Simulated Spaceflight Operations Under Sleep Deprivation and Confinement

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INTRODUCTION: This study investigated how operation complexity and type affect Chinese individuals' performance of simulated spaceflight operations under conditions of sleep deprivation and confinement (SDC).

METHODS: There were 20 male volunteers who were randomly divided into 2 groups: the SDC group ($N = 8$) and the control group ($N = 12$). During the 72-h experimental period, the volunteers were asked to perform 11 computerized spaceflight emergency procedures, varying in operation complexity and type, three times at the 9th, 33rd, and 57th hours, respectively. Operation times and errors of each spaceflight emergency procedure were recorded. Three complexity levels (i.e., low complexity, high complexity, and combined complexity) and three operation types (i.e., two-way judgment, manual operation, and mixed operation) were identified according to an operation complexity measure and an engineering definition.

RESULTS: Mixed model ANOVAs indicated that performance of the three complex operations and three operation types were negatively affected by SDC. Moreover, the results showed that the operation time of manual operation (10.67 ± 1.706 at the 9th hour, 13.94 ± 4.261 at the 33rd hour) and mixed operation (4.88 ± 0.247 at the 9th hour, 5.15 ± 1.308 at the 57th hour) increased significantly with the increase of waking time. It was also shown that the high complexity operation and manual operation got less variation in operation time compared with low complexity and two-way judgment, respectively.

CONCLUSIONS: The result indicated that the task assignment with high complexity requiring cognition could be a useful way to counteract the effect of SDC. It was also implied that psychomotor abilities were more easily affected by SDC than perception and judgment.

KEYWORDS: sleep deprivation and confinement, spaceflight emergency procedures, operation complexity, operation type.

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It is a well-known fact that the extreme conditions of both living and working in space, such as microgravity, narrow spaces, isolation, sleep disturbances, and high cognitive loading, may seriously influence astronauts' performance or even lead to mission failure.[14] A serious safety issue during the spaceflight mission is how to adapt to the space environment while maintaining operational performance. Optimizing the work-rest schedules of astronauts has been viewed as an important factor in maintaining behavioral health and performance efficiency in space.[3,19] But the question of how to optimize activities during flight remains for Chinese astronauts. Limited research and knowledge exist about the performance of the Chinese population under extreme conditions. This study attempted to uncover how the extreme conditions presented affect the operating performance of Chinese subjects and to determine one task design which could counteract the negative effects.

Cognitive decrements in spaceflight have been realized from a large number of anecdotal reports and observations since the early stages of spaceflight.[14,16] Many studies have distinguished some nonspecific stressors which may impair the cognitive and psychomotor performance of astronauts, such

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as cumulative sleep loss, increased workload, or the physical and emotional burden of adapting to the conditions in space.[6,14,21] Among those nonspecific stressors, sleep disturbances during spaceflight were identified as one of the most crucial factors contributing to impaired performance of astronauts.[21] Due to the small number of astronauts performing spaceflight and the difficulty of performing experiments in a spacecraft, two Earth-bound models were mostly used to simulate what might be expected to occur in spaceflight: 1) space simulation, such as submarines and polar explorations; and 2) sleep deprivation.[14,26]

The first model is mainly used for field research, focusing on isolation and confinement as the primary variable of interest in manned spaceflight. The researches based on this model always explore the effects of simultaneous exposure to multiple space-related stressors (i.e., isolation, chronic sleep deprivation, confined space, perception of risk, noise, etc.) on cognitive performance and complex task performance.[7,25] Sauer reviewed a number of studies that were carried out with a PC-based task environment called the Cabin Air Management System to examine how crewmembers adapted to various stressors.[25] None of the studies provided evidence for decrements in primary task performance. However, some results showed selected decrements in secondary task performance.[25] These results can be explained by the compensatory theory.[8,9] According to this theory, as Kanas and Manzey pointed out, even though individual performance functions may become impaired under the impact of stressors, this may not necessarily lead to overt performance decrements in complex tasks; instead, the individual can compensate for these stress effects and protect overall performance.[14]

The second model focused on sleep deprivation. Some researchers have studied the possible effects of sleep restriction or deprivation on cognitive performance.[1,2,27] These articles suggest that restricting sleep to less than 6 h per night results in cognitive performance decrements. These decrements include increased response times and more frequent lapses in simple reaction time tasks, slowing of performance in mental arithmetic tasks, or impaired working memory functions. In the context of aviation, some researchers have explored the effect of sleep deprivation on simulated flight performance.[17,24] Li et al. found that simulated flight performance scores decreased with time during sleep deprivation.[17] Furthermore, Russo et al. concluded that acute sleep deprivation degraded visual perception, complex motor, and simple motor performance.[24] However, the compensatory theory was also supported by some experiment results.[10,18] Combined with time pressure and workload, short-term sleep deprivation (less than 24 h) showed no significant effect on performance in a dynamic air traffic control task.[18]

Task characteristics were identified as one important factor affecting sensitivity to sleep deprivation when taking computerized tests.[12] A series of researches were conducted on task complexity, task duration, and task type.[4,5,12] It was shown that complexity can improve the sensitivity to sleep deprivation by increasing the required demands, but it can also reduce the sensitivity by improving volunteers' motivation.[12] Therefore, there is no clear consensus about the attenuated effect of task complexity. Several studies showed that the effects of sleep deprivation may be weakened as the cognitive demands of a task increased.[5,6] Conversely, Pilcher et al. found that performance on complex cognitive tasks did not significantly decrease while performance on vigilance tasks decreased significantly during sleep deprivation.[23] Wilkinson found that long-duration (e.g., 30-min) tasks were more impacted by sleep deprivation than were short-duration (e.g., 1-2 min) tasks.[28]

