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The effect of colour environments on visual tracking and visual strain during short-term simulation of three gravity states

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ABSTRACT

This study investigated the effects of nine colour environments on visual tracking accuracy and visual strain during normal sitting (SP), −12° head-down bed (HD) and 9.6° head-up tilt bed (HU). In a standard posture change laboratory study, fifty-four participants performed visual tracking tasks in nine colour environments while in the three postures. Visual strain was measured by means of a questionnaire. The results showed that in all colour environments, the −12° head-down bed rest posture significantly affected visual tracking accuracy and visual strain. During the three postures, the participants' visual tracking accuracy in the cyan environment was significantly higher than that in other colour environments, and their visual strain was the lowest. Overall, the study adds to our understanding of how environmental and postural factors impact on visual tracking and visual strain.

1. Introduction

When astronauts are exposed to a microgravity environment, microgravity induces a variety of physiological effects, such as space motion sickness, cardiovascular disease, space disorientation, Spaceflight Associated Neuro-ocular Syndrome etc. (Steinberg et al., 2012; McPhee and Charles, 2009; Clément et al., 2020; Lee et al., 2017). In addition to these physiological variations, astronauts also experience unconscious changes in brain function (Kozlovskaya et al., 1985; Prisby et al., 2006). Variations in brain function have a significant impact on the various operational capabilities of astronauts. Among them, the problem of visual ability is particularly noticeable because vision is closely related to astronauts' performance in almost all missions (Corchs and Deco, 2002; Clément and Reschke, 2010). Spaceflight tasks are the main cause of stress to the crew's visual system, including the experimental operation of various on-board payload devices, computer and physical interface control, rendezvous and docking tasks, on-board payload maintenance and daily self-exercise. Besides, the crew's time on the space station includes work, life and rest. All this means that crew members typically use their eyes for 12–15 h during a day of in-cabin life, and typically spend 6–10 h concentrating on using their visual abilities while performing experiments and operations, which significantly increases their visual stress. A number of studies have found that 29% of the astronauts who took part in short-term missions and 60% of those who participated in long-term missions reported having experienced varying degrees of visual problems (Mader et al., 2011; Reschke et al., 1994; Tomilovskaya et al., 2011). NASA's "VIIP" project found that for astronauts in a microgravity environment, increased intracranial pressure and intraocular pressure damaged the optic nerve and affected vision (Taibbi et al., 2012). The Russian Aerospace Agency conducted an unstable tracking mission and four reaction-time mission tracking tests on three astronauts during a 30-day long-term mission and found that tracking errors almost doubled when comparing the results before the flight to those during the flight (Linder et al., 1988; Kergoat and Durand,

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1996). In a −15° head-down bed rest simulation microgravity task performed in China, it was found that the intraocular pressure and near vision of the participants significantly increased, their overall visual ability decreased, and strong visual strain was generated after only 30 min of induction (Yu and Jiang, 2016). Another study summarised the health and performance of 31 astronauts in orbit who performed missions on the International Space Station (ISS) from 1989 to 1995. It reports that eye-brain coordination of all astronauts significantly decreased during the process of visual target capture, but returned to normal 48 h after they returned to the ground (Reschke et al., 2017). Therefore, the performance of visual tracking tasks reflects a kind of eye-brain coordination ability, and the movement of the eyeballs is the guarantee that the brain continuously obtains signals. The brain's control of the eyes is the basis of tracking.

The headward fluid shifts caused by microgravity are believed to be the main cause of astronauts' eye problems and other physical problems (Guell et al., 1993; Stella et al., 2021). Extensive studies have generally used the method of head-down bed rest to simulate the headward fluid shifts in order to induce the microgravity effect in the normal gravity of Earth (Convertino, 2010; Meck et al., 2009). A number of studies conducted 4 h of −12° head-down bed rest (HDBR) 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 and to simulate the headward fluid shifts and cardiovascular changes in space more effectively (Ong et al., 2021; Zhang and Hargens, 2018; Li et al., 2020). A 9.6° head-up tilt (HU) bed rest method has also been developed to simulate the physiological effects of lunar gravity (Baranov et al., 2016; Malaeva et al., 2018). The studies by Watenpaugh (2016), Richter et al. (2017) and Baranov et al. (2016) summarise the use of 9.6° head-up tilt to simulate the physiological and psychological changes of lunar gravity on humans. Earlier studies by NASA and others used the normal sitting position to simulate Earth's gravity and explore the physiological and behavioural changes between Earth gravity and microgravity (Lawley et al., 2017; Blomqvist and Stone, 1991). They provide exploratory evidence for changes in physiological and behavioural performance in this state. In some short-term bed rest studies that have been carried out, the researchers used Optical Coherence Tomography (OCT) related equipment to examine the fundus and optic nerve of the participants, and found some physiological changes similar to the condition of astronauts after orbiting, such as optic disc oedema (Chiquet et al., 2003; Li et al., 2020). As a manifestation of the basic functions of the eyes, the neural pathways and the comprehensive functions of the corresponding brain regions, visual tracking ability, which is closely related to astronauts' operational capabilities, has also been found to be significantly reduced. This includes known problems affecting manoeuvres such as reduced visual perception, blurred vision and increased eye pressure (Yu and Jiang, 2016; Shehab et al., 1998; Yu et al., 2021). Moreover, long-term exposure to the isolation and confinement of the cabin environment can cause negative emotions such as visual monotony, anxiety and depression. These severe stress reactions could seriously affect the success of a space mission. In terms of visual ability, existing short-term bed rest studies have focused on features such as near vision, visual field and visually evoked potentials (Xu et al., 2002; Zhao et al., 2006; Yu et al., 2021). However, there are still only few studies on how to improve and optimise human visual tracking ability and visual strain under different gravity states.

