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Short-term virtual reality simulation of the effects of space station colour and microgravity and lunar gravity on cognitive task performance and emotion

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Abstract

This study implemented a short-term virtual reality examination of the impacts of environmental colour and posture changes (to simulate microgravity and lunar gravity) on cognitive task performance and emotions. In a standard posture change laboratory study, sixty participants performed a simple cognitive task battery (finding A's test and number comparison test) and an emotional state questionnaire within nine different colour scenes while using three postures (normal sitting (SP), -12 ° head-down bed (HD) and 9.6 ° head-up tilt bed (HU)). The results showed that in all colour scenes, the HD posture significantly reduced the participants' task performance and level of positive emotions. There was also some variability in task performance and emotional reaction by scene colour. Overall, the study adds to our understanding of how environmental and postural factors impact on cognition and emotion.

Keywords:

Colour environment; Virtual space station; Cognitive task; Emotion

1. Introduction

Since the beginning of manned space flights, the investigation and evaluation of astronaut performance has been the research focus of astronaut training centres in various countries. Finding the best training method to maximize human performance in space has become an important intervention for manned space missions [1, 2]. In recent years, many countries have focused their spaceflight plans on getting manned missions to asteroids, the Moon or Mars [3]. Obviously, this is very different from the current mission of the International Space Station (ISS), including aspects such as duration, environmental control and life support, mission operations, crew teamwork as well as multicultural conflict and resolution [4]. These differences will pose new challenges to maintaining human emotions and mission performance for long-term manned space missions.

In manned space missions, extreme conditions in the space habitat can harm the health and performance of astronauts [5, 6]. The critical environmental stressor in space is the change of gravity [7]. Some studies have shown that astronauts are very sensitive to environmental stressors during space missions, and changes in gravitational conditions as the main stressor can cause changes in the human sensorimotor system [8, 9, 10]. This requires humans to undergo complex adaptive processes, including various neurophysiological changes in the sensorimotor system, which may affect information processing and cognitive abilities [11]. Therefore, the use of bed rest experiments (HD) in a ground environment to simulate the different microgravity states of humans during spaceflight has become the main research method to analyse human physiological and psychological changes [12]. Extensive studies have used the method of head-down bed rest (HDBR) to explore the laws of physiological and psychological changes underlying human adaptation to microgravity [13, 14]. Some of these studies conducted 4 hours of -12 ° head-down bed rest to simulate the headward fluid shifts that occur in microgravity, rather than the commonly used long-term -6 ° HDBR, before choosing a more severe angle to evoke a response within a shorter time frame of the condition and to simulate the headward fluid shift and cardiovascular changes more effectively in space [15, 16]. In addition, a 9.6 ° head-up tilt (HU) bed rest method has also been developed to simulate the physiological effects of lunar gravity [17,18]. Studies by Segizbaeva (2016), Richter (2017) and Malaeva (2018) investigated the use of 9.6 ° head-up tilt to simulate the physiological and psychological changes of lunar gravity on humans [19, 20, 21]. They provided exploratory evidence for negative impacts on cognitive performance in this state, on tasks such as visual tracking [22, 23, 7], grammatical reasoning [24, 25], and consistency proofing [26, 27], through to measures of higher attention function (e.g., attention shift, dual task execution etc.) [28, 29].

Moreover, due to stressors such as microgravity, isolation and restrictions on physical movement, astronauts are prone to negative emotions such as anxiety and depression, which can then affect their ability to work and cognitive function [30, 27, 113], as well as their wellbeing in a broader sense [31]. The exploration of emotions has long been a focus of attention for space agencies and associated researchers, and emotions play an important role in the conduct of human space missions [115]. Researchers believe that, in addition to many potential physical and technological risks, psychological risks may be one of the most serious threats posed to crew members during space exploration [116]. During construction of the International Space Station (ISS), NASA assessed the emotional state of the ISS crew on a weekly basis using the Positive and Negative Affective Scale (PANAS) and the Profile of Mood States (POM) questionnaire, tools with which the detailed emotional elements provide a good indication of changes in the crew's emotions [117,118]. The Personal Subjective Report and Brief COPE Inventory were also used to assess the crew's response to problems and emotions [119]. Further, in ground-based simulations, NASA and the European Space Agency have used various scales to investigate the emotional state of crew members in extreme environments (e.g., polar regions, deep sea) [120,69]. Some studies have used the POMS to assess the emotions of participants in simulated isolated, confined, extreme (ICE) environments for 105 days and above, and have found changes in emotions over time [121]. Moreover, the PANAS, Patient Health Questionnaire, Subjective Mood Report, Beck Anxiety Inventory (BAI), and Beck Depression Inventory (BDI) have also been frequently used to find evidence of general emotional characteristics and psychological risk during simulated different spaceflight stress missions.