There have been over 100 studies conducted on the two models. The majority of them focused on the effects of stressors on cognitive functions, mental tracing ability, and emotion, but only a few studied task performance in the context of spaceflight. Most researchers studied sleep deprivation as an isolated factor and were not concerned with the confounding effects of sleep deprivation and confinement. Those studies found that there are a multitude of stressors in space that can affect human performance in different ways, but they may not directly cause performance decrements in highly trained operational mission tasks.[14] Moreover, the effects of sleep deprivation are a function of task characteristics, such as time on task, level of task (primary or secondary), and task workload (complexity).[4] Therefore, this study aimed to explore the combined effects of both sleep deprivation and confinement on the operating performance of computerized spaceflight procedures with different levels of complexity and type. This research is essential for developing mitigation strategies for the negative results of sleep disturbance and confinement in China's spaceflight missions.

METHODS

Subjects

Our between-subjects experiment was approved by the ethics committee at the Astronaut Center of China prior to volunteer recruitment. As most current Chinese astronauts are men and new candidates are mostly selected from male engineers, we recruited 20 male students who majored in science and engineering from several universities to replicate the selection criteria of Chinese astronauts. The volunteers attended the experiment based on their consent and were randomly and equally divided into a sleep deprivation and confinement (SDC) group and a control group. The eight volunteers in the SDC group were from 21 to 23 yr of age (mean = 22.0, SD = 0.75) and the 12 male volunteers in the control group were from 21 to 26 yr of age (mean = 22.0, SD = 1.34). There were no differences in age between the two groups ($P = 1.0$).

The volunteers in the SDC group passed a general physical examination and a mental health evaluation measured by the Eysenck Personality Questionnaire and the SCL-90 rating instruments. They were asked to stay awake for 3 nights in an isolation room and execute assigned cognitive tasks as well as the 11 operational units for each of the 3 d. In the original design, there were 12 volunteers in both groups. However, the data of four volunteers in the SDC group was lost due to a technical failure. Consequently, only the data of eight volunteers in the SDC group were analyzed in this study. The 12 volunteers in the control group executed the 11 operational units in a laboratory without sleep deprivation or confinement at the same time period each day as that of the SDC group.

Equipment

A spaceflight task simulation platform (STSP) was developed using Microsoft Visual Basic and Microsoft Office Access. Through this platform, 11 spaceflight task units were presented with computerized procedures. Their complexity values ranged from 0.9 to 1.32. The complexity values were computed by a spaceflight operation complexity measure which will be described below.[31] All operations were completed using a mouse on the STSP. The operation times and error counts in the experiment were recorded and saved in an Access database.

The 11 spaceflight operational units were chosen from the spaceflight operation handbook of Chinese spacecraft and described as emergency operating procedures in the STSP. They were operations to deal with malfunctions of spacecraft subsystems. These subsystems included environmental control and life support, thermal control, navigation and control, and electrical power subsystems. They included three typical task types of spaceflight operations: two-way judgment, manual operation, and mixed operation, which will be described in the Design section.

Under emergency situations, operators perform tasks referring to paper-based or computerized procedures.[11,13,30] In spaceflight, emergency operating procedures are traditionally available as printed documents. However, computerized procedures have become a new trend. Two typical presentation styles for computerized procedures in nuclear power plants were compared by Xu et al. and the style constructed by one-and two-dimensional flowcharts was found to be superior to the other.[30] The superior presentation style was adopted in this study for the emergency operating procedures, which is shown in **Fig. 1**.

The left section of the chart is a one-dimensional flowchart which lists the 11 total units and highlights the current unit. The middle section is a two-dimensional flowchart which describes the operational sequence of the current unit. The right section presents brief instructions and the states of system variables, which change with time. In the upper-right corner of the screen there is a clock showing the remaining time for the current unit, which replicates the time pressure faced by operators in an emergency environment.

Design

As evidenced in the literature review, the characteristics of operational tasks would influence the effects of sleep deprivation.[4,12,22] Therefore, in this study, task complexity and type were also considered as independent variables independent of sleep deprivation and confinement.

Sleep deprivation and confinement. The experiment lasted for approximately 72 h (over a 4-d span). The operational data was collected during 16:40–17:40 on each day. Three levels of sleep deprivation were examined: level 1 (9 h), level 2 (33 h), and level 3 (57 h). During the experiments, volunteers were monitored through video cameras and kept awake with a bell. The control group conducted 11 operational units during the same period.

Operation complexity. The complexity values of the 11 units were determined by a spaceflight operational complexity measure which has been validated by one experiment and astronaut training for several missions.[31] The measure uses a weighted Euclidean norm based on four factors: complexity of operation step size (COSS), complexity of operation logic structure (COLS), complexity of operation instruments information (COII), and complexity of space mission information (CSMI).[31]

$$\mathrm{OC} = \sqrt{(0.1725\times \mathrm{COSS})^2 + (0.3821\times \mathrm{COLS})^2 + (0.1965\times \mathrm{COII})^2 + (0.2487\times \mathrm{CSMI})^2}$$

The four factors were calculated by graph entropy, which defined two kinds of entropy measures for a graph: the chromatic information content (or the first-order entropy), and the structural information content (or the second-order entropy), which was proposed in Mowshowitz's work.[20] In the case of a program control graph, first-order entropy can be used to evaluate the regularity of the control logic of a given program, while second-order entropy can be used to evaluate the number of hierarchical levels (or size) of the control graph, and thus can represent the amount of information required to understand the graph.

