# Senses as Drivers for Space Habitats Design in Microgravity

Monika Brandić Lipińska[1] and Layla A. van Ellen.[2]
*Hub for Biotechnology in the Built Environment, Newcastle University, NE1 7RU, UK*

Volker Damann[3]
*International Space University, Strasbourg, 67400, France*

**Moving into off-planet environments require different approaches to design, mainly due to the fundamental physical changes astronauts perceive through their senses. Indeed, adjustments to off-planet conditions have important psychological and physiological implications and it cannot be presumed to be directly transferable from terrestrial habitat design. This paper focuses on microgravity environments and studies evidence reports and other documents on human performance in space in order to have a concise overview of the effect of space conditions and weightlessness. The study of the senses that affects health and comfort highlights the importance of changes in the perception of space, vestibular system, and proprioception. On top of that, it also demonstrates the importance of subjective perception. This paper then connects these studies with established architectural design methods such as the use of colours, spatial layout, and haptic surfaces resulting in a set of specific design responses for microgravity habitats. These suggestions and the follow up guidelines could enable the development of habitats that enhance astronauts' adjustment to microgravity environments and overall comfort.**

## I. Introduction

HUMANS living in space are constrained by habitat design, which provides shelter from extreme environments. Habitats are often designed with an efficient engineering approach, focussed on safety, function, and budget. At the same time, many studies[1–6] have highlighted the importance of designing space habitats that will respond to a broader range of astronauts' wellbeing and comfort.[7] Indeed, physical and mental performance and the ability to work are crucial factors for a space mission. Architecture acts as a protective layer between the harsh space environment and astronauts' wellbeing.

There are fundamental differences in how astronauts perceive the environment through their senses and perform in microgravity conditions, compared to terrestrial environments. Changes in sensory input and perceived experiences are closely linked to human health and comfort.[8] In this paper we define health as the balanced requirements between both physiological and psychological wellbeing aspects. Health is closely linked to comfort, which is when these requirements are met by the environment.[9] In order to ensure astronaut's health and conclusively mission success, development of habitats that will help with the adjustment to such conditions may play a crucial role, especially in long-duration space missions.[10]

The research gives an overview and understanding of the functioning of the human sensory system and the role of the senses in human health and comfort. Subsequently, this manuscript investigates the role of human senses in shaping architecture and the impact of the built environment on comfort. This paper (including the design suggestions) is based on theoretical research, literature review and studies of evidence reports, all addressing human performance in space and the design of space vehicles and habitats.[11,12] The conducted study encompasses two areas of research - comfort in architecture on Earth, and the effects of space conditions on human senses. The research is structured following factors emerging from the environment and its perception. Although this paper focuses on microgravity, many of the health factors described are also relevant for space habitats in general. The study of sensory comfort highlights the importance of changes in the perception of space, vestibular system, and proprioception for astronauts' health. The outcome of the project is an attempt at connecting the research on human performance in space, with architectural design theories. The design suggestions show the potential and relationships between astronauts' health and the habitat

---

[1] PhD candidate, Hub For Biotechnology in the Built Environment, monika@lipinscy.pl

[2] PhD candidate, Hub For Biotechnology in the Built Environment, Devonshire Building, Newcastle Upon Tyne

[3] Medical Doctor, International Space University

environment. The proposed scaffold for design strategies stresses the need for further development of the design suggestions for microgravity habitats.

## II. Factors affecting astronaut's senses

The human sensory system is a direct link between the world and ourselves. Each of the human senses developed during our evolution to help us survive and adapt to our living environment, Earth.[13] However, there is a limit to human tolerance to environments and in particular to extreme environmental conditions such as space. Piantadosi[13] defines physiology as the field dealing with human needs which is strongly linked to architecture; as the limits to human tolerance is defined by four variables: physics of the environment, limits to human physiology, length of exposure, and behavioural adaptation. Although great advancements have been made in biotechnology, the limits to human physiology cannot be re-designed which leaves three variables that we can influence. The physics of the environment can be adjusted to our needs via habitat design and this study defines and identifies the factors emerging from space environments. The length of exposure can theoretically be adjusted but it would be a challenge for deep space missions. The fourth variable, behavioural adaptation, enables us to keep an active equilibrium with our direct environment, for example how our bodies shiver when cold. These behavioural adaptations are strongly linked to human comfort, especially on psychological aspects. Therefore, the main factors that can be analysed and translated to habitat design are the factors affecting comfort emerging directly from the environment.