Studies have used the head-down bed rest paradigm to simulate the psychological effects of spaceflight [32, 33], and have suggested that it can also simulate in-flight isolation and restrictions. Various emotion scales are also often used as tools to investigate emotions in studies where bedrest simulates different gravities. In particular, the Positive and Negative Affect Scale (PANAS) has been used to investigate the emotional state of participants in head-down bed rest studies [69,122]. Liu et al. (2011) used the PANAS to find that the emotions of female participants in head-down bedrest for 15 days experienced a shift from stress to calmness and from distress to adaptation [123]. Researchers have also used PANAS to also find emotional changes for participants in HDBR of different durations. It was found that participants' negative emotional states increased significantly during head-down bed rest conditions and that this symptom became progressively worse over time [34, 35,32, 36]. This may be caused by factors such as visual strain due to headward fluid shift, and back pain during bed rest [37, 38]. Besides, some short-term bed rest studies have found significant changes in level of hormones such as cortisol in subjects [39]. Thus, subjective reports using emotional rating scales such as the PANAS and questionnaires that investigate other psychological characteristics provide an effective, simple, and practical method of recording emotional responses. However, there are no findings yet as to whether the colour of the environment improves this emotional problem during bed rest.

Colour is also commonly an important part of the working environment. An appropriate colour environment can significantly improve human emotional and physiological performance, thereby optimising work performance [40, 41, 42, 112]. In a European Space Agency report, some anecdotal reports also show that the interior decoration of the space station (such as colour and photos) has a positive impact on the physical and mental health of people who have been living in a restricted and isolated environment for a long time [43]. In the early phase of ISS construction, the Soviet orbital space station Salyut 6 used soft pastel interior colours to provide a more harmonious atmosphere [44]. The ISS plan also mentioned that multiple different colours should be avoided because this would quickly cause visual saturation. Instead, they suggested using dark colours in a small area to limit the diversification of medium brightness and saturated colour [45]. However, there is limited related research on colour for improving task performance and providing positive emotional support for astronauts. In an Earth environment with normal gravity, extensive research has found that the colour of the environment can effectively regulate humans' emotions and performance during work [46,47,48,49]. Clarke and Costall (2008) found that cold colours such as blue and purple were thought to alleviate negative emotions and anxiety symptoms, while red and orange were thought to increase arousal levels [50]. Other studies have found that blue stimulates more pleasant, calming emotions than red and yellow [51,52,53]. Besides, previous studies have found that colour environments also affect performance, particularly when performing fine tasks, with more errors occurring in white or grey environments than in coloured environments, and that performance is significantly optimised in both warm and cool colour environments, relative to achromatic environments [48, 54]. Thus, literature to date indicates that the colour of a scene plays an important role in the performance of humans in work processes. However, little existing work has explored this across different simulated gravity states.

The current study was designed to examine changes in task performance and emotional changes during bed rest in simulated microgravity. As part of this approach, we explored how to optimise this state through changes to the colour of the environment. The present investigation used three postures (normal sitting position (SP) to reflect conditions on Earth; -12° head-down (HD) bed rest to simulate microgravity; and 9.6° head-up tilt (HU) bed rest to simulate lunar gravity) to simulate the impact of the colour of scenes on human task performance and emotional state in different microgravity states. The aims of this study were to determine (Q1) How do the different gravity states simulated by the three postures affect task performance and emotions? (Q2) How does the colour environment affect task performance and emotions during the three postures? Based on previous findings, the following hypotheses were established: (i) The different states of gravity simulated by the three postures would have different effects on task performance and mood, and task performance and mood would be lower during bed rest than during normal sitting. (ii) The nine colour environments would have different effects on task performance and emotions during the three postures, and that task performance and emotions would be superior in cold colour environments.

2. Method

2.1 Participants

Sixty students from China studying a general psychology course took part in the study. The age of the participants was 23.7±2.6 years. The group was composed of 30 men and 30 women. They were all right-handed and had normal vision (none were near-sighted). All participants passed the Ishihara colour-blindness test. They were screened using the Eysenck Personality Questionnaire (EPQ), and all were extroverted or stable. All had passed a health-screening assessment and had no heart or cerebrovascular disease nor any history of neurological and/or psychiatric disorders and had undergone a physical examination including a tilt test. During the 24 hours before the experiment and during the experiment, all participants were asked to avoid caffeine, alcohol, prescription drugs and smoking. The experiment was reviewed and approved by the Research Ethics Committee of the University of Leeds (FAHC 19-073).

2.2 Scene setting

The interior scene of the crew cabin of the International Space Station was developed using the joint platform of Rhino 6.0 and Unity 2019. MATLAB R2020a (MathWorks, USA) was used to generate a virtual task for the participants to complete during the experiment. The Keyshot 4.0 version rendering program was used to simulate the space station cabin scene. The panorama is shown in Fig. 1A. The ceiling and the floor of the laboratory cabinets on both sides of the crew cabin scene were depicted in one main colour, while the colour of the handrails and inherent equipment was kept the same as the original products to minimise interference from other colours. The average illuminance of 400 lx and the correlated colour temperature of 4500 K were configured in accordance with the lighting requirements of the space station's crew cabin. The participants had to wear a head-mounted display (HMD) to watch the scene. The handle controller was represented as a virtual hand in the scene. The participants had to use the handle controller to perform tasks in the scene. The nine scenes where the HMD was placed are shown in Fig. 1B. This method has been used in previous studies and verified for its accuracy in representing actual scenes [54, 55, 56].