The weights for the 4 complexity factors were determined among 10 astronauts through the use of the Fuzzy Analytic Hierarchy Process method and set-valued statistics.[31] Firstly, 10 Chinese astronauts made pairwise comparisons among the 4 factors. After this the weight of each factor judged by an astronaut can be determined by the Fuzzy Analytic Hierarchy Process method. Finally, the 10 sets of weights were calculated with the Hadamard set-valued statistics method to get the final weights.

Three complexity levels were defined: low complexity, high complexity, and combined complexity (the whole procedure). Based on the complexity values, the top 20% was defined as high complexity (complexity values within 1.22–1.32: 7^{th} and 9^{th} units) and the bottom 20% were defined as low complexity (complexity values within 0.9–1.1: 4^{th} and 10^{th} units). All the 11 units together were regarded as combined complexity.

Operation type. In the procedural operations of spaceflight, there are three operation types which are two-way judgment (cognitive motor or vigilance), manual operation (psychomotor), and mixed operation. Two-way judgment asked operators to make a two-way decision after checking the subsystems' situation (as shown in Fig. 1). Manual operations are completed by manipulating simulated buttons on a computer screen (as shown in **Fig. 2**). Mixed operation is a combination of the two operation types. In one unit, some of operation steps are two-way judgment, others are manual operations (as shown in **Fig. 3**).

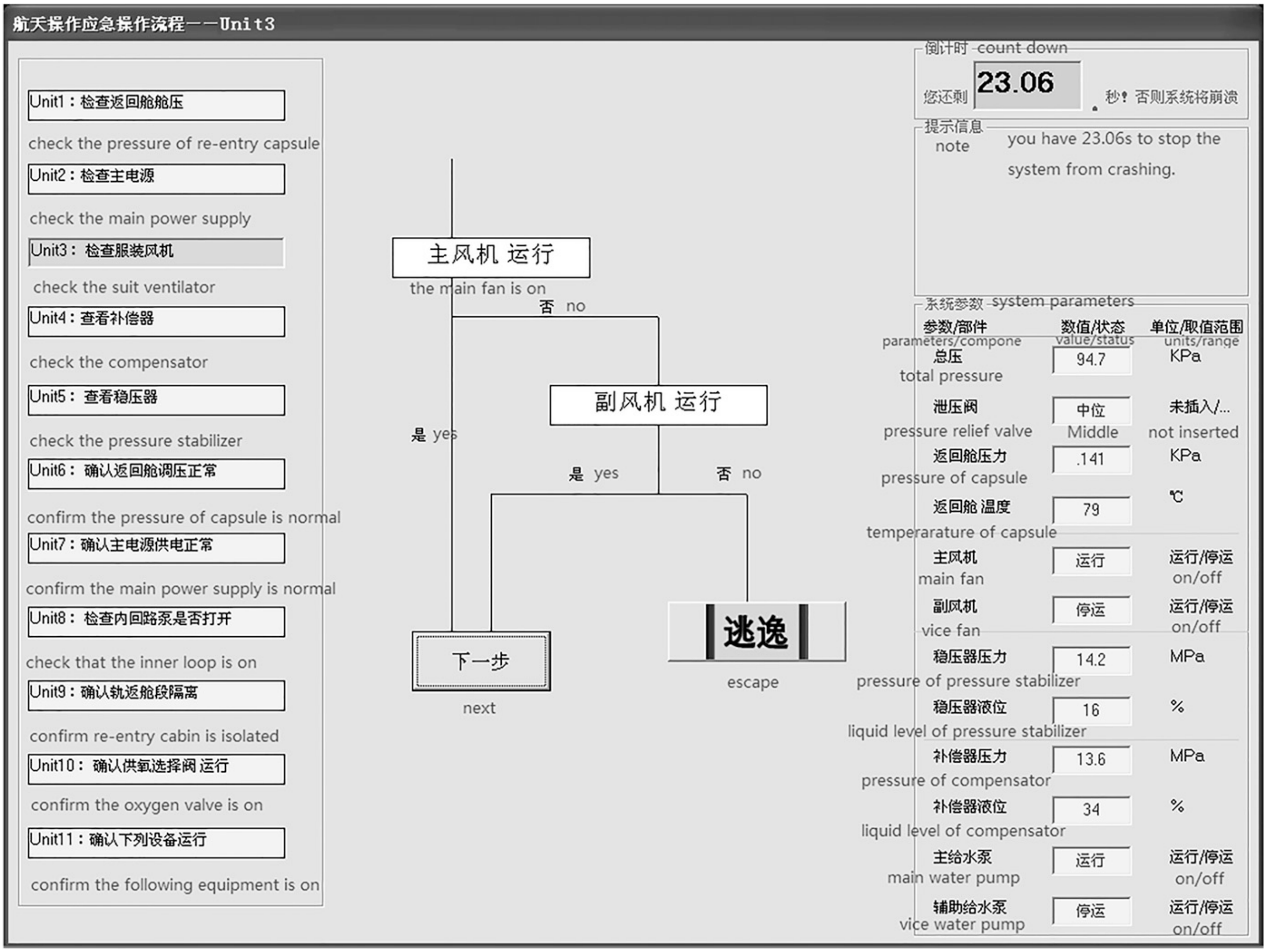

Fig. 1. Example of two-way judgment.

