Colour schemes to reduce stress response in the hygiene area of a space station: a Delphi study

Abstract

This paper aims to explore colour schemes to reduce stress response in the hygiene area of a space station. We conducted a two-stage exploratory Delphi-study with 30 international experts. It was found that the overall environment, stool-urine collection device, garbage collection interface and negative pressure package interface of the hygiene area most affected astronauts' experience. Remarkably, experts have highest visual requirements for the cleanliness of the overall environment and for stool and urine collection devices in the hygiene area. These tend to have low saturation and low blackness colours, while the garbage collection interface and negative pressure package interface have conspicuity and discernibility visual requirements. It was found that experts tend to choose high saturation and high brightness colours.

1. Introduction

With the development of the space industry, long-term space flight and crewed deep space exploration will be the main tasks for future international spaceflight (Loerch, 2015; Spudis, 1999). The space station, as an orbital spacecraft in which astronauts are resident for a long term, provides significant stressors which have yet to be eliminated (Harrison, 2010). Stressors are factors that cause systemic adaptation syndromes, which usually affect astronauts in a negative and arousal manner (Alfano et al., 2018). In this context, these can be classified as: flight risks (the most critical); the environment (e.g. vibration and g-force during ascent, microgravity, lighting, noise, isolation, etc.) (Tachibana et al., 2017); mission workload (e.g. busy fatigue or excessive monotony); and interpersonal relationship of the crew (Yuan et al., 2019). These stressors will influence the performance of astronauts and even the success of missions (Alfano et al., 2018). Some stress responses have a positive effect, helping astronauts adjust their physical and psychological states following changes in the environment (Boyd et al., 2009), but others can lead to physical illness or serious psychological problems (Kanas and Fedderson, 1971).

Reducing the stress response of the space station has been studied from multiple perspectives. Researchers from NASA and the Russian Space Agency focused on the psychological selection of astronauts (Suedfeld et al., 2012; Alfano et al., 2018; Kanas et al., 2009; Landon et al., 1994). They found that psychological training of astronauts would improve their behaviour and performance, so that they could fully understand the content and progress of space missions, thus better adapting to various space stressors (Connolly and Arch, 2005; Anania et al., 2017; Clement et al., 1987). In addition, NASA and Russia proposed safeguarding measures such as remote speech-feature recognition and psychophysiological-monitoring during missions (Tafforin et al., 2019). Some studies have also found that the psychological problems caused by stress response will be relieved to some extent through the use of remote video, psychological counselling and other safeguards (Boyd et al., 2009; Suedfeld, 2005). With a new round of development of international long-term crewed flights and deep space exploration (e.g. lunar outposts and Mars exploration) (Campa et al., 2019), there is an urgent need to update psychological safeguards to prevent accidents and to deal with mental health problems caused by changing mission requirements. NASA's Human-System Integration Standard states that a well-designed living and working environment can reduce stress, thereby improving the performance and wellbeing of the entire crew (Liskowsky and Seitz, 2010). The European Space Agency reported that while the interior colour of a space station is important to the experience, the use of appropriate colours can reduce astronauts' stress response, improve their visual experience, enhance efficiency, and reduce operational errors (ESA, 2008). 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 in a restricted and isolated environment for a long time (Sgobba, 2017).

Colours have a significant impact on human perception and psychology; much research has been conducted on the application of colour schemes into safety assurance and accident prevention in various industries (Acking and Küller,1972; Yi et al., 2012; Mahnke, 1996; Manav, 2007). Fleyeh (2004) used a colour scheme that improved human perception of roads and traffic signals, thereby improving safety. Effective use of colour schemes can also improve living and working conditions for minimal expense (Hsiao, 1995). The effective configuration of colour is not only conducive to improving psychological comfort, working performance, safety, and environmental satisfaction, but also helps to reduce environmental stress, work fatigue, and physical and mental problems (Mahnke, 1996). In the early phase of International Space Station (ISS) construction, the Soviet orbital space station, Salyut 6, used soft pastel interior colours to provide a more harmonious atmosphere (Szocik et al., 2018). In Salyut 7, these were replaced by two contrasting colours to help distinguish between left and right walls (Jiang et al., 2020). Although Oman's (2007) experiments indicate this might help spatial orientation, they did not provide a reason for changing the colour scheme. Furthermore, the ISS plan also mentions that colours should be used effectively to relieve visual stress (Benaroya, 2018). At present, effective coding theory suggests that the stimuli that cause human visual stress are completely different from the common visual stimuli in nature (Barlow, 1961; Simoncelli, 2003; Olshausen,2004; Machens et al., 2005), but the most common stimuli of the natural environment can be represented by particular statistical regularities (Atick and Redlich, 1992; Field, 1994; Olshausen and Field, 1996; Simoncelli and Olshausen, 2001). Some studies have found that visual pressure is highly correlated with the luminance of visual stimuli, and spatial correlation decreases with distance remarkably consistently across different scenes. In addition, when establishing the conditions for colour to relieve visual pressure, it is also necessary to increase the recognisability of space and interface information. The luminance of natural scenes has a Fourier amplitude spectrum that decreases with increasing spatial frequency according to the reciprocal of frequency (Field, 1987; Geisler, 2008). Previous studies have found that discrimination performance is optimal when stimuli have a $1/f^{\alpha}$ spectrum (Knill et al., 1990; Parraga et al., 2000; Geisler et al., 2001). Similarly, images with amplitude spectra that depart from $1/f^{\alpha}$ are usually uncomfortable to look at (Fernandez and Wilkins, 2008; Juricevic et al., 2010; O'Hare and Hibbard, 2011; Penacchio and Wilkins, 2015). However, there is limited related research on colour schemes for improving stress and providing psychological support for different space station functional areas.