The most researched environmental factors for comfort are temperature[14,15] (dry-bulb, surface and relative), wind/air flow[16], (relative) humidity[16], radiation (direct/indirect), precipitations, and shade (from environment such as trees)[14,15,17,18]. The understanding of the relationship between the human senses and perception, and the built environment is critical when it comes to the development of space habitats. Indeed, the previously mentioned environmental factors are far more extreme from what we know on Earth, and very much unsuited to human life.[19] Changes or lack of gravitational force acting on the human body, altered natural dark-light cycle, and space radiation are some of the major changes affecting human health. Weightlessness, followed by the changes from upright to neutral posture and the angle of sight, sensory deprivation and overload, and disruptions in the circadian rhythm - all have an effect on human overall performance in space. The next sections are going to explain and explore these issues further.

During space missions, two types of psychological stressors occur: (1) hypo-arousal, triggered by sensory deprivation such as isolation and darkness, and (2) hyper-arousal, triggered by sensory overload, like fire or loud noises.[20] These sensory experiences vary depending on each individual (see section D. on subjective perception). However, it has been demonstrated that living and working in space can act as a trigger for discomfort, mostly due to habitability issues (limited space with lack of privacy) and interpersonal stressors (a large workload carried out by the astronauts, separation from family and friends).[21] In this paper, we define hypo-arousal as a phenomenon that may be observed as under-responsiveness to stimuli in one's environment and hyper-arousal as an abnormal state of increased responsiveness to stimuli. Hypo-arousal can lead to lethargy, inattention, apathy, or boredom[22] while hyper-arousal leads to increased levels of alertness and anxiety and elevated heart rate and respiration.[23]

### A. Circadian Rhythm

One great example that achieves balance between the environment and organisms, is the circadian rhythm. Humans, as well as animals, plants, and every organism developed on Earth, have their own biological cycle, which derives from Earth day-night cycles. The sync of the circadian rhythm is following a so-called *zeitgeber* (time cue) which emerges from the environment and is perceived through our senses. These time cues are related to the temperature and various aspects of daylight such as colour, intensity, and brightness[32]. Space habitats have fewer daylight variations, for example, Caballero-Arce, Vigil-de Insausti, and Benloch-Marco[33] show the lack of colours and variations on the ISS compared to outdoor environments on Earth. Disruptions in circadian rhythm can lead to sleep loss and changes in sleep patterns and deteriorations in a sense of time.[21,34] Moreover, daylight also affects mood and overall health. Indeed, light therapy has been proven to help fight low mood, seasonal affective disorder[35], depression, and it actively helps the production of vitamin D. It can, therefore, help astronauts adjust better to different "time zones" and artificial seasons[32]. Hence, it is important to carefully design a system of (artificial) lighting for a space habitat, following the lighting patterns from Earth with various colours and intensities throughout the artificial day. These types of lights are so-called circadian or melanopic (alternative method of measuring the effects of light on human biology) lighting and are already integrated into the WELL building standard.[36]

### B. Sensory Deprivation

Human brains have a preference for stimuli seeking behaviours. Arias and Otto[24] demonstrate the detrimental effects of sensory deprivation on the human senses, especially triggered by a dynamic between both acute and chronic stressors that are likely to occur during deep space missions. Low-stimulus environments are a cause of structural brain changes over a long period of time and lead to boredom, fatigue, and reduction in task interest as well as the emergence of psychiatric disorders and altered behaviour.[2]

One of the main causes of sensory deprivation is the sense of touch. Humans use tactile sensory input to gather functional information, responsible for creating a.o.intimacy.[25] In microgravity this sense is particularly affected, as astronauts feel less (or no) pressure on their feet which would normally occur when a person stands. Space habitats also tend to be characterized by the absence of textural and material diversity[26]. Another difference is that, contrary to space, on Earth outdoor and indoor environments vary depending on location, topography and climate, and socio-economic and cultural aspects[3,17]. This is even present inside the built environment as the presence of greenery is often prefered.[27] This preference derives from the concept that humans have evolved to develop an innate relationship with nature, which is part of the complex concept called biophilia. To address these health aspects, studies[28] show the positive effect of having pictures and projections of nature in Isolated and Confined Environments.