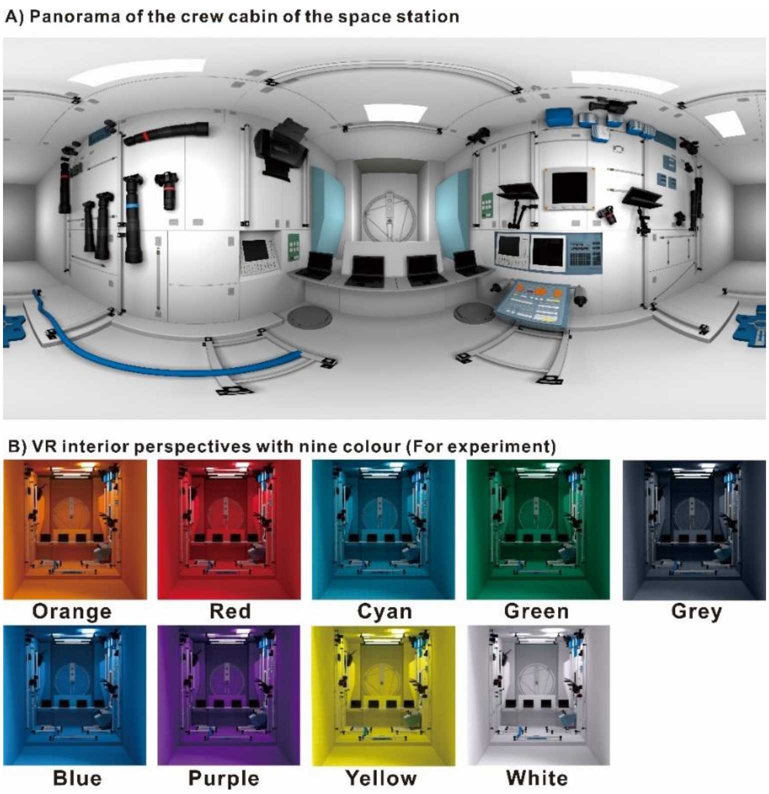

Fig. 1. A) Panoramic view of the crew cabin of the space station, B) VR scene of the crew cabin in the nine main colours used in the experiment

2.3 Values of colour scenes

The nine main colours used were red (R), orange (C), green (G), blue (B), yellow (Y), (purple (P), cyan (C), grey (G) and white (W). Whilst most of these environments are more chromatic than may be expected from a space station, colours with high chroma were used to maximise the impact of the colours on the participants' workload and task performance. This method has been extensively used in previous studies [57, 54, 58, 59, 60]. Table 1 shows the CIE (Commission Internationale de L'Eclairage) L * a * b * values of the colours used.

Table 1. CIE L * a * b * of each coloured scene

N	Hue	L	a	b	R	G	B
1	red	56.4	68.8	33.8	244	64	82
2	orange	74.0	31.2	66.4	254	158	53

3	yellow	93.8	-10.2	81.0	251	241	60
4	green	59.8	-41.6	8.3	34	163	128
5	cyan	65.5	-27.3	-24.4	52	174	202
6	blue	63.8	-16.0	-38.2	64	165	222
7	purple	49.7	58.8	-56.9	174	71	217
8	grey	53.4	-1.2	-11.3	117	129	147
9	white	93.2	0.27	-10.3	253	249	255

2.4 Apparatus and materials

The experiment was carried out in a standard posture change laboratory. The rotating bed controlled by the software program can assume any posture from +90 ° to -90 °. The VR scenes were configured using the HTC Vive VR system (HTC) and SteamVR. The resolution of each eye of the head-mounted display (HMD) was 2160×1200 pixels, and the refresh rate was 90 Hz. The field of view was 100 ° horizontally and 100 ° vertically.

For cognitive load tasks, we used the Ekstrom Kit of Factor-referenced Cognitive Tests (ETS) [61]. This task is designed to measure the proofreading accuracy related to various cognitive abilities and is widely used in visual search or cognitive processing tests [62]. This same type of task also appears in task performance studies that examine colour scenes [48, 63]. The task includes two subcomponents: the finding A’s test and the number comparison test. In the finding A’s test, a word list appears in the centre of the virtual crew cabin. Participants need to use the handle to click on all the words containing the letter "A" to mark the horizontal line. In the number comparison test, participants need to compare a series of digital pairs, find inconsistent digital pairs and click "X" to mark them, as shown in Fig. 2. For each test, 200 items were randomly selected from the ETS (100 find-A and 100 number comparison). Thus, the items and their order differed in each test for each participant. Test-retest reliabilities for each subtest were above 0.93 for the number comparison test and above 0.84 for the finding A's test. The ETS is highly correlated with measures of cognitive ability [64, 65]. This method is widely used in research involving spatial cognition and task performance to measure the impact of different environmental factors on task performance [66, 67, 68].