Of the many functional areas in a space station, the present study focused on the hygiene area. The collection and disposal of human metabolic waste play a vital role in supporting human life in space (Link Jr et al., 2007). In addition to its normal functioning, the waste collection and treatment process should minimize the generation of negative environmental stressors and the excessive stress of astronauts. According to analysis by the Russian Space Agency and NASA's interviews with astronauts (Connolly and Arch, 2005), the existing hygiene area of the ISS has inadequate design and usability, including: enclosed space, poor colour and light experience, insufficient dealing with foul odours, difficulty of manipulating complex and low fault tolerant hardware, fixed position and device shape, and poor handrail performance. These can cause increased astronaut stress which, in the long term, will lead to physical diseases (e.g. constipation or abnormal excretion), serious psychological problems (e.g. depression, insomnia and headaches), and deteriorating social relations (Ganse and Ganse, 2020).

Given the high cost of spaceflight, limited availability of astronauts participating in actual flights, and the high flight safety requirements, it is difficult to conduct strict tests (Law and Vanderploeg, 2012). Ground simulation experiments are also time-consuming and costly, within which many test factors are difficult to control (Tafforin, 2015). Therefore, it was decided to adopt a qualitative and empirical method to analyse the stressor and device elements of the hygiene area, the visual perception requirements of various devices, and the colour scheme to reduce the stress response. The Delphi-method will be employed as it has been found to be of value in researching complex issues in emerging topics when knowledge is held by a limited number of geographically scattered experts (Barnes and Mattsson, 2016; Silveira et al., 2018). Further, the method has been found suitable for addressing problems, identifying opportunities, and developing forecasts in general (Hong et al., 2019) and technological forecasts in particular (Jiang et al., 2017). This article shows the process of selecting the target device to which the colour scheme is to be applied, together with the results of a case study using this scheme. The present study is expected to improve psychological comfort and reduce stress response by providing simple and convenient safeguarding measures (colour scheme) thereby contributing to the literature on space stress and psychological protection.

2. Methods

2.1 Research design

Preparation procedures were set up for the space station hygiene area devices, stressors, and related visual perception needs before conducting the Delphi study (Bokrantz et al., 2017; Hulme et al., 2017; Baker and Redfern, 2005; Jiang et al., 2017). Firstly, we analysed the International Space Station and the hygiene area of the upcoming "Tiangong" space station and identified 10 devices. Secondly, based on the particularity of the hygiene area and the long-term psychological needs of astronauts (Kanas and Fedderson, 1971), preliminary interviews were conducted with experts from European Space Agency and China Astronaut Center. 12 stressors and 9 type of visual perception needs were provided for this research. See Figure 1.

Following the guidelines outlined by Dillman et al. (2014) and according to the established procedures of empirical research, this study created two questionnaires representing the first and third stages of Delphi study.

(1) The questionnaire for the first stage was divided into three parts: (a) assessment of stressors that have a significant impact on astronauts in the hygiene area; (b) evaluation of devices matching the stressors; and (c) assess the visual perception needs that match the devices. Its purpose was to screen the stressors that require urgent improvement, the corresponding device and visual perception need.
(2) Between the first and second stages, based on the visual perception needs of the first stage, a colour sample that matches it was established.
(3) The second-stage questionnaire combined the colour samples with the first-stage results for experts to match, with the aim of selecting the colour scheme of the hygiene area device.

The first- and third-stage questionnaires were completed by the same expert participants with a 10-week interval (approximately) which enabled interim analysis and the development of individual feedback. Each stage was carried out in two iterations for two reasons. Firstly, iterative and carefully controlled feedback helps experts to reach consensus. Experts can communicate and learn from each other effectively. Secondly, this approach limits fatigue among experts in order to ensure a high response rate. There was also the consideration by many researchers (e.g. Woudenberg, 1991) that most revisions occur only after the first iteration.