### C. Sensory Overload

Contrastingly, in space, humans can also experience sensory overload. It happens when there is more stimuli collected by a sensory modality than can be processed.[29] Sensory overload is linked to the presence of a low filtration capacity and is detrimental to human health.[30] It leads to loss of focus, inability to ignore loud sounds, strong smells and intensive lights, and overall discomfort. History of human spaceflight has few noticeable examples of such situations; e.g. when Apollo Skylab 1 crew first arrived and many alarms were sounding, or when there were crises on the Mir, including the Progress collision.[31]

### D. Subjective perception

Humans experience the world in various ways depending on their backgrounds. Although the sensory input can be similar, the reactions and feelings of the body interpret these sensory inputs differently. There have been many studies analysing how gender, age, culture, and (dis)abilities affect our perception of the environment as well as our comfort levels[14,37]. Although we know what factors affect our health and subsequent comfort, the extent to which they are affected and the resulting design suggestions are not fully developed yet. Hence, the design should be flexible to accommodate for subjective perception. Additionally, on the individual level, perceptual information in regards to light, temperature, hearing, and taste also all differ from norms on Earth.[10]

### E. Environmental adaptation

Human senses and perception might not always provide accurate situational awareness. For example, the vection effect (the sense of movement purely based on the viewing sense) is disturbing the perception of our surroundings such as experiencing movement while being sat in a stationary train next to a moving train. While this example is harmless on Earth, it could potentially be dangerous in space as this environment is entirely unique and presents high risks compared to living on Earth. Environmental factors such as extreme temperature fluctuations, radiation, microgravity, etc. have all been cited as challenges for space exploration. However, changes in the gravitational force acting upon the human body affect all senses drastically differently than on Earth.[21]

We use a focussed methodology that follows terrestrial architecture practices, such as the need to meet thermal comfort requirements first.[14,15] Therefore, although we recognize other environmental challenges such as the factors mentioned above, the research focus in this section is put on the changes in perception, specifically in the microgravity environment.

## III. Changes in perception in microgravity environment

During evolution on Earth, all physiological systems have been optimized for life in gravity. As a consequence, microgravity causes a series of physiological changes in human organisms that require adaptation.[19] Due to the lack of gravitational forces acting on the body, muscles relax, hence - in space - natural posture is a position in which "there is the least tension or pressure on nerves, tendons, muscles, and bones".[38–40] Astronauts' neutral posture, which is depicted in Figure 1, allows for a whole new range of body movements, which consequently leads to a different workspace definition.[41] Humans use four cues to determine the subjective vertical: visual, vestibular, proprioceptive and the isotropic vector (responsible for the perception of body axis as vertical).[42–44] The brain uses information from the vestibular system in the head and from proprioception throughout the body to understand body dynamics and kinematics, including its position and acceleration.[45] Misinterpreting changes in these sensory inputs, caused by microgravity conditions, may lead to errors in estimating the velocity, distance or orientation.[6] The microgravity environment is also a cause for the fluid shift, from the lower to the upper parts of the body, which results in a diminished ability to smell and taste.[6]