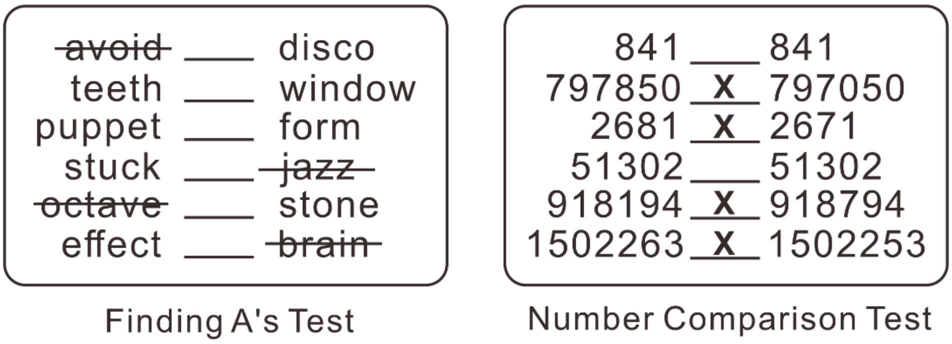

Fig. 2 Sample tests based on Ekstrom's Kit [61]

The Positive and Negative Affect Scale (PANAS) has been widely used to investigate the emotional state of participants in head-down bed rest studies [117-118]. Evidence from previous studies has demonstrated the high reliability and validity of the PANAS as an emotion rating scale during analogue human spaceflight missions, including use of the bed rest experiment paradigm [69,112,122-123]. The PANAS was used to evaluate participants' positive and negative emotions [69, 70]. The score range for each item is between 1 and 5 points. PANAS is a scale consisting of 20 items, 10 PA and 10 NA, respectively. Each item involves an adjective to represent the emotions and feelings of posture and colour when the participants are doing their homework. The Chinese version of PANAS has good validity and reliability [71, 72]. In a study of 853 college students, the internal consistency of the scale was α = 0.90 for positive effects and α = 0.92 for negative effects [73].

2.5 Design and Procedure

A 3 (posture) × 9 (colour environment) × 3 (task: cognitive load task, positive emotion, negative emotion) repeated measures design was used. The participants performed two cognitive load tasks in each of the nine colour environments during each posture. The postural conditions completed by different participants were counterbalanced, and the colour environment, the two parts of the cognitive test and the items in each part of the test were randomised for each participant. The dependent variables were error rate and positive and negative effect on the cognitive load task in the nine colour environments during the three postures.

The participants were taken to the laboratory at 9:00 AM and allowed to relax for 30 minutes to adjust to their surroundings. They then used a 5-point emotion scale to report their emotional state in the past week, where 1 meant not feeling anxious or depressed, and 5 meant extremely anxious or depressed, to minimize the deviation of the participants' emotional baseline between the three sessions [74]. The experiment was carried out in a room without sunlight. In the week before the study, all participants had received training in the use of the head-mounted display (HMD) and virtual reality (VR), and all had passed the VR operation test. Before the experiment, the participants were introduced to the experiment process and the precautions and informed of the meaning of each topic of ETS and PANAS. They also had an understanding of the functions and definitions of the crew cabin of the space station. The participants were asked to accurately understand and evaluate according to their actual situation, and all signed an informed consent form.

The experiment was divided into three sessions: (1) The participants wore the HMD in a normal sitting posture (SP) for testing. (2) The participants rested in the −12 ° head-down bed rest position (HD) for three hours to induce the microgravity effect, and then wore the HMD to complete the test. (3) The participants rested in a 9.6 ° head-up position (HU) for three hours before wearing the HMD to complete the test. The order in which the three posture conditions was completed was counterbalanced across participants to minimize potential deviations due to the sequence. Each participant had a 72-hour break between each session test to avoid potential carryover effects. The specific experimental design and the timeline are shown in Fig. 3.

Before the start of the SP posture test, each participant was asked to wear an HMD to watch a white screen for five minutes to allow for chromatic adaptation. Subsequently, nine 3D colour scenes appeared on the VR HMD in random order. The participants used the handle controller to perform the finding A's test and the number comparison test in different colour scenes. After the task test, the PANAS questionnaire appeared in the centre of the crew cabin for the participants to fill out. The test content was presented in black in the centre of the crew cabin scene to ensure that the colour and sense of space stimulated the participants. This method has been used in previous studies [75]. Additional comments were collected at the end of the PANAS questionnaire, with participants given the option to provide any subjective comments on the perceived effects of different postures and colour environments on task performance and emotion. It took 4 ± 0.27 minutes to complete the task in each colour scene. The participants entered a dim white scene (dim<6lx) for two minutes after completing a task of each colour scene to allow them to rest in order to alleviate any legacy effects and colour stimulation from the previous scenes [76].