Procedure

The experimental task was to perform the 11 operational units presented as a computerized procedure on the STSP. One execution of the procedure was labeled a trial, regardless of which operational unit the procedure was terminated at or whether all 11 units were completed. At each sleep deprivation or controlled level, each volunteer was asked to complete five trials.

The sleep deprivation sub-experiment was conducted in the China Astronaut Training Centre and had four phases. The experiment process is shown in **Fig. 4**. The first phase was volunteer recruitment and screening. The second phase was training 1 to 3 d before isolation. The volunteers listened to the instructions of the experiment, then practiced the whole procedure on the STSP. The practice lasted about 30 min for each volunteer and did not end until the volunteer was able to complete five consecutive trials successfully (a criterion adopted in Xu et al.[30]). This would ensure that the volunteer correctly understood and was able to operate the platform with a certain level of fluency. The control group was trained with the same procedures as that of SDC group. The operation time of the SDC group and control group had no significant difference at any complexity level or type (all $P > 0.078$).

The third phase was testing right before isolation. The volunteers were asked to get a good night's sleep before the experiment. The third phase then began at 08:00. Each volunteer practiced the procedure for five trial runs and then took a pilot experiment for five trials. The fourth phase was the formal isolation and sleep deprivation experiment. After the testing in the third phase, the formal experiment began at 09:00 and ended at the same time on the 4th day. The volunteers undertook a five-trial formal testing from 16:40–17:40 every day.

The control group attended the experiments at the University of Science and Technology Beijing. There were 12 volunteers who were trained with the same procedure as that of SDC group, which lasted about 30 min, until they completed 5 consecutive trials successfully. At the formal experimental phase, they undertook a five-trial formal testing from 16:40–17:40 every day for 3 d.

Statistical Analysis

In this experiment three variables were taken into consideration: 1) operation time—the time in which a volunteer finished an operational unit or the whole procedure; 2) error count—the total number of error trials in one test; both operation times and