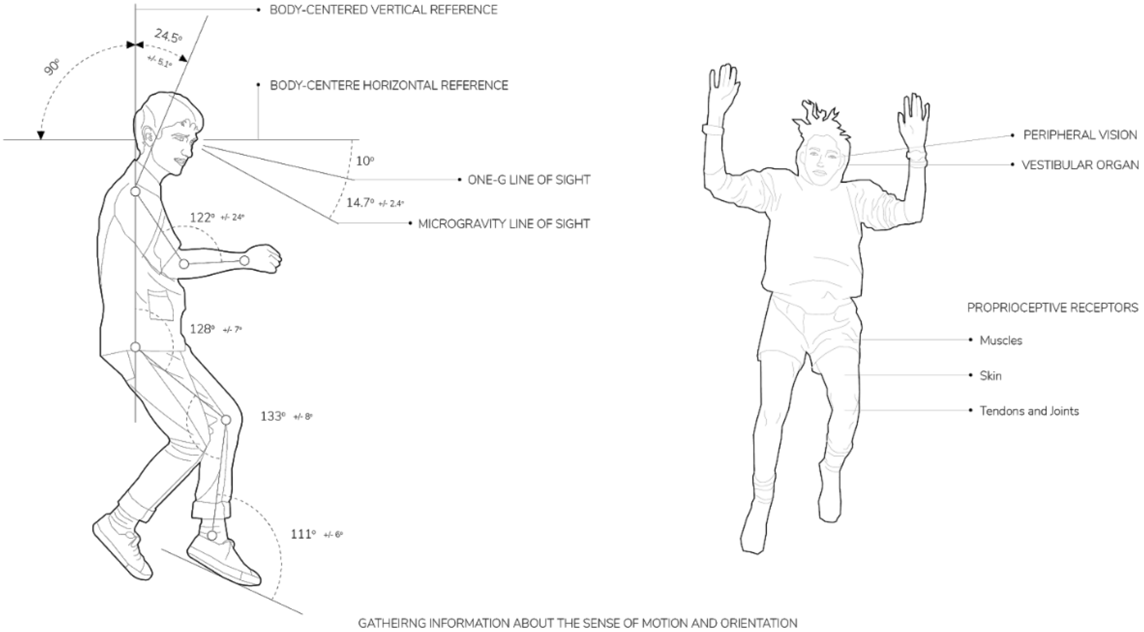

**Figure 1. The angle of sight in microgravity (NASA Man-System Integration Standards[5]) / Gathering information about the senses of motion and orientation. Adapted from Ref [11].**

### A. Vestibular System

The vestibular sensory system, responsible for providing our brain with information about motion, head position, and spatial orientation, greatly contributes to the sense of balance and spatial orientation.[45] The otolith organs in the ear canals - triggered by the pull of gravity - respond to all head movements (nodding up and down, shaking side to side, and tilting left and right),[45] and always know which way is 'up'. In a microgravity environment these cues are absent.[46] The otolith organs of the vestibular system are only stimulated by head translation movements, not by head tilt. Thus, the vestibular system no longer can figure where is 'up' and 'down'.

### B. Spatial Disorientation

Because the vestibular system does not work as intended in space, the brain gets confusing information about the orientation.[46] That can lead to troubles with mapping out the location of important features like space modules or emergency escape hatches and can affect the ability to perform complex operations. Astronauts may feel that they are tumbling or spinning, both with eyes open or closed.[47]

### C. Vection

The other disorienting impression that may arise in microgravity conditions, either on the whole body or on individual body parts (arms or legs) is vection. Vection is an illusion of self-motion, produced purely by visual stimulation. It generates the feeling that the body is moving when no movement is taking place. It can lead to dangerous situations onboard spacecraft, e.g. misinterpreting the direction and speed of objects during robotic operations.[48]

### D. Space Adaptation Syndrome

The leading theory standing behind the cause of the Space Adaptation Syndrome, also known as space motion sickness, which affects 70–80% of astronauts, is the sensory conflict theory. It occurs when patterns of sensory input (vestibular, proprioception and vision) are notably rearranged, and do not match with each other or differ from expectations, which can happen in microgravity conditions.[49] The severity of motion sickness increases with motion increase (particularly head movements), which causes sensory conflict and sickness.

### E. Proprioception

Proprioception is the ability to sense location, movements, and actions of the body.[50] In weightlessness, without stress on the joints, which tells how parts of the body are oriented to each other, proprioception is dampened. This disorientation is cause for 'space stupids' syndrome - when astronauts become queasy for the first few days in microgravity conditions.[51] The brain, not having all of the usual signals from the surroundings, works then by force of habit. It may cause strange experiences for astronauts, for example after waking up. They could be expecting the left and right or up and down based on personal sleeping patterns, and not on the observation of the surrounding.[52]

### F. Perception of Space Through Vision

In vacuum, lots of orientational cues are absent as there is no atmosphere and no overhead sun position and subsequently no shadow cues. The absence of atmospheric perspective and lack of air creates a sharp difference between illuminated, bright and completely dark areas. It decreases the perception ability and leads to a longer time for visual adaptation, which creates either glare or black shadows as can be seen in Figure 2. Hence, astronauts should avoid frequently moving back and forth from sunlight into shadow if they want to avoid glare fatigue.[53] A smaller amount of scenes with a linear perspective and familiar points of reference, lack of a fixed horizon and foreground or background, also decrease the ability to perceive objects and distances correctly.[54] These aspects, all connected to the vision, lead to degradation of perception of shape, distance, location and relative motion.[26] An additional issue corresponding with the vision, and affecting astronauts' productivity, is visual confusion. Usually, on board of space stations, objects are chaotically arranged, with different orientations in respect of an earthly practice.[26]