In the HD and HU postures, the participants first had a -12 ° head-down bed rest and a 9.6 ° head-up tilt bed rest, respectively, for three hours in a D65 light source environment. They could chat, listen to music, rest or do other activities during this period, but they were not allowed to use mobile phones, computers or other devices that interfere with light sources. After resting in bed for three hours, they wore the HMD to watch the white screen for five minutes to allow for chromatic adaptation, and then the experiment was the same as for the SP posture.

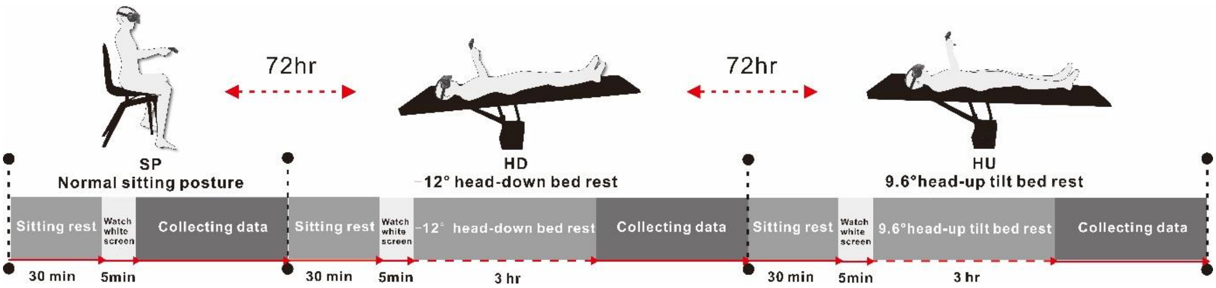

Fig. 3 Experimental design

2.6 Statistical analysis

A set of three 3 × 9 Repeated-measures ANOVAs were conducted to examine the effects of different postures and colours on error rates and emotions. To find out whether there were any significant differences in task error rates and emotions among different postures and colours, and to determine the statistical significance, α<0.05 was considered statistically significant. After any statistical significance (p<0.05), Tukey's HSD test was performed to follow up on statistical significance, and Bonferroni correction was used. The Statistical Package for Social Sciences (SPSS) was used together with MATLAB for all analyses in this study.

3. Results

We first analysed error rate on the cognitive task. A significant main effect of posture was observed, ($F(2,177) = 3.643$, $p < 0.01$, η_P^2=0. 39), indicating differences in error rates between SP, HD, and HU conditions**.** Task performance across the three postures is presented in Figure 4A. Follow-up comparisons indicated that HD had the highest error rate compared with the other two postures (SP:(p=0.018<0.05), HU:(p=0.031<0.05)), while there was no significant difference between SP and HU (p=0.085 >0.05). There was also a significant main effect of colour scene ($F(8,1611) = 3.148$, $p<0.05$, η_P^2=0.15). Error rates across the different colour scenes are show in Figure 5A. Further post-hoc tests found that, compared with other colour scenes, participants had a significantly higher error rate for the grey scene ($p=0.025<0.05$), Error rates for the other eight colour scenes did not significant differ ($p=0.342>0.05$), although these rates were numerically somewhat higher for gray and green scenes, and slightly lower for the cyan scenes. The two-way interaction between posture and colour environment was not significant (F (16, 944) =1.328, p=0.57, η_P^2 =0.013).

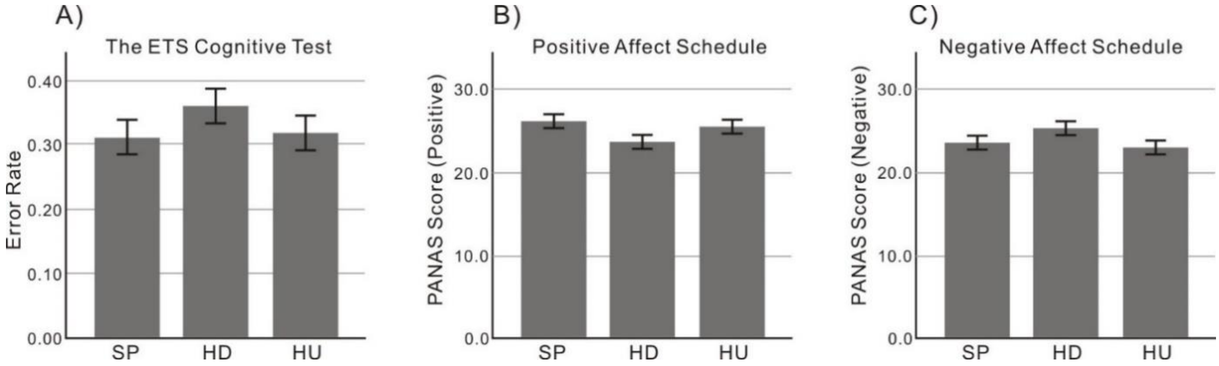

Fig. 4. (A) error rate of cognitive tasks; (B) positive emotional impact and (C) negative emotional impact during the three postures (The error bars show the standard error of the means.)