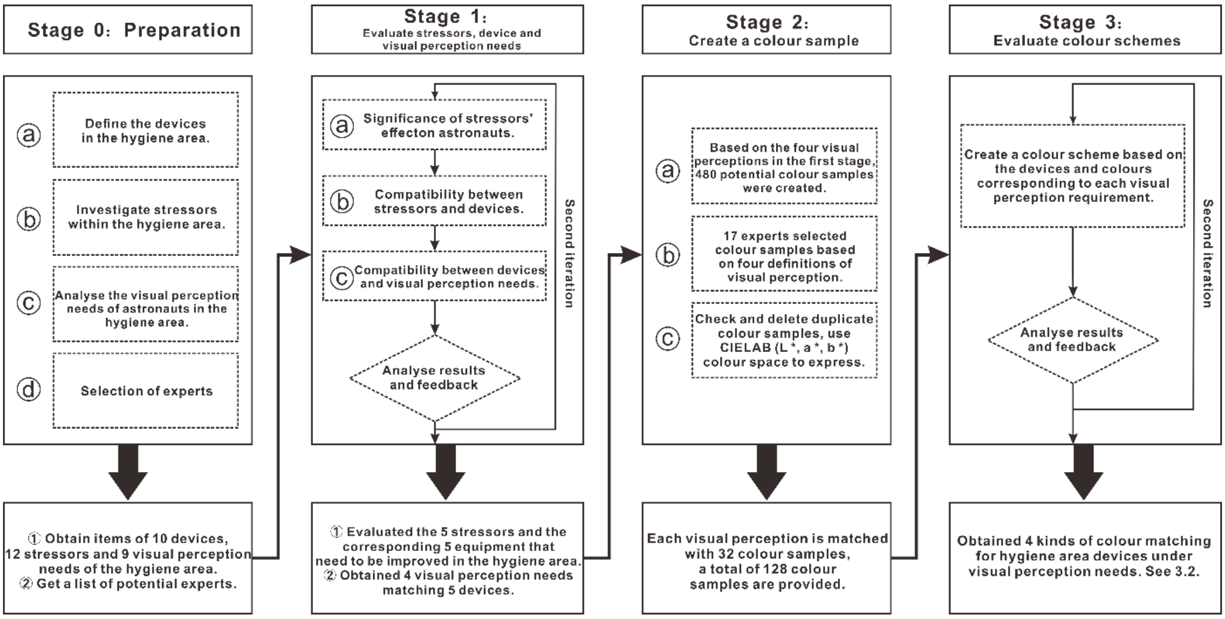

Fig. 1. Study design, own design according to Jiang et al. (2017) and Fritschy and Spinler (2019).

2.2 Selection of participants

Correct selection of participants is vital to a successful Delphi Study because this influences validity and reliability (Spickermann et al., 2014). The selection process outlined by Wechsler (1978) was adopted and this is comprised of three main stages: compile a list of potential experts in their respective fields; select experts based on predetermined criteria (e.g., reputation, experience or publications); estimate participation motivation and consider (monetary) incentives. Initially, a list of experts will be identified by reviewing academic, managerial, and popular press articles. Then, through subjective judgement, a final list will be identified based on pre-determined criteria (e.g., academic qualifications, professional expertise or political impact) regarding the issue under investigation (Hill and Fowles, 1975).

This study was approved by the University of Leeds Ethics Committee (No: FAHC 19-073). Fifty-nine experts participated in the screening process (Stage 0). Employing judgmental sampling based on qualifying tasks, 45 participants were deemed qualified for further participation (Larreche, and Moinpour, 1983). Overall, a total of 30 experts participated in the Delphi study, resulting in a dropout rate below the standard of 20–30% (Bardecki, 1984). Table 1 provides an overview of the sample.

Table 1. Profiles of participants.

Gender	Count	Percentage	Industry or occupation	Count	Percentage	Job level	Count	Percentage
Male	21	70%	Colour science	6	20%	Senior scientist	5	17%
Female	9	30%	Environmental well-being	4	13%	Senior Spacecraft Designer	12	40%
Country			Manned space flight	13	43%	Spacecraft engineer	7	23%
Germany	5	17%	Industrial design	3	10%	professor	4	13%
China	12	40%	Space science	2	7%	astronaut	2	7%
UK	3	10%	Microgravity and visual stress	2	7%	Professional experience		
Netherlands	4	13%	Stakeholder			3 to 4 years	3	10%
France	2	7%	Space agency	8	27%	5 to 10 years	6	20%
Japan	4	13%	Astronaut Training Center	12	40%	More than 10 years	21	70%
			University/Institute	10	33%			

2.3 Hygiene area of the space station

A 3D model was created based on a typical space station hygiene area. The area includes three categories: stool and urine collection device, control device and auxiliary device. Sample pictures consisting of black lines and white backgrounds (Fig. 2) were drawn.

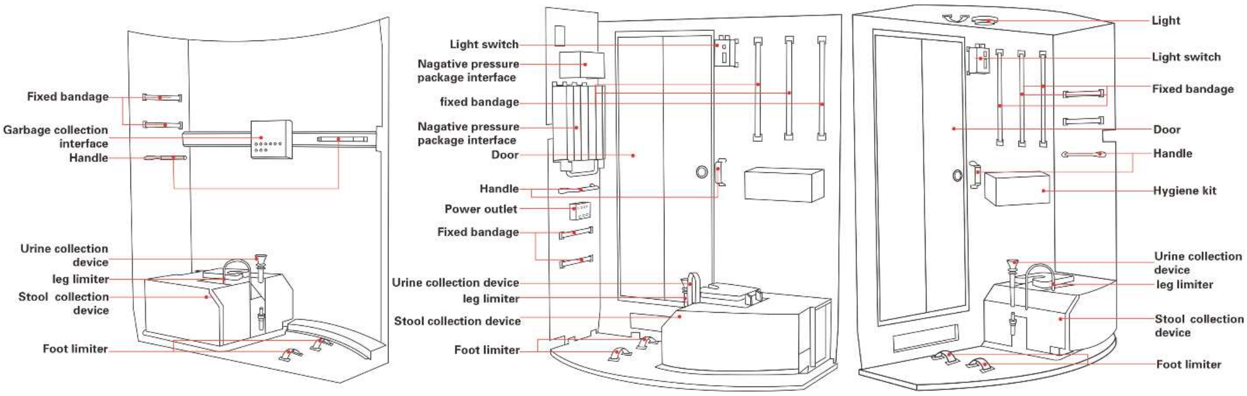

Fig. 2. Scenario of the space station hygiene area

2.4 Colour samples creation

The results of the first stage of the Delphi study indicated there are four visual perception needs: “cleanliness”, “harmony”, “eye-catching” and “distinguishability”. Before the second stage of Delphi study, a screening process was conducted to obtain colour selection samples for the hygiene area equipment. The screening process was as follows:

(1) From previous colour and visual perception studies (Kelly and Judd, 1976; Elliot et al., 2015; Adams, 2017), 120 colour patches were established for each visual perception. A total of 480 colour patches formed a colour filter pool for experts to screen. This method is widely used in Delphi studies (Dillman et al., 2014; Hulme et al., 2017).