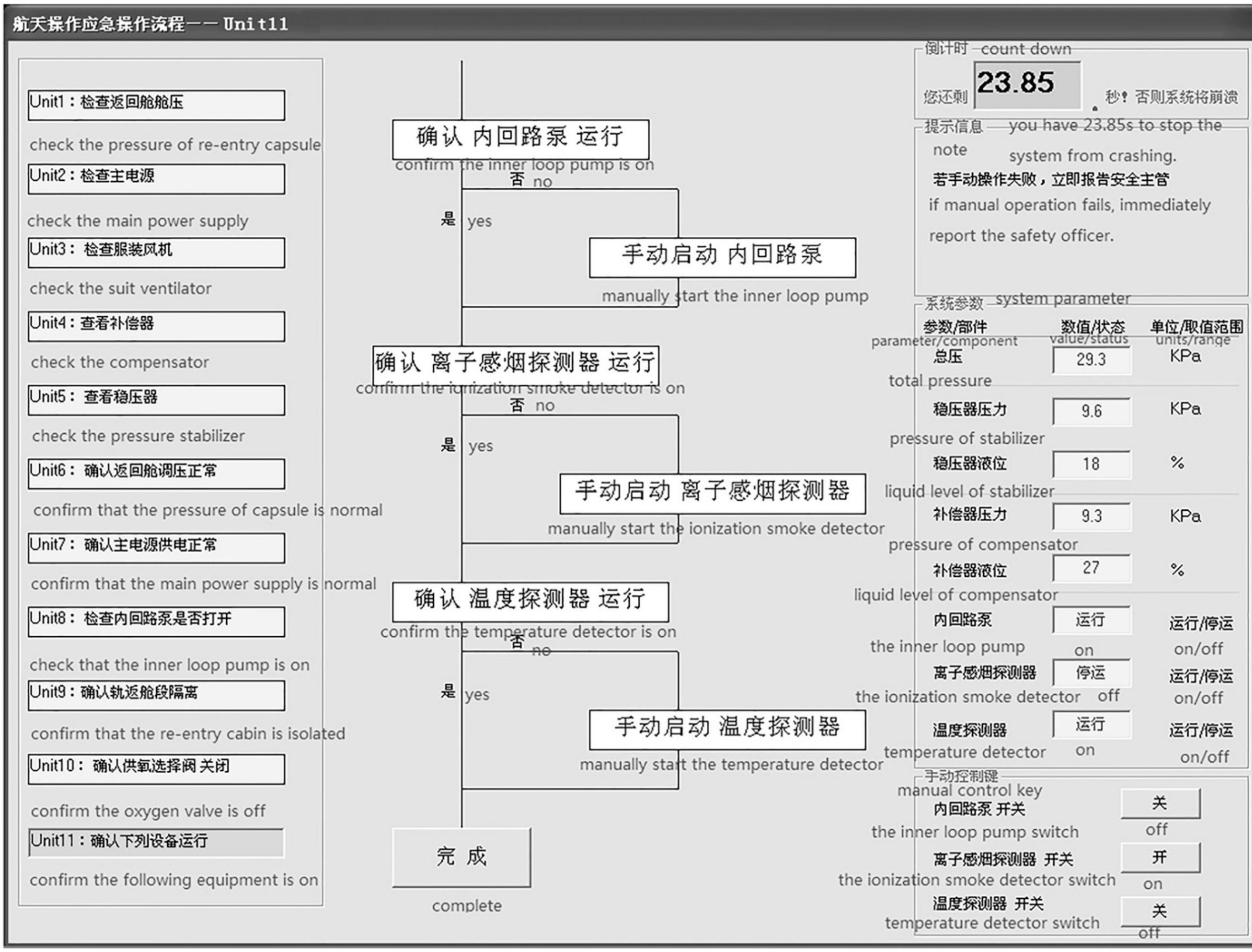

Fig. 2. Example of manual operation.

error count were recorded by the experimental system and saved into the database; and 3) operation time decline—the operation time at the previous sleep deprivation level divided by its difference from the operation time at the current sleep deprivation level. The results are discussed as percentages.

Operation time, error counts, and operation time decline were analyzed individually with a repeated-measures, mixed-effects ANOVA model. The effects of waking time on performance in the SDC group were tested by Kruskal-Wallis. All data was tested for significance at an alpha level of 0.05, chosen to determine whether any observed differences in the means were attributable to the experimental variables. Besides the mean and SD, the *F*- and *P*-values are reported. Post hoc comparisons were conducted on significant ANOVA results with the use of Tukey's multiple comparisons procedure. The results are reported as Huynh-Feldt effects.

RESULTS

Firstly, the data of the pilot experiment of the SDC group and control group were analyzed and no significant difference was found in operation time or error count. Then performance changes with the change of operation complexity were compared between the two groups, together with the performance changes in the SDC group. After that, we examined the difference in performance with different task types.

Overall, the mean operation time of the SDC group was significantly longer than that of control group [$F_{(1,18)} = 5.47$, $P < 0.01$]. The SDC group demonstrated increases in mean operation time as operation complexity increased [$F_{(1.75,31.5)} = 438$, $P < 0.01$]. ANOVA also indicated a significant interaction between sleep deprivation and operation complexity [$F_{(1.75,31.5)} = 5.11$, $P = 0.015$]. The combination of sleep deprivation and high operation complexity led to an increase in mean operation time (see **Table I**). No interaction between SDC and time was found in operation time [$F_{(1.51,27.2)} = 1.28$, $P = 0.287$]. No interaction between time and complexity factors was found in operation time [$F_{(3.54,63.6)} = 0.299$, $P = 0.971$]. For the SDC group, there was no statistically significant difference between time levels for operation time. In the SDC group, differences in the operation time across waking time levels were not significant for the low complexity task, high complexity task, or the whole procedure (Table I).