In the Earth environment, the colour of the environment affects people's cognitive ability, visual comfort and emotions (Livingstone and Hubel, 1988; Haber and Hershenson, 1973), as well as the brain's response to stimuli (Cano et al., 2009). Besides, studies on visual perception show that the processing of natural images, especially the recognition of interfaces and scenes, benefits from colour information (Gegenfurtner and Rieger, 2000; Hansen and Gegenfurtner, 2009). The use of colour in the environment is always purposeful. Some studies have shown that in ships, aircraft cabins and nuclear power plants, red and orange are commonly used for warnings. A cool colour environment, on the other hand, can alleviate people's visual strain and is often used in closed and isolated environments, such as ship bridges, main control rooms etc. (Mahnke, 1996; Jiang et al., 2020). Using appropriate colours in the environment can improve people's visual ability in a specific environment and optimise human performance (Bramão et al., 2011). In contrast, improper use of colours may cause various negative psychological reactions, which will ultimately affect people's performance (Mahnke, 1996; Jalil et al., 2012, 2012ztürk et al., 2012). Moreover, Livingstone and Hubel (1988) believes that a white scene that is too monotonous does not optimise human vision well, and being in a white environment for a long time will increase the risk of visual strain (Livingstone and Hubel, 1988). Mehta and Zhu (2009) conducted a series of six visual perception experiments, suggesting that blue should be used as the background for any creative work, while using a red environment can be used for some focused work. Greco et al. (2008) found that the best readability can be achieved by working in a light blue or cyan background. Visual tracking studies in the space environment have not provided definitive evidence to prove the important role of colour affecting the eyes. However, an analysis of work environments that attract visual attention has shown that colour plays a major role in affecting people's attention when they work (Tatler et al., 2005). NASA scientists are well aware of the benefits of colour in the environment on astronaut behaviour, and some anecdotal reports from the space station show that short-term space isolation and social deprivation show the emergence of visual impairment, cognitive errors and negative emotions, caused by monotonous environmental colour. A key example is Skylab-4, where the visual monotony of the white environment during the crew's operational tasks led to negative individual emotions, which caused a hostile atmosphere and poor interpersonal relations among the crew (Ettis, 2017; Jiang et al., 2022a,b). The subsequent Skylab crew found the interior of the spacecraft to be less than comfortable and highlighted the lack of colour ambience. The crew agreed that the spacecraft's main instrument panel, crammed with numerous colourful lights, could be more pleasant (Jiang, 2022; Gong et al., 2022). Some researchers believe that although the colour saturation of these environments is low or even imperceptible, prolonged exposure to such environments can have a long-term and subliminal effect (Mahnke, 1996). This amply demonstrates the remarkable effect that the use of coloured environments can have on astronauts in long-term isolation, and in confined and deprived environments.

Visual tracking is a typical part of any space mission, but no evidence of the impact of colour on visual tracking and visual strain during the simulation of different gravity effects has been found to date. Recording the effect of the colour (hue) of the crew cabin environment on visual tracking tasks will help evaluate the effect of colour on task performance and visual strain. This study therefore used three postures (normal sitting posture (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 an environment on visual tracking and visual strain in different gravity states. This article therefore addresses three main research questions: (Q1) How do the different gravity states simulated by the three postures affect visual tracking and visual strain? (Q2) How does the colour environment affect visual tracking and visual strain during the three postures? (Q3) Is there a correlation between visual tracking and visual strain?

2. Method

2.1. Participants

Fifty-four Chinese subjects with an average age of 23.7 ± 2.6 years participated in the study. The group was composed of 27 men and 27 women. They were all recruited as undergraduate or postgraduate students at university with a major in astronautical engineering or more than one course in space psychology or space medicine. Knowledge of manned space missions was used as an initial selection criterion. The participants were confirmed by eye examinations, and subjects with general accommodative dysfunction, binocular vision impairment and colour vision defects were excluded. All participants had used head-mounted displays (HMD) to play games or participated in a course on the use of HMD. All had passed a health screening assessment, 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 experiment, all subjects were asked to avoid caffeine, alcohol, prescription drugs and smoking. Prior to the experiment, the experimenters trained all participants on the space station crew cabin in order to give them an understanding of the cabin's function, definition and main tasks. The experiment was reviewed and approved by the Research Ethics Committee of the University of Leeds (FAHC 19–073).