(2) Participants consisted of 17 researchers from the colour science team, including 2 spacecraft designers. There were 8 British and 9 Chinese participants, all of whom have more than 10 years of professional experience in colour and/or spacecraft design. Before the evaluation, all observers were shown the definition of four visual perceptions. These definitions are based on the “Cambridge Advanced Learner’s Dictionary”. According to the expert’s native language, English or Chinese translations were selected.

(3) The experts evaluated the 480 physical colour patches in a dark room. These patches, each 3×3 inches, were presented one after another in a viewing cabinet illuminated by a D65 light source. The interior of the cabinet has a uniform grey of L^* of 50 as the background (Ou et al., 2004).

(4) Each expert was required to select the colour patches associated with the four visual perceptions.

(5) After the evaluation, 32 colours were selected (see Figure 3) for each of the four visual perception. The CIELAB (L^*, a^*, b^*) colour space was used (see E-Appendix 1).

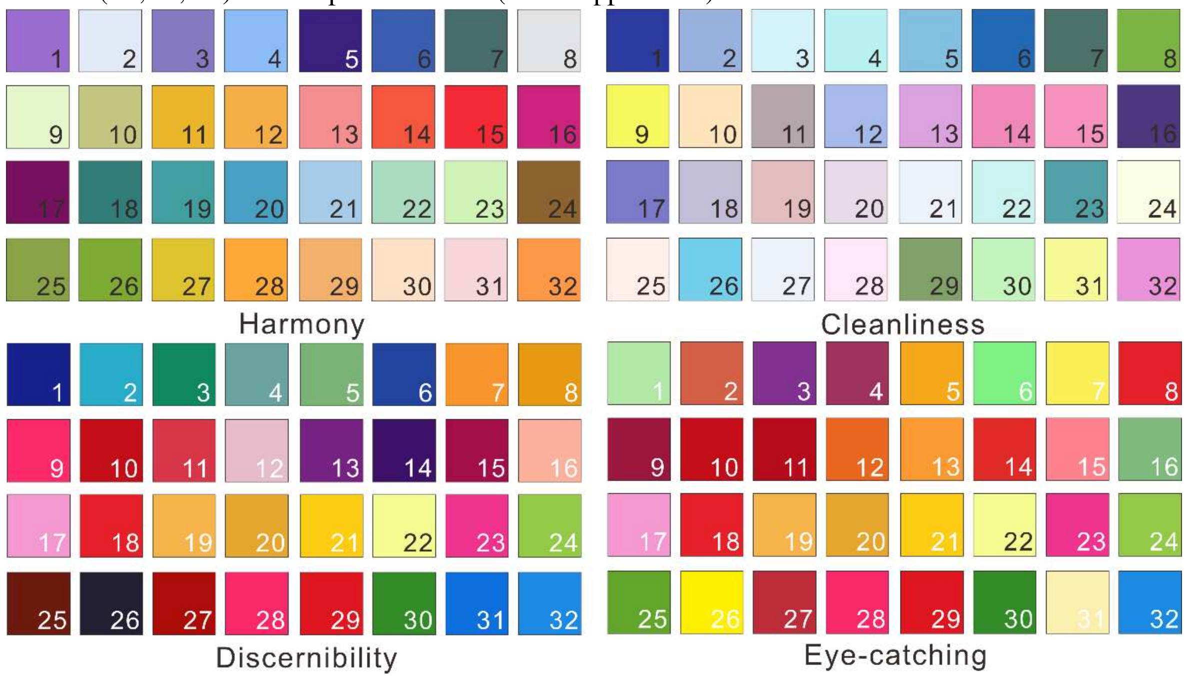

Fig. 3. Colour samples

2.5 Execution of the Delphi study

During each iteration of the Delphi study in the first- and third-stages of this research, an email was sent to the experts. In the first iteration, this included questionnaires, examples, and survey instructions. In the second iteration, all experts were notified of the specific changes made after the first iteration and were asked to fill in the questionnaire again based on the conclusion of the first iteration (Dillman et al., 2014).

The first stage contained three assessments. Among them, the prediction of the impact of stressors on astronauts required experts to evaluate the probability and the impact on astronauts using a 5-point Likert scale. The scale ranged from 1 (not probable: 0–20%), 2 (somewhat improbable: 21–40%), 3 (neutral: 41–60%), 4 (somewhat probable: 61–80%), to 5 (very probable: 81–100%). Additionally, for compatibility between the stressor and the device, and for compatibility between the device and visual perception needs, evaluation was based on single-choice questions. To maintain a balance between quantitative and qualitative data, experts needed to choose reasons that were comprehensive and clear.

In the third stage, a colour sample was formulated for experts to choose based on the final results from the second stage. At this stage, they were not shown pictures of the device corresponding to their selected colour. The colours they chose only represented the colours of the device they approved. Experts needed to choose the most suitable colour from four types of visual perception. They were also asked to state the reasons for choosing certain colours.

Questionnaires were provided in Chinese, German, English, France, and Japanese, to limit interviewer bias and lower participation barriers for respondents (Gracht, 2008). To limit the risk of bias in translation and ensure identical communication, every step underwent a rigorous forward-backward translation process (Brislin, 1970). The formulation of items, survey instructions, and question wording were reviewed by three authors and an independent experienced expert (the fourth author) to limit framing biases (Cheng and Wu, 2010).