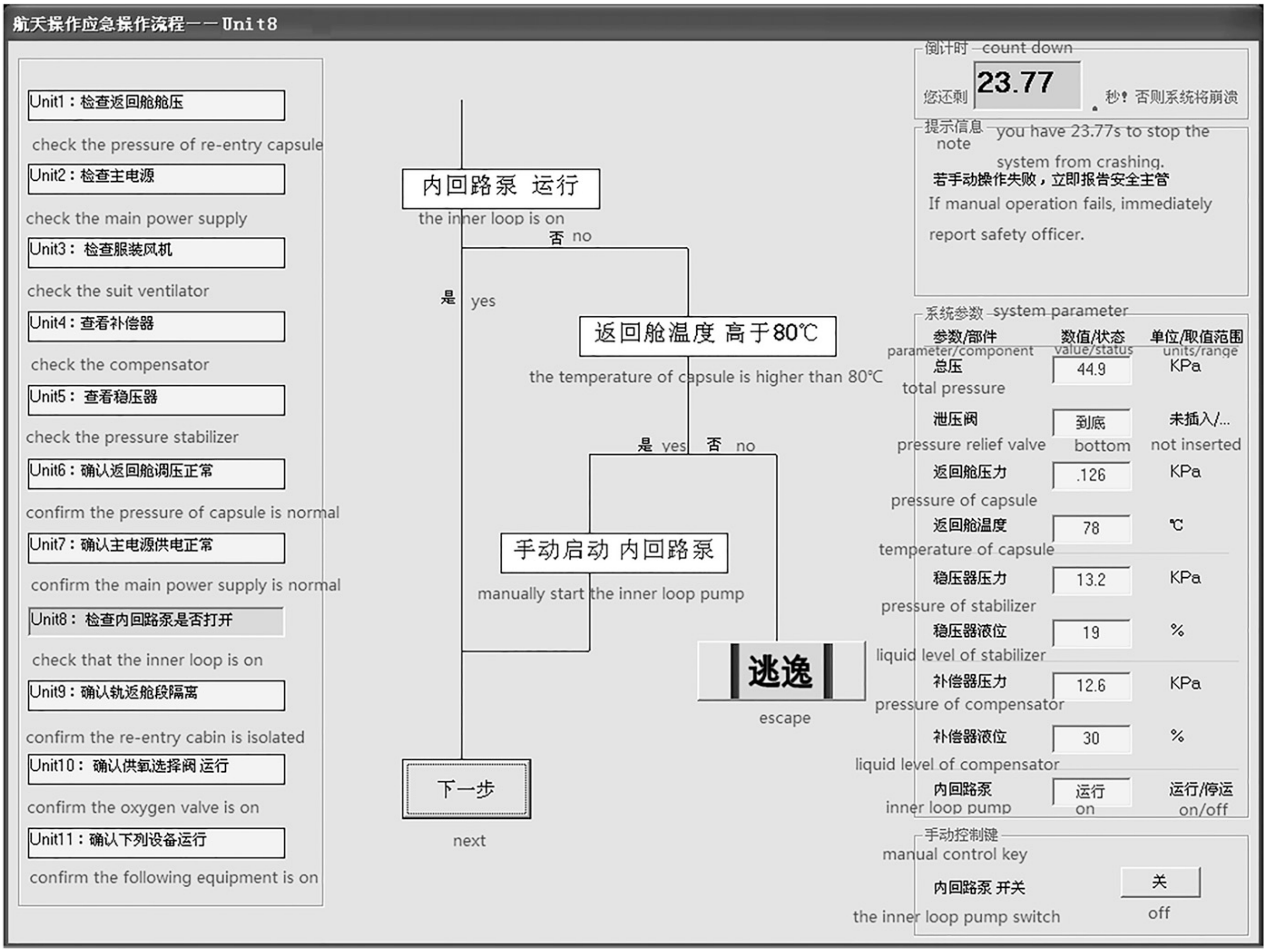

Fig. 3. Example of mixed operation.

The mean error count of the SDC group was significantly more than that of the control group [$F_{(1,18)} = 11.56, P < 0.01$]. The combined group demonstrated increases in mean error count [$F_{(1.19,\ 21.4)} = 7.53, P < 0.01$] as operation complexity increased. A significant interaction between SDC and complexity was found in error count [$F_{(1.19,\ 21.4)} = 8.30, P < 0.01$]. The combination of sleep deprivation and high operational complexity led to an increase in mean error count. No interaction between SDC and time was found in error count [$F_{(1.68,\ 30.2)} = 0.335, P = 0.716$], nor was any interaction between time and complexity found in error count [$F_{(1.68,\ 30.2)} = 0.089, P = 0.986$]. Though we can see the decrease of error counts with the increase of waking time from the mean in **Table II**, ANOVA did not show statistical significance [$F_{(1.68,\ 30.2)} = 1.010, P = 0.367$]. In the SDC group, differences of the error counts across three time levels were not significant for the low complexity task, high complexity task, or the whole procedure (Table II).

No significant difference for the operation time decline was found between the SDC group and the control group. Additionally, operation complexity had a significant effect on the operation time decline [$F_{(1.62,\ 29.2)} = 4.89, P = 0.02$]. Specifically, high-complexity operations (M = 13.96%, E = 8.883) showed less decrease as compared with the whole procedure (M = 24.46%, E = 6.368) ($P = 0.027$) in the SDC group.

In terms of operational type, the SDC group demonstrated significantly longer operation time as compared with that of the control group [$F_{(1,18)} = 14.3, P < 0.01$]. The combined group demonstrated a significant difference in operation time [$F_{(13.0,\ 23.4)} = 372, P < 0.01$] as the operation type changed. There was no statistically significant difference between time levels for operation time. No interaction between SDC and operation type was found in operation time [$F_{(13.0,\ 23.4)} = 1.78, P = 0.196$]. No interaction between SDC and time was found in operation time [$F_{(1.57,\ 28.3)} = 2.48, P = 0.086$]. ANOVA indicated a significant interaction effect of time level and operation type [$F_{(1.78,\ 32.0)} = 6.92, P = 0.004$] in this variable. In the SDC group, the interaction effects on operation time of different operation types were checked. Differences in the operation time of the SDC group across three time levels were not significant for two-way judgment operation (Z = 2.09, $P = 0.352$). However, results showed that more operation time was required for mixed operation (Z = 7.028, $P = 0.03$)

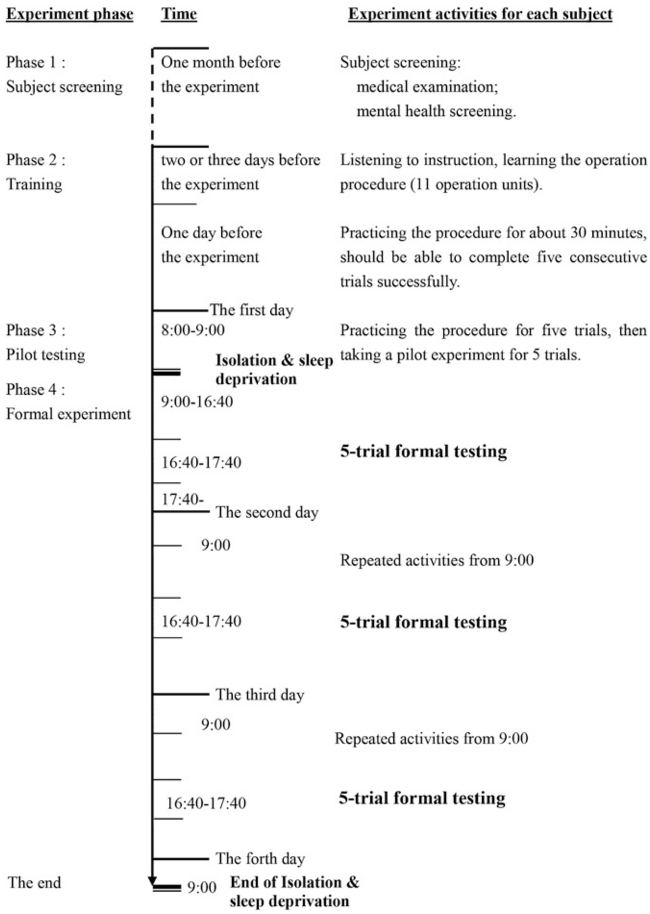

Fig. 4. The experimental process.