2.2. Scene setting

Before the study, a preliminary investigation of information such as 3D scenes, the structure and layout of the internal environment of the International Space Station (ISS) and the internal environment of the Chinese "Tianhe" core cabin was carried out to simulate a typical crew cabin environment (Fig. 1A and B). The ceiling and floor of the standard laboratory cabinets on both sides of the environment were covered with one main colour, while the handrails, docking hatch and inherent equipment used the original colour of the product as the secondary colour. The Keyshot version 9.0 rendering program was used to simulate the space station cabin scene, and 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 Unity (2020.2.0a21) 3D modelling tool was selected as the method for generating realistic internal perspective drawings, and a head-mounted display (HMD) was imported as the experimental scene. MATLAB R2020a (MathWorks, USA) was used to generate virtual tasks for the participants to complete during the experiment. They completed the tasks using an HMD handle (a hand-held controller linked to the virtual reality HMD) (Cha et al., 2020; Hidayetoglu et al., 2012; Qin et al., 2020; Jiang et al., 2021).

2.3. Values of colour scenes

The world has always been rich in colour, but the basic colours of colour theory include red, orange, yellow, green, cyan, blue and purple. These seven colours have been used in colour studies along with white and grey (Zhang and Hargens, 2018; Palmer and Schloss, 2010). Therefore, the nine main colours used in our study were red (R), orange (C), green (G), blue (B), yellow (Y), purple (P), cyan (C), grey (G) and white (W). Some earlier reports of human spaceflight found that the effects of low-saturation colours in space station environments on humans took three months or more to manifest. Therefore, most of the environments used in this study were 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, with the expectation that potential patterns of visual tracking by humans would be discovered in different colour environments (Kitayev-Smyk, 1971; Cha et al., 2020; Tantanatewin and Inkarojrit, 2018; Popov and Boyko, 1967; Jiang et al., 2021) Table 1 shows the CIE (Commission Internationale de L'Eclairage) L * a *b * values of the colours used.

2.4. Apparatus and materials

The experiment was carried out in a standard posture change

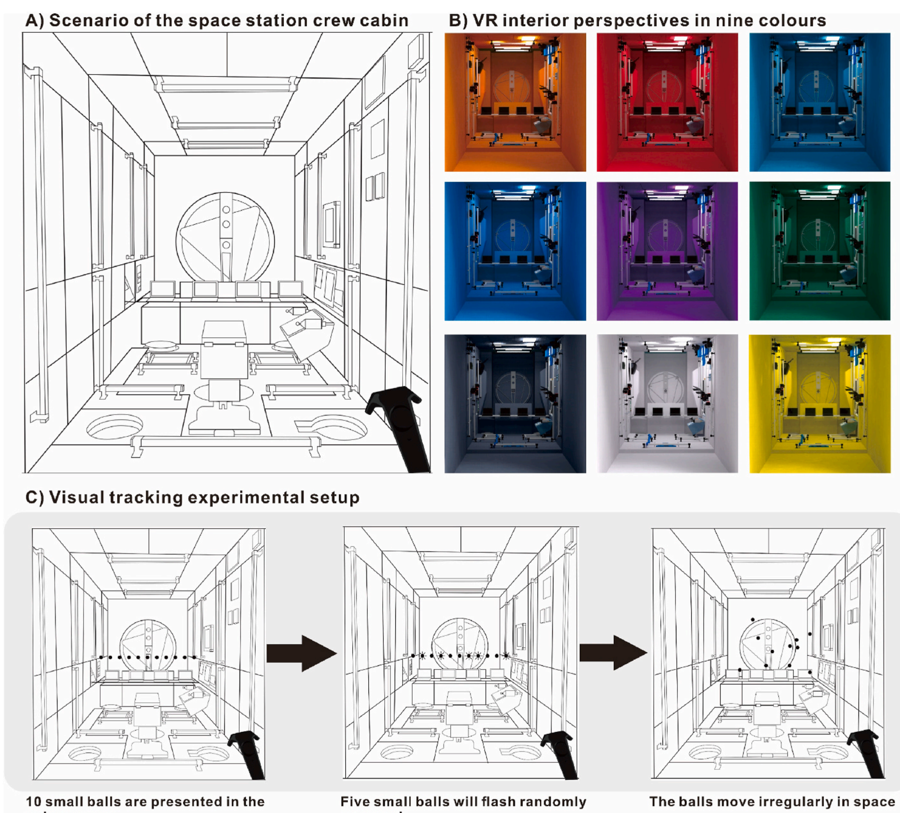

Fig. 1. A) The virtual reality environment of the crew cabin of the space station. B) The nine colours of the virtual reality crew cabin environment. C) Experimental task setting for visual tracking. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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	−41.7	8.3	34	163	128
5	cyan	65.5	−27.4	−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	0.3	−10.3	253	249	255