Three indicators suggest a high level of commitment and involvement. First, all experts answered the entire questionnaire. Second, 152 usable comments evaluating the expected probability were submitted. Third, since all experts had participated in the first and the second Delphi stage, the drop-out rate was zero. Compared to an average drop-out rate of 18% (Nowack et al., 2011), this indicates that experts were satisfied with the survey design and content, which was further supported by their positive responses. Hence, it is reasonable to conclude that this should lead to high-quality survey data.

3. Results

In the following sections, the final rankings of the two stages from the data collection will be provided (Tables 2-5). In the first stage, stressors, device and visual perception requirements were discussed in detail. In the second, experts chose a colour scheme based on the results of the first stage. These discussions will be explored following Delphi study based on the supplementary opinions provided by experts throughout the process, which will be compared to the literature in subsequent discussions (Patton, 2002; Gracht, 2008).

3.1 Assessing stressors that affect astronauts

The questionnaire first served to ask which stressors would affect the stress response of astronauts. Table 2 shows the percentage of the highest scores (PHS) in the two iterations of investigation. “Confined small space” and “smell” stressors received the most votes (60%) followed by “Usage time” (56.6%), “Environmental colour” (50%) and “Use and Operation of devices” (43.3%). This shows that the stressors that most affect astronauts are “Confined small space” and “smell", “Usage time”, “Environmental colour” and “Use and Operation of devices”.

In the results of the second iteration, it was found that the importance of “unisex” (ΔPHS -23.4%) and “spatial orientation” (ΔPHS -36.7%) decreased significantly in the second iteration. In addition, the PHS change showed that the results of the second iteration are more concentrated compared to the first iteration (information collection). This indicates that greater consensus had been reached after the second iteration.

Table 2. Stressors of hygiene area

Item	Probability iteration 1 (n=30) 1	2	3	4	5	PHS	Probability iteration 2 (n=30) 1	2	3	4	5	PHS	ΔPHS
Noise	2	9	12	5	2	6.7%	2	12	10	3	3	10%	3.3%
Smell	1	3	3	6	17	56.6%	0	2	4	6	18	60%	3.4%
Use and operation of devices	1	4	3	12	10	33.3%	0	1	5	12	13	43.3%	10%
Unisex	2	7	3	7	11	36.7%	5	6	10	5	4	13.3%	-23.4%
Usage time	0	1	4	11	14	46.7%	0	1	3	9	17	56.6%	9.9%
Confined small space	0	1	2	9	18	60%	0	1	2	9	18	60%	0%
Visual confusion	5	7	10	5	3	10%	4	9	11	4	2	6.7%	-3.3%
Light	7	16	3	3	1	3.3%	6	12	8	3	1	3.3%	0%
Environmental colour	2	3	1	15	9	30%	2	2	3	8	15	50%	20%
Temperature	6	13	4	3	4	13.3%	8	13	4	3	2	6.7%	-6.6%
Vibration	12	7	8	2	1	3.3%	12	8	8	1	1	3.3%	0%
Spatial orientation	2	1	9	4	14	46.7%	2	10	11	4	3	10%	-36.7%

3.2 Assessing devices related to stressors

In the second part of questionnaire, the results after two iterations of evaluation revealed that there are five devices matching the stressors that most affect astronauts. Smell corresponds to the stool collection device (14 votes, 46.7%) and the urine collection device (13 votes, 43.3%). Use and operation of devices corresponds to the garbage collection interface (10 votes, 33.3%), and negative pressure packaging interface (11 votes, 36.7%). The hygiene area environment corresponds to usage time (16 votes, 53.3%), confined small space (25 votes, 83.3%) and environmental colour (25 Votes, 83.3%) as can be seen from Table 3.

Table 3. Stressors and matching device in hygiene area of iteration 2

Probability iteration 2	Hygiene area environ-ment	Stool collection device	Urine collect -ion device	Foot / leg limiter	Garbage collection interface	Negative pressure package interface	Hygie -ne kit	hand -le	Fixed banda-ge	ventilator
Noise	1 (3.3%)	7 (23.3%)	9 (30%)	0	0	6 (20%)	0	0	0	7 (23.3%)
smell	3 (10%)	14 (46.7%)	13 (43.3 %)	0	0	0	0	0	0	0
Use and operation of devices	0	3 (10%)	6 (20%)	0	10 (33.3%)	11 (36.7%)	0	0	0	0
Unisex	0	14 (46.7%)	13 (43.3 %)	0	0	0	0	0	3 (10%)	0
Usage time	16 (53.3%)	7 (23.3%)	2 (6.7%)	0	2 (6.7%)	3 (10%)	0	0	0	0
Confined small space	25 (83.3%)	0	0	0	0	0	3 (10%)	0	2 (6.7%)	0
Visual confusion	20 (66.7%)	0	0	0	5 (16.7%)	5 (16.7%)	0	0	0	0
Light	30 (100%)	0	0	0	0	0	0	0	0	0
Environme ntal colour	25 (83.3%)	2 (6.7%)	2 (6.7%)	0	0	0	0	3 (10 %)	0	0
temperature	19 (63.3%)	0	0	0	0	0	0	0	0	11 (36.7%)
vibration	0	6 (20%)	8 (26.7 %)	0	2 (6.7%)	4 (13.3%)	0	0	0	10 (33.3%)
Spatial orientation	30 (100%)	0	0	0	0	0	0	0	0	0

3.3 Assessing the visual perception needs of devices

Based on the findings from the previous two parts, the visual perception needs of five devices were evaluated. After two iterations of voting, results indicated that the hygiene area environment required a sense of cleanliness (16 votes, 53.3%) and harmony (8 votes, 26.7%). Additionally, experts also believed that stool collection devices and urine collection devices that are in direct contact with the human body also need a high degree of cleanliness (25 votes, 83.3% and 22 votes, 73.3% respectively). This was followed by the eye-catching (10 votes, 33.3%) and discernibility (15 votes, 50%) of the garbage collection interface, and the eye-catching (12 votes, 40%) and discernibility (13 votes, 43.3%) of the negative pressure package interface (Table 4). This shows that because the operation interface has many interactive buttons, being eye-catching and discernible is important for astronauts' operations.