and manual operation (Z = 8.688, $P = 0.013$) when the waking time increased. The climax of performance time for mixed operation and manual operation were at the 57th hour and 33rd hour separately (see **Table III**).

When looking at the combination of different operation types, the SDC group demonstrated significantly more error counts as compared with that of the control group [$F_{(1,18)}$ = 11.8 $P < 0.01$]. The combined group demonstrated a significant difference in operation time [$F_{(1.16,\ 20.8)} = 13.4$, $P < 0.01$] as operation type changed. Results showed that two-way judgment operations received less error counts than the other two operation types [$F_{(1.16,\ 20.8)} = 15.73$, $P < 0.01$]. Nevertheless, there was no statistically significant difference between time levels for error counts. No interaction between SDC and time was found on error count [$F_{(1.28,\ 30.0)} = 0.480$, $P = 0.541$]. No interaction between time and operation type was found on error count [$F_{(1.42,\ 25.6)} = 1.19$, $P = 0.306$]. However, ANOVA indicated a significant interaction effect of sleep deprivation and operation type [$F_{(1.16,\ 20.8)} = 11.6$, $P < 0.01$] on this variable. The combination of sleep deprivation and high operational complexity led to an increase in mean error count. In the SDC group, the difference in error count across different time levels was not significant for two-way judgment, manual operation, or mixed operation (see **Table IV**).

In terms of operation time decline, no significant difference was found between the SDC group and the control group. However, operation type had a significant effect on the operation time decline [$F_{(2,\ 36)} = 3.16$, $P = 0.05$]. Specifically, manual operations (M = 15.38%, E = 4.106) showed a marginally significant decrease in the operation time decline as compared with two-way judgment (M = 21.68%, E = 10.75) ($P = 0.057$).

DISCUSSION

This study adds insight into the effects of sleep deprivation and confinement on the performance of Chinese operators when using computerized spaceflight procedures. Compared with the control group, the SDC group was exposed to more stressors, such as sleep deprivation, confinement, and isolation, which led to a significant performance decrease for all three complexities of the operations and all three types of operations. This experiment highlighted the effect of sleep deprivation, which is consistent with some literature.[17,24] In this study, we noticed that the participants in the SDC group showed some anxiety even before the formal experiment was started. This is a common phenomenon for challenging and risky experimental tasks. However, it remains unknown how this would influence the results.

A secondary objective of this study was to determine which task characteristics are sensitive to the simulated spaceflight work situation. The results indicated that the combination of sleep deprivation and high operational complexity led to an increase in mean operation time. However, the operational performance of three complexities of operations was not found to

Table I. The Mean Operation Time of Operational Units with Different Complexities.

		SLEEP DEPRIVATION		CONTROL GROUP	
TIME	COMPLEXITY	MEAN	SD	MEAN	SD
9th hour	Low complexity	5.60	1.463	4.45	1.006
	High complexity	12.49	1.369	11.07	1.944
	Whole procedure	5.94	1.374	5.77	1.069
33rd hour	Low complexity	5.04	1.581	4.64	0.680
	High complexity	10.90	2.840	10.90	1.933
	Whole procedure	5.81	2.108	5.40	0.744
57th hour	Low complexity	4.97	1.159	4.39	1.060
	High complexity	13.27	2.071	10.07	1.161
	Whole procedure	5.70	1.453	5.06	0.689

Table II. The Mean Error Counts of Operational Units with Different Complexities.

		SLEEP DEPRIVATION		CONTROL GROUP	
TIME	COMPLEXITY	MEAN	SD	MEAN	SD
9th hour	Low complexity	1.35	1.255	0.14	0.324
	High complexity	2.50	2.480	0.14	0.328
	Whole procedure	2.50	2.673	0.28	0.642
33rd hour	Low complexity	1.25	1.336	0.07	0.241
	High complexity	1.88	2.216	0.07	0.245
	Whole procedure	2.08	2.481	0.14	0.476
57th hour	Low complexity	0.94	1.294	0.00	0.000
	High complexity	1.77	2.458	0.00	0.000
	Whole procedure	2.08	2.481	0.00	0.000

be significantly different with the increase in waking time. These results are generally consistent with the existing research and the facts from real spaceflight missions. It also provides evidence in favor of the compensatory control model.[9,10]

In regards to this experiment, the variation in the results may be due to two reasons. The first is the interaction of various factors. Previous studies have shown that confined environment, isolation, sleep deprivation, and high cognitive workload may cause some damage to human cognitive ability separately; however, when they appear in conjunction, different results may be produced, e.g., the tiredness caused by sleep deprivation might be reduced by the high cognitive workload. The second reason for the varied results may be the learning effect. Despite the fact that the volunteers were trained before the experiment, the learning effect (performance improvement with practice) could still exist. A between-subjects experimental design was adapted in this study to avoid it and make the effect of SDC apparent. But the learning effect counteracted the impairment caused by sleep deprivation in the SDC group and no decrease was shown in performance.