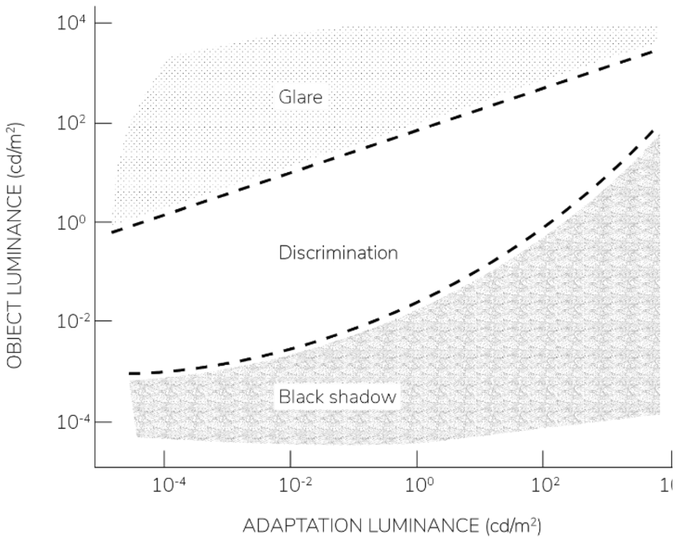

**Figure 2. A schematic illustration of the range of object luminances within which discrimination is possible for different adaptation luminances. The boundaries are approximate. (Adapted from [63])**

### G. Angle of Sight

The neutral posture - induced by the microgravity environment - besides affecting the astronaut's performance of movement, also affects the line-of-sight. The visual angle is shifted by about a 24-degree slope as a consequence of the tilting of the ''vestibule plane''. However, because of the different posture, the angle of sight may tilt down too.[41] Hence, a person should be oriented within approximately 45 degrees of the relative vertical to perceive the surroundings in a comparably normal fashion.

### H. Depth Perception and Myopia

On Earth, humans adapted skills to scale objects (and other people) on a horizontal distance, but not in height. In microgravity, where there is no difference between 'up' and 'down', astronauts tend to underestimate objects distances, like Apollo astronauts who reported difficulties with estimating distances of the objects on the lunar surface, which seemed closer.[55] Similar results have also been shown by ESA's 'Mental Representation of Spatial Cues during Space Flight' experiment.[56] In space, there are no intermediate distances - objects are only present in near or far space. In such conditions, humans' ability to estimate distance decreases.[54] This lack of objects at different distances is also a cause of myopia, or near-sightedness. Narrow space station modules, where astronauts cannot change focus between near and far objects to rest their eyes, prevent them from perceiving objects in distance. The only far-off object that can be observed is Earth, which, on the other hand, is too far to ensure proper eye rest.[26] On top of that, the risk of myopia is increasing as the vision range is shortened due to the neutral body posture.[26]

## III. Design Responses

The conducted research shows the significance of microgravity on the astronauts' perception, resulting in affected health and comfort. This section provides a table of design suggestions with examples as well as illustrations of the design examples. In terrestrial architecture, standards of living have improved overtime by using standard guidelines. Defining design guidelines based on comfort needs for microgravity conditions, represents an important step that the space architecture discipline must take. The following design suggestions are the first step towards such standards.

Based on previously mentioned factors it is critical to ensure a design configuration that will improve coordination and navigation in the habitat. The design of the interior spaces should benefit from mapping out the location so the astronauts won't get confused and lost. Additionally, using architectural principles and strategies, it may be possible to decrease symptoms of the Space Adaptation Syndrome. The set of strategies for the orientation of the habitat are suggestively depicted in Figure 3.