Table 4. Matching of hygiene area device and visual perception needs of iteration 2

Probability iteration 2	Comfort	Eye-catching	Clean-liness	Stability	Discerni-bility	Safety	Cue	Spacious-ness	Harmony
Hygiene area environment	2 (6.7%)	2 (6.7%)	16 (53.3%)	1 (3.3%)	1 (3.3%)	0	0	0	8 (26.7%)
Stool collection device	2 (6.7%)	1 (3.3%)	25 (83.3%)	0	0	2 (6.7%)	0	0	0
Urine collection device	4 (13.3%)	1 (3.3%)	22 (73.3%)	1 (3.3%)	1 (3.3%)	0	0	0	1 (3.3%)
Foot / leg limiter	2 (6.7%)	20 (66.7%)	2 (6.7%)	1 (3.3%)	0	0	5 (16.7%)	0	0
Garbage collection interface	1 (3.3%)	10 (33.3%)	1 (3.3%)	1 (3.3%)	15 (50%)	2 (6.7%)	0	0	0
Negative pressure package interface	2 (6.7%)	12 (40%)	2 (6.7%)	1 (3.3%)	13 (43.3%)	0	0	0	0
Hygiene kit	2 (6.7%)	5 (16.7%)	14 (46.7%)	2 (6.7%)	1 (3.3%)	3 (10%)	2 (6.7%)	0	1 (3.3%)
Light	16 (53.3%)	1 (3.3%)	2 (6.7%)	0	1 (3.3%)	1 (3.3%)	1 (3.3%)	0	8 (26.7%)
Handle	2 (6.7%)	21 (70%)	2 (6.7%)	0	0	5 (16.7%)	0	0	0
Fixed bandage	2 (6.7%)	19 (63.3%)	2 (6.7%)	1 (3.3%)	0	2 (6.7%)	1 (3.3%)	0	3 (10%)
Ventilator	9 (30%)	2 (6.7%)	2 (6.7%)	4 (13.3%)	2 (6.7%)	3 (10%)	0	0	8 (26.7%)

3.4 Assessing the device colour scheme

The second iteration of colour schemes were assigned statistically: the top five colours having the most votes for all visual perception colour schemes were chosen. Experts believed cleanliness-24 (12 votes, 40%) and harmony-9 (13 votes, 43.3%) to be the most suitable colours for the hygiene area environment. The stool collection device is most suitable for cleanliness-21 (13 votes, 43.3%), and the urine collection device is most suitable for cleanliness-10 (12 votes, 40%). Additionally, experts judged eye-catching-10 (10 votes, 33.3%) and discernibility-11 (12 votes, 40%) to be the most suitable for garbage collection interface, and eye-catching-11 (15 votes, 50%) and discernibility-29 (13 votes, 43.3%) the most suitable for negative pressure package interface.

Therefore, the results show that for the hygiene area environment and the stool-urine collection devices, experts preferred low saturation and low blackness colours. For garbage collection and negative pressure packaging interface, however, they preferred high saturation red, yellow, blue and green (see Table 5).

Table 5. The top five preferred colours of the device of iteration 2

Visual perception	Device		Top five colours chosen by experts (Probability iteration 2)					Total
Cleanli-ness	Hygiene area environment	Colour	24	3	30	4	28	30
		Votes	12(40%)	8(26.7%)	5(16.7%)	2(6.7%)	2(6.7%)	
	Stool collection device	Colour	21	22	25	24	27	30
		Votes	13(43.3%)	7(23.3%)	5(16.7%)	2(6.7%)	1(3.3%)	
	Urine collection device	Colour	10	31	24	3	28	30
		Votes	12(40%)	9(30%)	5(16.7%)	2(6.7%)	1(3.3%)	
Harmony	Hygiene area environment	Colour	9	23	30	31	8	30
		Votes	13 (43.3%)	9 (30%)	4 (13.3%)	2 (6.7%)	2 (6.7%)	
Eye-catching	Garbage collection interface	Colour	10	32	25	7	8	30
		Votes	10 (33.3%)	8 (26.7%)	5 (16.7%)	3 (10%)	2 (6.7%)	
	Negative pressure package interface	Colour	11	30	25	12	24	30
		Votes	15 (50%)	8 (26.7%)	4 (13.3%)	2 (6.7%)	1 (3.3%)	
Discerni-bility	Garbage collection interface	Colour	11	29	31	32	30	30
		Votes	12 (40%)	7 (23.3%)	5 (16.7%)	3 (10%)	2 (6.7%)	
	Negative pressure package interface	Colour	29	11	21	12	24	30
		Votes	13 (43.3%)	6 (20%)	4 (13.3%)	3 (10%)	2 (6.7%)	

4. Discussion

The identified factors, while distinct, are closely interrelated. As one expert put it, “The success of the final colour solution must be promoted by these elements. The lack of one element will lead to a low reliability of the final solution. What really matters is the rigor of the process.” This research uses the space station hygiene area as an example to discuss how experts can reduce the stress response that affect astronauts through colour application. Following two stages of questionnaires, the significant stressors and corresponding device in the hygiene area can be determined. Furthermore, the corresponding colour scheme through the connection between device and human visual perception needs can be finally established. This method has not been employed in previous research regarding space station habitability or human factors. As shown here, it can be used as a reference guide for spacecraft designers. It has also been confirmed that this progressive method can solve the problem of common factors. Finally, in four iterations of surveys in two stages, detailed supplementary opinions from experts were collected. If no source is clearly mentioned, the reasoning will be based on the opinions of Delphi experts.