Turning to the affect scales, and starting with positive affect, there was a significant effect of posture (F (2,177) =29.509, $p<0.05$, η_P^2 = 0.25). The data are illustrated in Figure 4B. Positive emotions were significantly lower in the HD condition compared with SP ($p=0.032<0.05$) and HU: ($p=0.048<0.05$). There was no significant difference between SP and HU postures (p = 0.22). There was also a significant main effect of colour on participants' positive emotions (F (8,1611) =2.328, $p<0.05$, η_P^2 =0.11). Compared to the other colours, red produced the lowest level of positive emotion ($p<0.05$) and cyan the highest level (p=0.036), see Figure 5B. The 2-way interaction was not significant (F (16, 944) =1.481, p=0.83, η_P^2 =0.025).

Finally, examination of negative affect revealed a significant main effect of posture (F (2,177) =7.962, $p<0.05$, η_P^2 =0.081). As illustrated in Figure 4C, negative emotions were significantly higher in the case of HD

(SP: (p=0.008<0.01), HU: (p=0.042)), with no difference between SP and HU (p = 0.17). There was also a significant effect of colour (F (8,1611) =2.494, p<0.05, η_P^2 =0.12). As shown in Figure 5C, participants had the highest level of negative emotions when working in the red scene (p=0.013), and the lowest level when working in the cyan scene (p<0.05). The two-way interaction was again non-significant negative emotion (F (16, 944) =1.752, p=0.52, η_P^2 =0.037).

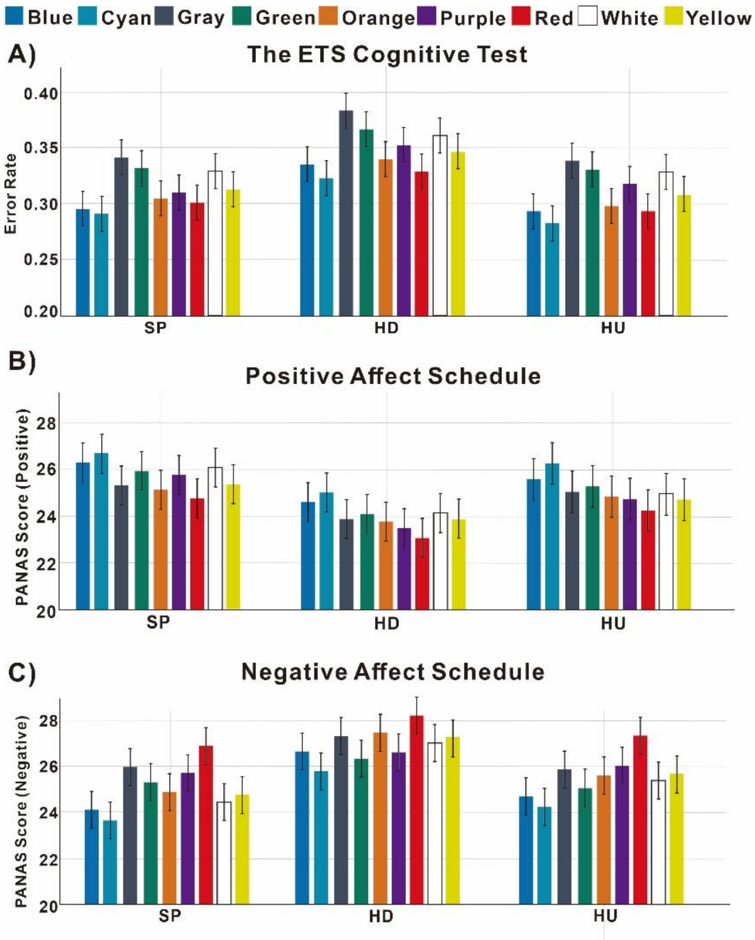

Fig. 5. (A) error rate of cognitive tasks; (B) positive emotional impact and (C) negative emotional impact in the nine colour scenes in the three postures (The error bars show the standard error of the means.)

4. Discussion

This study used virtual reality to evaluate effects of body posture and environmental colour on cognitive task performance and emotions. The results answered the research questions as follows: (Q1) In all colour scenes, the -12 ° head-down (HD) bed rest posture significantly reduced participants' task performance and positive emotions compared with normal sitting (SP) and 9.6 ° head-up tilt bed rest (HU) postures, and significantly increased negative emotions. (Q2) Across the three postures, variability in colour scenes affected task performance and emotions; the cyan scene produced improved emotional reaction and numerically (but not significantly) better task performance, while task performance in the grey scene was the least accurate. In the red scene, the level of negative emotions increased significantly. Finally, we also found that these effects of posture and colour did not interact for any of the outcome measures; posture had statistically equivalent impacts across the different colour scenes, and vice versa.

