presented obvious fatigue effect which was demonstrated in an increase of reaction times and a decrease of accuracy on the working memory task. This result was in accordance with the study of Meerlo et al. [22]. The present study operates from the viewpoint that the most feasible way to disentangle the effects of sleep deprivation and stress was to prolong the sleep deprivation time.

The physiological results showed that after both 72h sleep deprivation and 72h social isolation, the participants' galvanic skin response (GSR) significantly weakened in both resting state as well as during the working memory task. The decrease in sympathetic activity observed in our study was not specific for the sleep deprivation. This may be because the GSR, while used as an index of sympathetic activity, is unable to distinguish between the two conditions: social isolation and sleep deprivation. In addition, the decreased GSR during the working memory task after sleep deprivation was in accordance with the study of Zhong et al., who explored the effects of 36-hour sleep deprivation on participants' sympathetic and parasympathetic nervous system, and found that sleep deprivation changed the activity of sympathetic nervous system significantly [23].

In the present study, during the pre-test, the participants' HRV during the 2-back task was positively correlated with the 2-back accuracy in the social isolation condition. This may suggest that in the pre-test, participants whose HRV is larger may have a higher ACC on the later working memory task. Meanwhile, in the pre-test, the participants' reaction time on the 2-back task was negatively correlated with the HRV under resting state and 2-back task of the post-test which, may suggest that participants who have lower reaction times in the pre-test experience less variation in HRV in the post-test. The above results show that participants' performances in the working memory task have a relation with physiological reactivity under the social isolation condition.

Under the sleep deprivation condition, in the pre-test, the HRV under resting state was negatively correlated with accuracy in the post-test, which means that less variation in the HR during the pre-test is associated with a to higher accuracy in the 2-back task during the post-test.

The present study demonstrated that the effects of 72-hour prolonged sleep deprivation on cognition follow a specific pattern: after short-term sleep deprivation (12h), the anticipation of a specific stressor strengthened the performance of working memory task, but this effect was overpowered by the fatigue of sleep deprivation in 36h, which can be seen in the decline of working memory performance. Concluding, the accordance of physiology and cognition variation under extreme environments like social isolation and sleep deprivation had significant meaning for individual physical and mental health.

Disclosure Statement

The authors have declared that no competing interests exist.

Author Contributions

Author Yue Peng and Author Qing Liu did the conception and design of the study, acquisition and analysis of data, as well as the drafting of the manuscript and figures. Author Cornelis Hermanus van Heck modified and reorganized the paper.

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