4.1 The significance of the stressor’s impact on astronauts

First, the stressors considered to be the most important for astronauts in the hygiene area of the space station will be discussed. Naturally, experts prioritized Confined small space, followed by smell, use and operation of the device, use time and environmental colour. Confined small space (first) and smell (second) were the highest-ranking effects. Note that although both are related to the stress affecting astronauts, the former refers to the impact of the environmental area on human habitability, while the latter is related to the specific function of the hygiene area. It coincides with Zachary's (2020) argument that the few areas providing visual privacy, and the environment and specific functions determine the particularity of the stressor. An expert opined: "The small space environment will become the main stress response for astronauts who use the hygiene area. If the used area is too small and it is inconvenient to use, it will directly affect normal excretion." Other studies highlighted that a hygiene area should not be viewed as a single element in the corner of a small room, but as part of an interconnected system that is vital to human health and performance (Drudi and Grenon, 2014). One expert said: "I think the direct effect of odour is vital to all other aspects" which is consistent with earlier studies on the International Space Station. Due to its tightness, odour in the space station could lead to nausea and vomiting (Ortega et al., 2015). This was supplemented by another expert's comment, which emphasized the importance of mitigating smells through vision or other senses: "In addition to sealing and ventilating smell by device, it can also be relieved by visual sensory transfer."

In addition, experts emphasized that use time is a relevant factor for stress response increase: the longer the astronaut stays in the hygiene area, the more the discomfort astronauts due to the cramped environment, smell, and other related stressors. Use time is caused by the uncertainty, hesitation, and complexity of the operation. Therefore, the operation of numerous devices in the hygiene area should be guided and optimized by visual effects such as colour. Furthermore, time is also closely related to the use and operation of the device. As some experts pointed out: "In a small area, the high or low ease of operation and fault tolerance of the device directly affects the magnitude of the stress response of the astronauts during operation, how to guide the operation through colour or pattern markings so that the astronaut can complete the operation in the shortest time is an important part of alleviating the stress response of the astronaut". This is consistent with the conclusion of Olshausen (2004): an efficient representation maximises information while limiting metabolism. Finally, experts mentioned that the quality of the colour environment directly affects all aspects of astronauts' use of the area. Vision, as an important sense, directly affects astronauts' feelings, especially during excretion and private activities.

4.2 Compatibility between stressor and device

According to the experts, an astronaut's stress responses are affected by many factors, including the overall environment, atmosphere, device and operability, air flow, temperature, smell, and noise. The main stressors relate to various devices in the space station. Although the literature on astronaut ergonomics and space psychiatry broadly supports the correlation between space station device and stressors (Crucian et al., 2014; Day, 1963), the experts in this study clearly stated that it is necessary to improve the visual sense of the device to ensure high habitability. It is also necessary to use colour to render the atmosphere and form a guide for specific functions. The stool-urine collection device, garbage collection interface and negative pressure packaging interface are the main devices that determine the habitability of this area, which is consistent with Zachary's (2020) findings. The stool-urine collection device is currently recognized as a key factor affecting the comfort and habitability during operation (Feighery et al., 2001; Dietz et al., 1990). Colour optimization of the stool-urine collection device is a functional means to reduce the main stressors in the hygiene area, which can effectively reduce the psychological and habitable stress response. The garbage packaging interface and the negative pressure packaging interface are the only operation interfaces in this area. Experts have pointed out that designing the colour schemes on keys and panels of the interface can effectively reduce operational errors. In addition, for astronauts, the overall environment of the hygiene area is an important factor that directly determines overall stress. Furthermore, this factor is listed as the most important factor by experts in space station research, which has also received focused attention in other studies (Novikova et al., 2013). Mahnke (1996) emphasized that, compared with the natural environment, the atmosphere of the man-made environment, especially where extreme, often directly determines the human habitability preference and psychological stress state, which is expressed through emotion and behaviour.

4.3 Compatibility between hygiene area device and visual perception needs

In terms of visual perception needs, experts believe that good colour design is important, while the immaturity and subjective rationality of colour application constitute the main obstacle. It has been argued by some that device complexity is a key factor in the confusion of visual perception (Connors et al., 1985; Jiang et al., 2020). Discomfort also results from the observation of simple coloured images (gratings). It increases with the difference in chromaticity between their components, and the discomfort is associated with a large cortical haemodynamic response (Haigh et al., 2013). In this study, experts unanimously agreed that the colour application of the main functional device is very important. Their highly consistent selection of "cleanliness" in "stool and urine collection devices" and "overall environment" shows that the main needs of astronauts are determined by area functions. This also indicates that the colour application should be determined by the visual perception requirements of the specific area. In addition, the garbage collection interface and the negative pressure packaging interface in this area are both control interfaces. Here, colours should be based on the principle of making visual perception as "eye-catching" and "distinguishing" as possible to help astronauts operate quickly and easily. Secondly, experts further emphasized that, in this small area, visual perception is not only affected by the main functional device (e.g. stool-urine collection), but also influenced by small auxiliary devices such as handles, restraint bandages, and restraints. Since the narrow space contains a large number of such devices, the colour application for them directly affects the visual perception of the entire environment; therefore, it is necessary to consider the colours suitable for complex visual scenes and predict the discomfort ratings, particularly if the difference exceeds the modest colour difference expected in natural scenes (Wilkins et al., 2021). Some experts claimed that the colour application of harmonious small auxiliary devices can help the hygiene area achieve a clean and orderly impression. Conversely, improper colour application will cause confusion in the overall environment, which will lead to irritability and low efficiency.