Each operational type displayed disparate results. Differences in the operation time of the SDC group across three time levels were not significant for the two-way judgment operation. However, results showed that there was significantly more operation time required for mixed operation and manual operation when the waking time increased. Specifically, the longest time needed for mixed operation and manual operation was at the 57th hour and 33rd hour separately. Harrison and Horne concluded that sleep deprivation impaired complex cognitive task performance when the task required such cognitive skills as decision making, innovative thinking, revising plans, and effective communication.[5] It is apparent that decision-making skills were needed for each of the three types. But manual operation requires additional psychomotor abilities compared to two-way judgment. It may be implied that sleep deprivation not only impaired the cognitive process, but also influenced the speed and accuracy of operation.

The operation time decline reflects the effects of constant intervals of SDC after different sleep deprivation times (sleep deprivation levels). It was shown that operation complexity and type have a significant effect on the operation time decline, especially high complexity operations and manual operations, which showed less decrease as compared with the whole procedure and two-way judgment, respectively. These results can also be understood in the context of the controlled attention model.[15] According to Kane and Engle's theory,[15] controlled attention enables higher-order functioning on complex cognitive tasks and, therefore, prevents performance decrease on high complexity operations and manual operations. Pilcher et al. also provided primary evidence on the use of the controlled attention model to better understand the effects of sustained operations and sleep deprivation on performance across a variety of tasks.[23]

This study used simulated spaceflight operations, but also well-established cognitive tasks as some research has. The operational complexity of an operational unit was computed from a well-tested complexity measure (Zhang et al.[31]). It was supposed that the operation units with higher complexity levels required more time and cognitive demand. However, according to the results of previous studies,[5,21] the performance of

Table III. The Mean Operation Time of Operational Units with Different Operation Types.

		SLEEP DEPRIVATION		CONTROL GROUP	
TIME	TYPE	MEAN	SD	MEAN	SD
9th hour	Two-way judgment	3.17	0.589	2.35	0.657
	Mixed operation	4.88	0.247	3.70	0.779
	Manual operation	10.67	1.706	10.04	2.186
33rd hour	Two-way judgment	3.35	1.313	2.03	0.428
	Mixed operation	4.35	0.757	3.58	0.706
	Manual operation	13.94	4.261	9.67	1.841
57th hour	Two-way judgment	2.82	0.686	1.86	0.399
	Mixed operation	5.15	1.308	3.56	1.198
	Manual operation	10.97	2.216	9.45	1.664

Table IV. The Mean Error Counts of Operational Units with Different Operation Types.

		SLEEP DEPRIVATION		CONTROL GROUP	
TIME	COMPLEXITY	MEAN	SD	MEAN	SD
9th hour	Two-way judgment	0.00	0.000	0.00	0.000
	Mixed operation	2.50	2.480	0.14	0.324
	Manual operation	2.71	2.510	0.21	0.518
33rd hour	Two-way judgment	0.00	0.000	0.00	0.000
	Mixed operation	1.88	2.216	0.07	0.241
	Manual operation	2.29	2.510	0.07	0.241
57th hour	Two-way judgment	0.00	0.000	0.00	0.000
	Mixed operation	1.77	2.458	0.00	0.000
	Manual operation	1.98	2.517	0.00	0.000

operations with low complexity was affected by sleep deprivation more easily than those with high complexity because of their monotonous nature. On the other hand, the high situational awareness inspired by high complexity can counteract the fatigue caused by sleep deprivation.[4,20,29] As a suggestion, to avoid the effects of sleep deprivation, work-rest schedules in spaceflight should be designed carefully, taking into account proper allocation of operations with different complexity levels and operation type along the time span. There also were some implications when considering the theory of skill acquisition and retention. For simple tasks and two-judgment operations, operators can easily reach the skill plateau where it is not easily affected by sleep deprivation.

It should also be pointed out that the limited number of volunteers who participated in the experiment were students rather than astronauts. Most current Chinese astronauts are men and new candidates are generally selected from engineers. Therefore, we recruited male students majoring in science and engineering from several universities to meet the selection criteria from the aspect of educational background and gender. However, if we want to apply the results to task design and astronaut training for China's spaceflight, further research needs to be conducted among Chinese astronauts following the same experimental paradigm.

Overall, sleep deprivation combined with other performance influencing factors would lead to significant impairments of overall performance for Chinese operators. Further discussions showed that operations with different complexity and type had different sensitivity levels to sleep deprivation. Some implications can be elicited from these results. First of all, the negative emotions, such as nervousness and irritability, induced by sleep deprivation may be one of the influential factors in decreased performance. It implies that during spaceflight much attention should be paid to emotional control and mental accommodation. Secondly, the results emphasize the importance of training, either in ground facilities or in space, to counteract the negative effects of the extreme environment and to maintain the astronauts' performance. Additionally, the results of this study may imply that a reasonable combination of tasks with different complexities and types could be helpful in counteracting the effects of sleep deprivation. Understanding the effects of sleep deprivation and confinement on the Chinese population is essential for the development of fatigue countermeasures and the design of work-rest schedules.

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