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 eyepiece 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 the visual tracking task, we used the multiple object tracking (MOT) paradigm (Jiang, 2022). This paradigm is designed to measure the visual attention related to humans' ability to track moving objects. The MOT paradigm has been used in previous studies and has shown better measurements than 2D multiple object tracking in terms of spatial perception, visual strain etc. (Tinjust et al., 2008; Plourde et al., 2017; Tullo, 2015). It is widely used for visual search or eye-brain coordination tests when astronauts are in bed rest to simulate microgravity training (Yu et al., 2021; Bernardin and Stiefelhagen, 2008; Yu and Jiang, 2016). In our study, it was used as the primary task of the experiment to help measure the participants' task performance in three postures and nine colour environments and to determine whether visual strain while operating the task would be altered. The advantage of the MOT paradigm is that multiple objects can move to different depth positions with different speeds. We combined this paradigm with 3D rendering of the space station crew cabin. The procedure of the task was as follows: When the participants put on the VR equipment to start the task, ten black balls with a diameter of 2° viewing angle were presented in the 3D crew cabin, and five of them flashed as a mark. After the flashing stopped, the ten black balls moved irregularly at a viewing angle of 1°/s, stopping after 10 s. The participants needed to use the handle to click in order to find the five black balls that had been marked by flashing before the move (Fig. 1C).

In this study, the visual strain questionnaire from Chu et al. (2011) was used to assess the participants' visual strain during the tasks (Hayes et al., 2007; Chu et al., 2014; Hue et al., 2014). The questionnaire includes ten questions referring to symptoms such as "blurred vision", "dry eyes" or "tired eyes". Symptoms are reported on a scale from 0 (none) to 10 (very severe), with a score of five representing a moderate response (Chu et al., 2011). In this study, the internal consistency of the scale was $\alpha = 0.95$.

2.5. Procedure

The experiment took place between March and April 2022. The participants were taken to the laboratory at 10:00 a.m. and rested for 30 min after entering, to relax and adjust to their surroundings. The experiment was carried out in a room without sunlight. Before the experiment, all participants confirmed that they fully understood the content and precautions of the experiment and had an understanding of the functions and definitions of the crew cabin of the space station. They also signed an informed consent form.

The experiment included three postures. For the SP posture, the participants wore the HMD in a normal sitting posture for testing. For the HD posture, they rested in the −12° head-down bed rest position for 3 h to induce the microgravity effect, and then wore the HMD to complete the test. For the HU posture, they rested in a 9.6° head-up position for 3 h before wearing the HMD to complete the test. The sequence between the three postures was balanced to minimize potential deviations due to the sequence. Each participant had a 72-h break between the posture tests to avoid potential carryover effects. The specific experimental design and timeline are shown in Fig. 2.

Before the start of the SP posture test, each participant was asked to wear an HMD to watch a white screen for 5 min to allow for chromatic adaptation. Subsequently, nine 3D colour environments appeared on the VR HMD in random order. The participants used the handle controller to perform visual tracking tasks in the different colour environments. The visual tracking test was repeated five times for each colour environment, with the spatial position of the black ball being randomly presented by the computer in each test. After the task test, the visual strain 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 colour environment to ensure that the colour and sense of space stimulated the participants (Cha et al., 2020). It took 80 ± 0.51 s to complete the task in each colour environment. The participants entered a dim white environment (dim<6lx) for 2 min after completing a task of each colour environment to allow them to rest in order to alleviate the legacy effects and colour stimulation of the previous tasks (Shergill, 2012).

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 3 h under 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 and other devices that interfere with light sources. After resting in bed for 3 h, they wore the HMD to watch the white screen for 5 min to allow for chromatic adaptation, and then the experiment was the same as for the SP posture.

2.6. Statistical data analysis

Repeated-measures ANOVAs were conducted to examine the effects of different postures and colours on visual tracking accuracy and visual strain, to check whether there were significant differences in visual tracking accuracy and visual strain among different postures and colours, and to determine the statistical significance; $\alpha < 0.05$ was considered statistically significant. Tukey HSD post-hoc tests were conducted in pairwise comparisons in order to help this study determine whether the relationship between the two sets of data was statistically significant (Abdi and Williams, 2010), and Bonferroni correction was used to keep the probability of statistical error as small as possible by controlling for a p-value threshold (Armstrong, 2014). η_p^2 (Bakeman, 2005) and Cohen's d effect measure (ES) (Cohen, 2013) were further used to examine the effects of visual tracking performance and visual strain. A Pearson correlation coefficient test was performed on the results of visual accuracy and the degree of visual strain. SPSS (version 24; IBM Corporation; Armonk, NY) was used for all analyses in this study.

3. Result

We first analysed the omnibus effect sizes and post-hoc pairwise comparisons for the three postures, observing the effect of colour on visual tracking performance and visual strain during the three postures. This was followed by further omnibus effects analyses and pairwise comparisons of the nine colours during each posture, where we observed that different colours during different postures also affected visual tracking tasks and visual strain. The unit means, standard deviations and Cohen's d for the nine colour environments on visual tracking and visual strain during the three postures are summarised in E-Appendix 1. The key findings of this study are presented in the next sections.