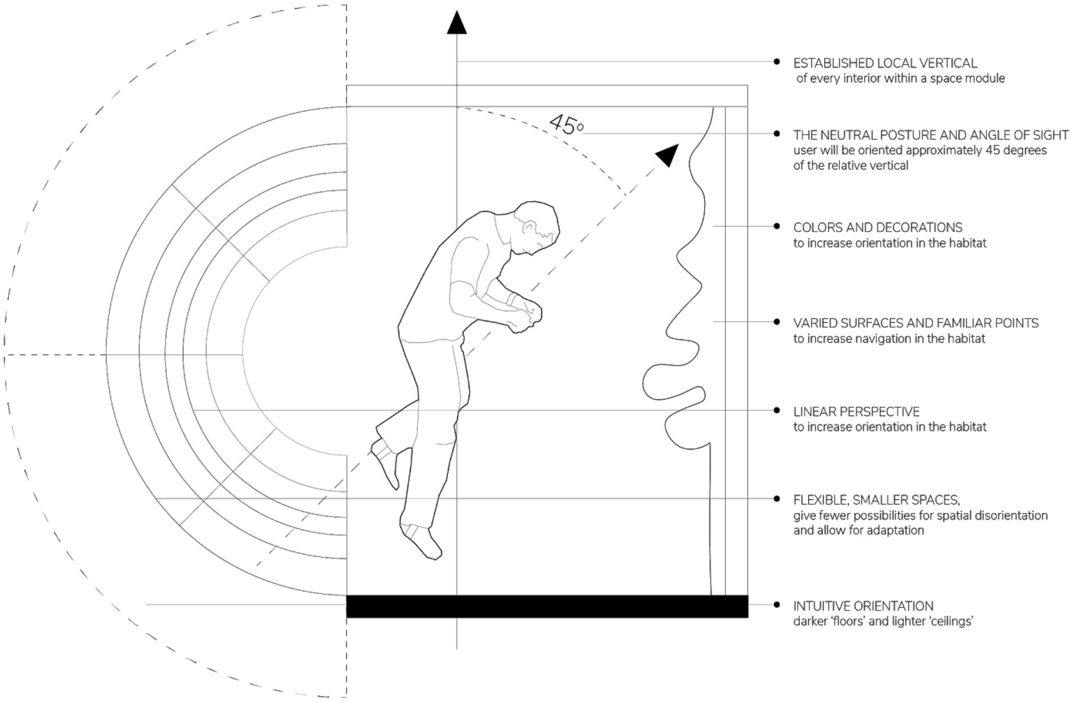

**Figure 3. Orientation within the habitat**

Figure 4 and 5 present ideas for sensory stimulation through colour, lighting, and haptic design. These ideas can improve the safety of astronauts moving around the different spaces of the habitat. These are very important elements in the architectural environment, as they have a significant effect on comfort.[33] In microgravity, tactile input gets predominance over the vision. It is crucial to design bearing in mind the human body's tactile sensors.[48] The skin can read texture but also weight, density, feel (a.o. cosiness) and temperature of objects, which are also important parts of experiencing spatial surrounding. In order to ensure astronauts' comfort, it is crucial to provide multi-sensory aspects of experiencing nature following the point made about biophilia. It is especially important in outer space, where humans are really far from Earth, and cannot directly experience any natural sensations.