4.1 The effect of colour scenes on task performance and emotions during the three postures

This study found that in any colour scene, the participants' task error rate during HD was significantly higher than that during SP and HU, which indicates that their task performance was significantly reduced during -12 ° head-down bed rest. This replicates and extends outcomes from previous studies showing that. performance of cognitive tasks was much lower than normal, and attention was reduced, during head-down bed rest [77,78,79]. It is suggested that this occurs because participants are easily distracted in microgravity, which is related to the acute effect of cephalad fluid shift during head-down bed rest, and causes negative changes in the waveforms of event-related potentials, leading to cognitive processing disorders [80, 15]. Similarly, NASA found that when astronauts perform cognitive tasks such as comparison or counting tasks during head-down bed rest training, the microgravity effect causes a decline in their cognitive performance [14]. In contrast, performance on the cognitive task during the 3-hour 9.6° head-up tilt (HU) was not significantly different from the normal sitting state. This may be the result of the absence of significant physiological and psychological changes in the short-term lunar gravity state. Based on previous records of the 11-person lunar landings documented by the US Apollo programme, astronauts' subjective reports of cognitive abilities (e.g., sensory, verbal, perceptual and thinking) were similar to those shown under the Earth's gravity state, though motor coordination problems were encountered on the lunar surface due to low gravity [124-126]. Furthermore, the effects of the lunar gravity state on cognitive abilities induced by HU may be consistent with the findings of previous physiological studies. Although little is known about cognitive studies in lunar gravity, some physiological studies using HU to simulate lunar gravity have shown that the physiology of lunar gravity states is not significantly different from that of Earth gravity states [19,127]. Given that cognitive abilities are higher-level human information processing processes that are strongly linked to physiological experiences and psychological states, this somewhat validates the findings of this study. Similarly. in the case of lunar gravity, posture adjustment, object handling and mechanical tasks (such as bolt tightening) do not appear to cause major problems [81, 82]. However, other studies suggest that the impact of lunar gravity on human performance is still unclear [83, 84, 85, 86]. Therefore, in the future, head-up tilt bed rest time should be studied over increased durations to further determine the possible impacts of lunar gravity.

Subjective reporting of emotional states on the PANAS changed across the three posture conditions. In the HD posture, the level of negative emotions in the nine colour scenes was significantly higher, and the level of positive emotions was significantly lower. The majority of participants also stated that in the HD posture, the head-down bed rest produced feelings of Irritability and slight head swelling, which would also increase the level of negative emotions in this state. This is consistent with the conclusion of Benvenuti (2013), who found that three hours of head-down bed rest can significantly affect the emotional response [33]. This negative emotional change is due to the HD posture, which changes the activity of the prefrontal cortex of the brain [87, 88]. Other EEG studies have demonstrated that HD induces greater delta and theta EEG activity and slower reaction time. The observed increase of slow rhythms accompanying negative emotions is a clear marker of cortical inhibition [89, 90]. In contrast, the emotional response during the 3-hour 9.6° tilt-up bed (HU) period was not significantly different from the normal sitting state. This is similar to some 9.6° head-up tilt bed rest studies that have simulated the lunar gravity state, finding that participants' subjective responses and physiological performance could tolerate analogues for shorter periods of time [91, 20]. Extensive research has concluded that emotions are derived from both feedback from physiological responses and from cognitive appraisals of the situations that lead to those responses [128,129]. The physiological changes in fluid regulation and endocrinology during the HU are closer to the normal sitting state than during the HD. As a result, the increase in negative emotions is correspondingly more moderate. This is similar to the finding that elevating the head during HU bed rest results in a relative 'outflow' of fluids from the head, which reduces swelling, and also reduces aerodynamic resistance in the airways [130,131]. In contrast, continuous -6° head-down bed rest for 30 days to longer will reveal some emotional [92], task performance [29] and physiological (e.g., muscle and bone density) [93] changes. Thus, it may take longer to elicit the effects of lunar gravity on human emotions and performance [94, 95].

4.2 The impact of colour scenes on task performance and emotions

Considering that the microgravity effect has an impact on human task performance and emotions, we decided to compare the effects of nine colour scenes on human task performance and emotions during the three postures. Overall effects of scene colour emerged on all outcome measures. Compared with the other colour scenes, the task error rate in the grey, green and white scenes was higher. Task error rate in the cyan scene was also numerically lower, although this did not reach statistical significance. These findings are broadly similar to some previously reported outcomes. Kwallek (1996) found that when undergraduates performed comparison tasks, they made significantly more errors in white classrooms than in red or blue classrooms [48]. When AL-Ayash (2016) compared the task performance in a colour environment and in an achromatic environment, they found that the performance in an achromatic environment such as white and grey was lower than in a colour environment [51]. Some studies suggest that because the colour environment is more satisfying and vibrant, this will lead to better performance [96, 97, 98]. The numerically lower task error rate for the cyan scene in our study is similar to the conclusions of others, although caution must be exercised here, given it did not reach statistical significance. Abbas (2006) believes that cool colours can calm people and relieve heart rate activation [99]. The majority of participants of our study also said that cool colour scenes can enhance the clarity of the field of vision and help to perform tasks faster, which is consistent with the conclusion that cool colours can enhance human visual perception [52, 46, 41]. Therefore, if the task performed is meticulous and difficult, a certain degree of saturated colour conditions may increase the level of arousal, thereby improving task performance. This finding supports the Yerkes-Dodson law on the relationship between arousal and performance [100]. However, the red scene did not achieve the best performance in this study. It may be that the highly saturated colour causes excessive arousal and has a negative impact on task performance [50, 101, 114], and also reduces cognitive performance to a certain extent [54].