3.1. Visual tracking and visual strain in the three postures

The results show that the visual tracking accuracy during the three

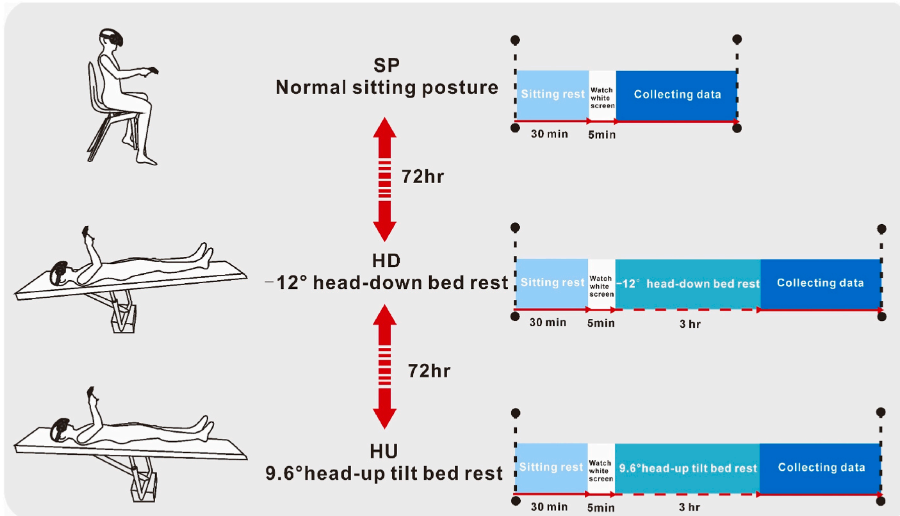

Fig. 2. Experimental design.

postures had significant differences (F (2,159) = 3.925, p = 0.022 < 0.05, $\eta_p^2 = 0.059$). Further post-hoc tests found that accuracy in the HD posture was significantly lower than the other two postures (SP: (p = 0.046 < 0.05, Cohen's d > 0.21), HU: (p = 0.014 < 0.05, Cohen's d > 0.19)), but there was no significant difference in accuracy between SP and HU (p = 0.057 > 0.05, Cohen's d < 0.05). Furthermore, there was no significant difference in accuracy between SP (M = 0.685, SD = 0.06) and HU (M = 0.695, SD = 0.07). (Fig. 3).

There was a significant difference in visual strain during the three postures (F (2,159) = 3.14, p = 0.046 < 0.05, $\eta_p^2 = 0.053$). Further post-hoc tests revealed that visual strain was significantly higher in the HD posture than in the other two postures (SP: (p = 0.025 < 0.05, Cohen's d > 0.23), HU: (p = 0.049 < 0.05, Cohen's d > 0.18)), but there was no significant difference in visual strain between SP and HU (p 0.064 > 0.05, Cohen's d < 0.03). Furthermore, there was no significant difference in visual strain between SP (M = 3.182, SD = 1.34) and HU (M = 3.270, SD = 1.27) (Fig. 3).

3.2. *Effect of the nine colour environments on visual tracking and visual strain during the three postures*

3.2.1. *Visual tracking (accuracy rate)*

Fig. 4 A shows that during SP (F(8,477) = 3.877, p = 0.028 < 0.05, $\eta_p^2 = 0.034$), HD (F(8,477) = 3.62,p = 0.039 < 0.05, $\eta_p^2 = 0.054$) and HU (F(8,477) = 1.468,p = 0.046 < 0.05, $\eta_p^2 = 0.023$), a significant omnibus effect of all nine colour environments on the accuracy of visual tracking was found. However, we found that for visual tracking accuracy, the two-way interaction between posture and colour environment was not significant (p > 0.05, Cohen's d < 0.14), suggesting a similar pattern of effect of colour on visual tracking during the three postures. The post-hoc pairwise comparative summaries revealed that the accuracy rate in the cyan environment was the highest in the three postures. It was significantly different from the white and grey environments (p < 0.05, Cohen's d > 0.21), while there was no significant difference from the other six colour environments (p > 0.05, Cohen's d < 0.15). The accuracy rate in the grey environment was the lowest in the three postures, which was not significantly different from the white and purple environments (p > 0.05, Cohen's d < 0.13), and was significantly different from the other six colour environments (p < 0.05, Cohen's d > 0.22).

3.2.2. *Visual strain*

The results showed a significant omnibus effect of the colour environment on visual strain during SP (F (8,477) = 1.904, p = 0.042 < 0.05, $\eta_p^2 = 0.032$) and HU (F (8,477) = 1.753, p = 0.028 < 0.05, $\eta_p^2 = 0.029$). Besides, we found that for SP and HU, the two-way interaction between posture and colour environment was not significant (p > 0.05, Cohen's d < 0.12). Further post-hoc tests found that the participants experienced the highest visual strain in the red environment. There was no significant difference compared with the orange environment (p > 0.05, Cohen's d < 0.11), but it was significantly different from the other colour environments (p < 0.05, Cohen's d > 0.32). The visual strain caused by the cyan environment was the lowest, with no significant difference compared with the other colour environments (p > 0.05,