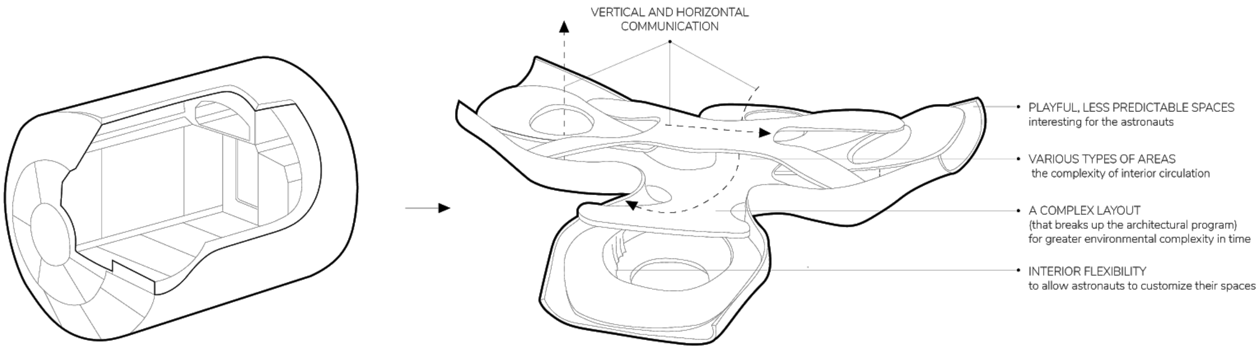

**Figure 4. Sensory Stimulation Through Spatial Design inspired by the Endless House by Frederick Kiesler.**[59]

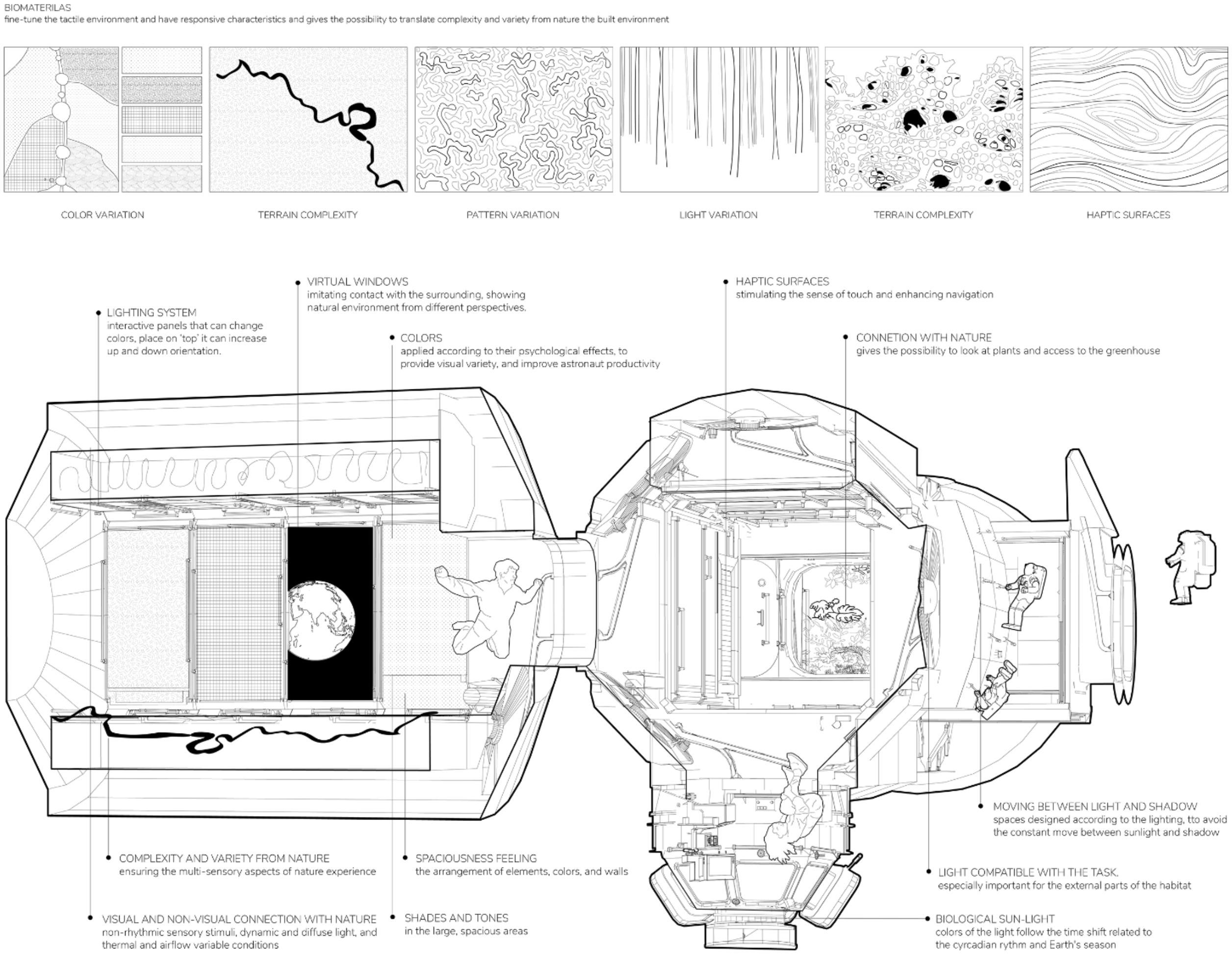

**Figure 5. Sensory Stimulation Through Colour, Lighting and Haptic Design**

Some design decisions, besides improving astronauts' wellbeing, may also have a direct effect on physiological health. One of the examples is to respond to the risk of astronaut's myopia, with design. It could be beneficial to give astronauts the possibility to focus on distant objects, which will answer the demand for proximal sight and accommodation of the crystalline lens.