4.4 Compatibility of hygiene area device and colour

The colour of a complex human-machine system includes two parts: environment and device. When astronauts interact with them, their visual demands will be higher than that of the earth due to microgravity. One expert opined: "in long-term crewed space missions, the human eye will gradually slowdown in response to colour over time, and as the chromaticity difference between the components is smaller, the visual resolution will decrease." This is consistent with the conclusions of some visual experiments that simulate weightlessness. When in a state of microgravity, the human eye's sensitivity to colour decreases significantly, and it is difficult to distinguish the similar hues with small colour differences (Schlacht et al., 2009; Yu et al., 2016; Mader et al., 2016). This was supplemented by another expert who commented that the visual stress of astronauts in microgravity has increased significantly. This may be due to an increase in intraocular pressure caused by the increase in fluid flowing to the head, which causes the axial distance of the eyeball to become larger causing the dioptre to become larger and lowering colour contrast sensitivity, this is similar to Mader's (2011) conclusion. Therefore, it is necessary to appropriately increase the colour contrast of the operating interface to help astronauts improve their operating efficiency and reduce fault tolerance.

For the hygiene area, as experts' selection showed, the colour scheme falls in mainly two types: cleanliness and harmony. Experts were more inclined to choose light blue, light green, off-white, light grey and other less saturated (low chroma) colours, with off-white and light green being much more common. Relevant studies have shown that in relatively high-end hotels or public consumption places, toilets typically use cool colours with lower chroma, which is determined by the specific functions of the environment (Siamionava and Tomas, 2018; Tantanatewin and Inkarojrit 2018). For the urine collection device, the results of this study show a difference in colour matching. The stool collection device was mainly in low-saturation tones of off-white, light greyish blue, and light green. The urine collection device was flesh coloured. Experts believed that the stool collector must maintain a clean visual appearance. As for the urine collector device which is smaller and moulded to the human body, experts believed that it's colour not only needs to give people a clean visual impression, but also it needs to be relatively eye-catching. Therefore, in the colour matching of the hygiene area and the colour application of stool and urine collection devices, it can be inferred that experts prefer low-saturation cool colours. Moreover, according to the function of the device, it is necessary to increase or decrease the colour saturation and change the warm and cold colours. This method is also used in complex human-machine systems, such as nuclear power plants, submarines, and warships in special environments (Laxar, 1998). Undoubtedly, it is necessary to consider the specific functions of the equipment and environment to seek colour matching.

A further interesting finding was that, in the colour selection of the garbage collection interface and the negative pressure packaging interface, experts were consistent in the two visual perception choices of "eye-catching" and "discernibility". They preferred red, yellow (Y), green (G) and blue (B) and other single-tone highly-saturated colours. Most emphasized that these high-saturation colours should be used for buttons and operation keys, but they should not be used in a large area of vision environment. These high-saturation colour buttons should form a strong contrast with the white interface. This is consistent with the view that colours should not be considered in isolation but should be used in context to be discernible (O'Connor, 2010; Mahnke, 1996). On the other hand, they pointed out that interface design should also take into account the colour and function classification, operation sequence, font, button size, and spacing.

5. Conclusion and implications

Taking the example of a space station hygiene area, this study has analysed the stressors and related devices that matched the stressors. The study has also proposed ways to effectively reduce stress response in the area through visual perception requirements and colour matching. Using colour to improve the stressor of the space station, combined with the advantages of visual perception, it provides a guide for reduction in the stressor of the hygiene area, thereby potentially alleviating the stress response of astronauts.

The problem of space station stressors involves many stakeholders (e.g., designers, engineers, and astronauts). They must understand how to effectively improve astronauts' experience by using various methods to reduce in-cabin stressors. There is no explicit literature suggestions on how colour can optimize astronaut's stress response to solve the psychological problems of astronauts in future space design. With this respect, this study took the hygiene area as an example to investigate colour schemes to reduce astronaut stress response. Through the Delphi two-stage study composed of 30 international experts, this article identified the significant factors of the stressor, the main device that affects the stressor, and matched the visual perception needs leading to a colour scheme for that device being proposed.

For designers and manufacturers, these results imply that further development of colour as a source of effective control and reduction of space station stress is required. It is necessary to overcome shortcomings in technical application and safety. In addition, considering only the colour application of the device without regard to the materials, spraying process and light, and the chromaticity difference of the visual scene on the human visual stress, etc., will always restrict the method to the conceptual stage. Therefore, it is recommended to actively integrate innovations in the colour application process. Moreover, the needs of astronauts in different countries for colour could be cross-cultural, but it is the current goal to find the common-basic needs of human beings for colour. Experts agreed that people must believe in the benefits of this method. Moreover, they believed that achieving this goal requires viable testing on different cases. Although fundamental research is also very important, as one expert put it: “The solutions in the aerospace field must have been successfully verified repeatedly.” Therefore, it is recommended that these findings be implemented using an interdisciplinary team which includes aerospace, computer, colour, material and process experts. These teams will work together (e.g. through pilot cases) to verify the feasibility of the colour solution.

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