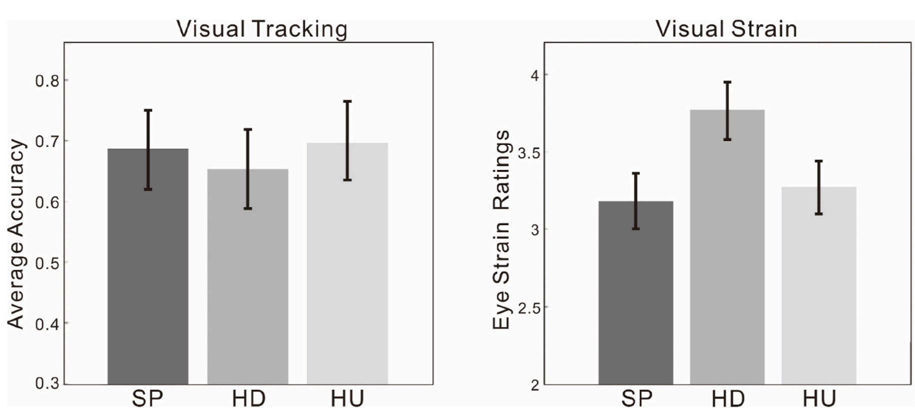

Fig. 3. Visual tracking accuracy and visual strain during the three postures.

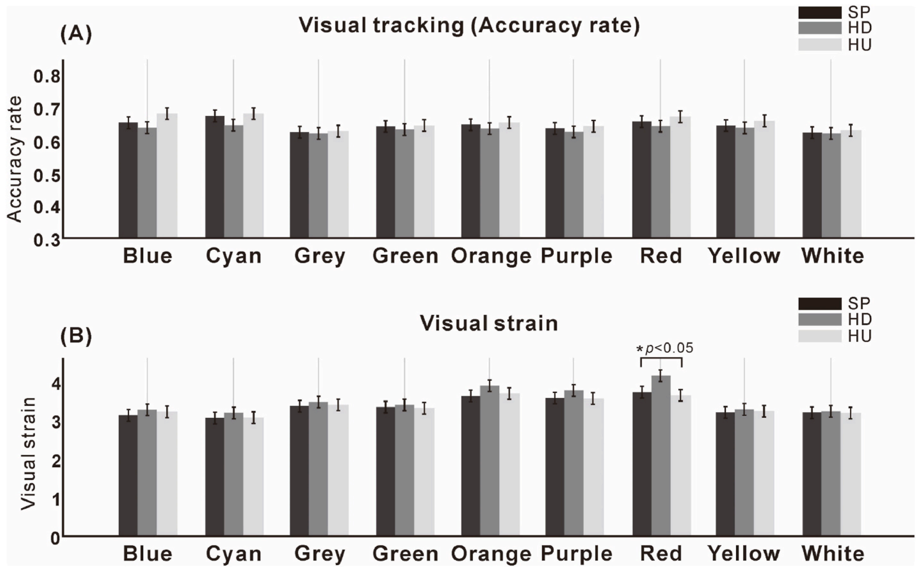

Fig. 4. The impact of the nine colour environments on visual tracking and visual strain.

Cohen's d < 0.09), while the difference to the red and orange environments was significant ($p < 0.05$, Cohen's d > 0.40). This shows that the red environment had a significant effect on the increase in the participants' visual strain during SP and HU, followed by the orange environment, while the cyan environment caused the lowest visual strain (Fig. 4 B).

The colour environment also had a significant effect on visual strain during HD ($F (8,477) = 1.492$, $p = 0.049 < 0.05$, $\eta_p^2 = 0.025$). Post-hoc tests found that the red environment caused higher visual strain. There was no significant difference compared with the orange and purple environments ($p > 0.05$, Cohen's d < 0.08), while the difference to the other six colours was significant ($p < 0.05$, Cohen's d > 0.31). Furthermore, it was also found that the visual strain induced by the red environment during HD was higher than during SP and HU ($p = 0.037 < 0.05$, Cohen's d > 0.34), indicating that there was a significant interaction between the HD posture and the red environment. (Fig. 4 B).

3.3. *Correlation between visual accuracy and visual strain*

The Pearson correlation coefficient was used to test the correlation of visual tracking accuracy and visual strain during the three postures. The results show that visual accuracy and visual strain in the three postures were significantly negatively correlated (SP: $r = -0.89$, $p = 0.011 < 0.05$; HD: $r = -0.79$, $p = 0.046 < 0.05$; HU: $r = -0.82$, $p = 0.036 < 0.05$).

4. Discussion

This study evaluated the effects of nine colour environments on the participants' visual tracking and visual strain during normal sitting posture (SP), -12° head-down bed rest (HD) and 9.6° head-up tilt bed rest (HU). The results show that compared with the SP and HU postures, the -12° head-down bed rest posture (HD) significantly affected visual tracking accuracy and visual strain (Q1). During the three postures, the participants' visual tracking accuracy in the cyan environment was significantly higher than that in the other colour environments, and visual strain was the lowest. In contrast, in the grey environment, the participants had the lowest visual accuracy, while the red environment induced the highest visual strain (Q2). In the three postures, there was a significant negative correlation between visual tracking accuracy and visual strain in the nine colour environments (Q3).