This study also found that the level of negative emotions in the red scene was higher than that for the other eight colour scenes, followed by the orange scene, and that the cyan scene had the lowest level of negative emotions, followed by the blue scene. This shows that cool colours such as blue and cyan can effectively alleviate the impact of negative emotions [102]. Studies have indicated that warm colours such as red and yellow produce more stimulation and arousal, while cool colours such as blue and green are calming [101, 54, 103]. The latter colours are considered to be cool, calming and relaxing, which can relieve anxiety and depression levels [104, 105]. In contrast, some studies claim that people will be more nervous in a red environment, and that this colour will increase the arousal of the heart rate [106, 63]. Moreover, early NASA studies of spacecraft internal cabins also found that, for example, Skylab crews believed that light blue or cyan internal cabins may be more likely to relieve fear and anxiety than brownish-yellow and brown cabins. According to them, a brownish-yellow visual environment would increase their anxiety and tension especially when the rocket is overweight during the ascent and return phases [107]. Furthermore, some anecdotal reports of astronauts state that a tan environment increases the feeling of "dizziness", "cannot relax" and even a certain sense of nausea [108]. A Roskosmos research report states that an orange or brown environment would intensify the sense of depression and closure in the narrow space of the spacecraft, strengthen the visual pressure on the crew and further induce negative emotions in the crew [107].

4.3 Limitations and future directions

In this study, we used saturated colours for testing to investigate the effects of a strong manipulation of colour scenes on task performance and emotions of participants. However, some studies have found that participants usually prefer working in a colour environment with low saturation and lightness [98]. In the future, the scope of colour stimulation might be expanded, for example by dividing into four types (saturated, light, muted and dark) to explore the impact of colour on human task performance and emotions. Secondly, this study analysed the impact of colour scenes on humans through task tests and emotional questionnaires. Due to the complexity of emotions and cognition, any measurement method has its limitations. In order to explore the complex stress changes in humans during a task, some studies have used physiological indicators to index degree of arousal, finding that certain colours can significantly affect heart rate and lead to changes in EEG and brain blood oxygen levels [109, 110]. Therefore, a multivariate approach combining measures of subjective experience (e.g., observer ratings, scales and phonological measures) and cognitive task performance (correctness, speed of response) with physiological recordings commonly used in spaceflight human factors studies (e.g. galvanic skin response (GSR), heart rate (HR) and heart rate variability (HRV) and brain activity (EEG and fNIRS)) would allow for a full demonstration of the effects of spaceflight and its impact on an individual's emotions. Thirdly, this study explored the effects of colour scenes on humans when sitting in a normal sitting posture, during -12 ° head-down bed rest and during 9.6 ° head-up tilt bed rest. So far, prior studies have been carried out on long-term head-down bed rest (15 days or longer) to explore the performance of humans during bed rest [111], but no study related to the colour environment has been found. The duration of bed rest should be extended in the future, and in particular the effect of the colour environment on participants during longer-term 9.6° head-up tilt bed rest postures needs to be examined to obtain the effect of the colour environment on humans during different time periods in bed rest. Finally, our participants were all Chinese undergraduate or graduate students. In the future, consideration should be given to working with populations more analogous to those from which astronauts are drawn (e.g., pilots and soldiers) who may have relevant experience and demographic characteristics (e.g., age range), to obtain more realistic results regarding the emotional and cognitive abilities of crew members in different colour environments during simulated different states of gravity.

5. Conclusion

In this study, we examined the effects of colour scenes on human cognitive tasks and emotions in three postures: normal sitting posture, -12 ° head-down bed rest and 9.6 ° head-up tilt bed rest. Our study found that the -12° head-down bed rest posture significantly reduced task performance and positive emotions, while task performance and emotional state in the 9.6 ° head-up tilt bed rest posture were not significantly different from the normal sitting posture. This suggests that in the short-term humans experience a greater negative stress response during simulated microgravity than during simulated lunar gravity and Earth gravity. The grey scene significantly reduced the performance of cognitive tasks, while the red scene increased the level of negative emotions. Therefore, such colours should be avoided in large areas in spacecraft interior cabins, while cool scenes such as cyan may optimise human emotions and task performance. These findings will provide useful design references for human environmental colour requirements in microgravity and lunar gravity.

Declarations of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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