4.1. *Visual tracking and visual strain in the three postures*

During the SP and HU postures, the participants' visual tracking accuracy and visual strain were better than during the HD postures. The HU posture had a higher tracking accuracy rate than the other two postures, although this did not reach statistical significance. During HD, the performance of the visual tracking tasks decreased significantly, indicating that the simulated microgravity state of -12° head-down bed rest significantly affected the participants' visual tracking ability. This is consistent with Heaton et al. (2014) view, who claims this may be caused by impaired eye movement. Visual tracking performance is closely related to eye movements including smooth eye movements and saccades, while the headward fluid shifts during bed rest compress the eyeballs, which causes deformation of the eyeballs and reduces the eyes' ability to track movement. Besides, during the -12° head-down bed rest posture, the direction of gravity on the eyeballs has also changed, which affects the control accuracy of the eyeballs by the eye muscles (Mader et al., 2011; Chiquet et al., 2003). In a study conducted by ESA on the International Space Station, the astronauts' eye movement ability was also found to decrease, and it was found that the position error rate of the crew's visual gaze in a microgravity environment increased significantly, while their response ability decreased (Tomilovskaya et al., 2011). Moreover, compared with the SP and HU postures, visual strain increased significantly during the HD posture. The results of visual strain were able to show the physiological phenomenon of pressure on the participants' heads in the HD position due to the backflow of body fluids, which was expressed subjectively. This validates some studies that report slight pressure and swelling of the eyes during -12° head-down bed rest. This is similar to the conclusions of earlier studies. During the short-term head-down bed rest period, the intraocular pressure in both eyes is significantly increased and obvious visual strain is induced, indicating that the eyes are rapidly affected by the increase in headward fluid shifts (Mader et al., 1993; Huang et al., 2019). We also found that visual tracking and visual strain during the HU posture were lower than during the HD posture, while there was no significant difference from the SP posture, which indicates that short-term simulation of lunar gravity will not induce high visual strain and affect the brain-eye coordination ability. However, some studies have shown that performing 9.6° head-up tilt bed rest for six days or longer to simulate lunar gravity will have a certain impact on human physiology. Overall, however, eye movement and brain-eye coordination during lunar gravity are better than those during microgravity (Goswami et al., 2012;

Cavanagh et al., 2013). Therefore, a longer time is needed to further explore the impact of 9.6° head-up tilt bed rest on visual tracking and visual strain.

4.2. Impact of the colour environment on visual tracking and visual strain

We investigated the effects of nine colour environments on visual tracking and visual strain during the three postures, and found that in all three postures, the cyan environment had the highest visual tracking accuracy, followed by the blue and red environments, while the grey environment caused visual tracking to be the worst, followed by the white and purple environments. According to the theory of cool and warm colours (Witkowski and Brown, 1977; Bleicher, 2012), an environment of cool colours such as cyan and blue may optimise visual tracking ability in bed rest simulating microgravity and lunar gravity, which proves that a cool colour environment can enhance human visual perception and can also make people feel calm (Dalke et al., 2006; AL-Ayash et al., 2016; Ettis, 2017). But an interesting finding is that although the red environment caused the highest visual strain, the visual tracking accuracy in the red environment was higher than that in the other colour environments except for cyan and blue. This may be due to the fact that certain saturated colour conditions will increase the level of arousal compared with achromatic environments such as white or grey, thereby improving task performance (AL-Ayash et al., 2016; Kwallek et al., 1996). However, in this study, the red and blue environments did not produce the best performance. According to Yerkes-Dodson's law (Yerkes and Dodson, 1908), this may be due to the high chroma of the colours leading to excessive arousal and negatively affecting task performance (Clarke and Costall, 2008; Kurt and Osueke, 2014). When the task is complex and requires a high mental load, excessive arousal in a red environment will reduce performance (Cha et al., 2020). Besides, the higher visual stress in the red and orange environments compared to the other colours during the three postures also suggests that warm colour environments stimulate the visual system somewhat more than cool colour environments, increasing visual strain and load, and that the highly saturated red colour also causes excessive arousal and intensifies visual stress response. This is more pronounced in the HD posture, as the body is in a microgravity state and body fluids flow backwards into the head, leading to congestion and pressurisation of the head. Whereas the high arousal of a red environment subjectively appear to further increase the perception of advancement and pressure, cool colour environments such as cyan seem to give a sense of calmness, stability and retreat, somewhat reducing the sense of head pressure caused by the microgravity effect and helping individuals to be clear and focused when performing the task, which is consistent with Mahnke (1996) and Wise and Wise (1988). As early as in the anecdote report of the American Aerospace Laboratory Skylab, it was discovered that astronauts reported that light blue or light green crew cabin colour schemes may be more popular than brown and orange schemes. They considered it difficult to find small objects like spoons or ballpoint pens in a brown-yellow environment (Wise and Wise, 1988). Moreover, Vakoch (2011) reported that during an 11-day space mission, the astronauts all agreed that they felt heart palpitations in yellow and brown environments, and even some nausea, but blue alleviated this effect to a certain extent. But what is surprising in our experiment is that purple also caused higher visual strain during the HD and HU postures.

4.3. Correlation between visual tracking and visual strain

In the three postures, the visual strain of the nine colour environments had a significant negative correlation with the accuracy of visual tracking, which shows that the higher the accuracy of the visual tracking task, the higher the attention and the continuous movement of the human eye, which significantly increases visual strain. This is similar to previous research conclusions. Lencer and Trillenberg (2008) believe that visual tracking of the human eye requires dynamic prediction of target speed and trajectory, memory of the target and the use of visual feedback to continuously adjust the line of sight to improve accuracy. The visual function of this linkage will increase the strain on the eyes.

4.4. Potential benefits and limitations of ambient colour on visual tracking and visual stress

According to the findings of this study, the test crew was more visually affected by the microgravity environment in which the simulated orbiting space station or manned spacecraft was located compared to Earth gravity and lunar gravity, as evidenced by poorer visual tracking performance and higher visual strain. In addition, we also identified the potential benefits of using an appropriately coloured environment for crew members in microgravity or lunar gravity and the potential relationship between visual tracking performance and visual strain. Although only nine basic colours with high saturation were used as environmental colours in this study, cyan in cooler colour environments was found to improve visual tracking performance and appropriately reduce visual stress, albeit to a lesser extent. In addition, warm colours, exemplified by red, appeared to have a negative effect on visual strain; this was more pronounced in the presence of microgravity effects. From this, we can conclude that the use of the nine highly saturated environmental colours in three states of gravity can reveal potential fundamental hue design patterns in extreme environments, which could provide some reference for the internal environment of future long-term space missions or manned missions in planetary habitats. Besides, the study could potentially provide a reference for colour schemes for specific extreme environments, such as future Antarctic scientific research stations, deep sea research stations and submarine environments. Furthermore, it may also be able to provide some colour references for the design of infectious disease hospitals, isolation chambers and treatment areas after the Covid-19 era, to help optimise the psychological or visual perception of healthy people or patients.

However, we need to state clearly that although this study used nine highly saturated colour environments for the three gravity effect experiments, the effects on human visual tracking and visual strain found from the results were limited, which is in line with the extensive earlier literature findings that colour, as a fundamental element in the environment, has long-term and subliminal effects on humans and may have a number of multifaceted effects (e.g. visual monotony, negative emotions, operational errors, etc.) (St-Jean et al., 2022; Shi, 2013). More work is therefore needed to help validate the current findings.

4.5. Limitations and future directions

Firstly, this study used visual tracking tasks and a visual strain questionnaire to analyse the impact of colour environments on humans. Other studies have found that the brain-eye coordination function can also be characterised by EEG, brain blood oxygen changes and eye movement changes. These physiological responses could therefore be used in future to report task effects (Ding et al., 2021; Wilcox et al., 2014; Mathew et al., 2020). Secondly, future manned missions to the Moon will expose astronauts to varying degrees of lunar gravity (low gravity). Currently, there is very limited research on the physiological effects of exposure to lunar gravity levels (i.e. between μ and 1) on the human body (Richter et al., 2017). Only twelve astronauts – from the Apollo missions – were exposed to lunar gravity, with exposure times ranging from 21 to 74 h (Goswami et al., 2012; Jiang, 2022). However, the exposure time was too short to assess the effect of lunar gravity on their various types of responses while performing operational tasks (Goswami et al., 2012). Future research should build on this foundation and further validate and extend the present conclusions during manned missions to the Moon. Thirdly, this study explored the effect of colour environments on visual tracking tasks when sitting in a normal sitting posture, during −12° head-down bed rest and during 9.6° head-up tilt bed rest. So far, many studies have used long-term head-down bed rest

(30 days - longer) to explore the performance of humans during bed rest (Scott et al., 2021), but no study related to the colour environment has been found. In future, the bed rest time should be extended in order to obtain the effect of the colour environment on humans during different time periods in bed rest. Fourth, in order to maximise the impact of colour environments on the participants' task performance and visual strain, we used saturated colours for testing in this study. However, some studies have found that the saturation and brightness of the colour environment have significantly different effects between genders (Küller et al., 2006). Besides, this study used short-term experiments to explore the potential impact of basic colour hues on human visual tracking tasks. In contrast, the environmental colours of the space station have a long-term and subtle effect on the crew, and in future it would be useful to employ colours that are more suitable for the spacecraft environment, enrich the environmental elements that affect the visual perception of the crew (operational payload, signals, other crew members etc.) and conduct long-term isolated analogue missions to explore the long-term effects of colour on humans. In future, more consideration should also be given to changes in saturation and chromaticity in colour environments, so as to be closer to spacecraft colour scheme applications.

5. Conclusion

The visual tracking and visual strain experienced by the study subjects in nine colour environments during three postures showed that the microgravity state induced by -12° head-down bed rest somewhat affected the accuracy of visual tracking and visual strain in this experiment, Performance in this posture was lower than in the normal sitting posture and the 9.6° head-up tilt bed rest posture. The study also explored the possibility that a cooler colour environment, such as cyan, might help to optimise visual tracking accuracy and reduce visual strain compared to a warm colour or achromatic environment. The findings provide some support that the colour of the environment may have a positive effect on visual tracking and visual strain in microgravity. This exploration can provide a potential colour reference for visual performance in future manned spaceflight missions. More work is needed, however, to further validate the impact of colour on space missions and crews in more general terms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2023.103994.

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