Following the conducted research, table 1 shows the design suggestions that are responding to the changes caused by the space environment and microgravity conditions on health and comfort. The suggestions are divided into categories focusing on specific issues derived from health effects previously covered. Each category is divided further into subcategories which consist of design suggestions, and further explanation of how these responses work. The table is structured in such a way that it is adjustable for future development; new suggestions (and categories) can be easily added. The suggestions responding to sensory deprivation and overload, and circadian rhythm issues, are acting directly on the comfort requirements previously mentioned (lack of colours, light etc.). Contrarily, design suggestions responding to the changes in the vestibular system, and perception of space through vision, are not aiming to 'heal' these physiological changes. Rather, the aim is to help with the adaptation to the conditions that cause them. Through mindful design, it may be possible to increase the astronauts' orientation (diminished by microgravity conditions) and minimize the negative effects of Space Adaptation Syndrome.

The set of following design strategies can act as a scaffold that can be developed and updated over time. It aims to positively affect the astronauts' wellbeing, and performance, resulting in safety and mission success.[57]

| WHAT IT RESPONDS TO? | DESIGN SUGGESTIONS | HOW IT RESPONDS? |
|---|---|---|
| A \| CIRCADIAN RHYTHM | | |
| **1. MOOD, ALERTNESS, SLEEP & WAKE CYCLES** | **A.1** - Recreate natural colour variations during the course of a whole day. | Provide a sense of time passing, elevated mood. |
| | **A.2** - Include lighting design<br>● Use dynamic and diffuse light.<br>● Apply colours of the light in a way that it follows the time shift related to the Earth's seasons. | Adjusting internal biological clock which enables adequate wake and sleep cycles. |
| B \| SENSORY DEPRIVATION | | |
| **1. SPATIAL BOREDOM** | **B.1.1** - Design playful spaces.<br>● Create various types of areas and ensure the complexity of interior circulation, so the spaces are less predictable.<br>● Transform circulation, with changing horizontal and vertical dimensions, according to changing functions and needs. | Engages astronauts' perception through the complexity of the design spaces. |
| | **B.1.2** - Plan an increasingly complex arrangement as spaceflight lengthens.<br>● Design a dynamic layout that will break up the architectural program, and discard pre-defined functions inscribed in a space. | Reduces spatial boredom through achieving greater environmental complexity over time. |
| **2. BIOPHILI A** | **B.2.1** - Implement 'visual and non-visual' connection with nature.<br>● Give astronauts the possibility to look at plants and have access to the greenhouse.<br>● Apply adaptive thermal and airflow conditions, | Connection with nature reduces anxiety and stress, and increases directed attention. |
| | **B.2.2** - Translate complexity and variety from nature to the habitat environment.<br>● Use biomorphic forms and patterns<br>● Design hierarchical complexity<br>● Use colour variation, form complexity, light variation, pattern variation, terrain complexity and haptic surfaces as tools. | Ensures the multi-sensory aspects of nature experience, which reduces anxiety and stress. |
| **2. BIOPHILIA** | **B.2.3** - Apply pictures and projections of natural landscapes and animals.<br>● Use pictures that are complex, dynamic and detailed. | Helps prevent boredom and instigate conversations. |

| | | |
|---|---|---|
| **3. VISUAL MONOTONY** | **B.3.1** - Apply colours according to their psychological effects.<br>● For relaxing spaces (e.g. private quarters, infirmary) use calming hues such as blue or green, as well as neutral colours such as white or grey.<br>● For active spaces (e.g. training zones, work areas) use vibrant tones such as red, or orange.<br>● Use panels that can change colours. | Provides visual variety, and improves astronaut productivity and overall health. |
| | **B.3.2** - Use haptic surfaces to stimulate the sense of touch and to compensate for the monotony of the environment.<br>● Contrast smooth and rough surfaces. E.g. use soft (cushioned) material for the interior of the private quarters. | This tactile stimuli produces a calming effect and enhances navigation by providing orientation cues (see D.1.). |
| | **B.3.3** - Use (virtual) windows.<br>● Place screens throughout the habitat's common areas showing the natural environment from different perspectives. | Imitates the contact with the surrounding environment, to increase the sense of belonging. |

### C | SENSORY OVERLOAD

| | | |
|---|---|---|
| **1. SPATIAL CONFUSION** | **C.1.1** - Increase interior flexibility.<br>● Allow astronauts to customize their private quarters.<br>● Use curtains (e.g. instead of solid walls) for flexibility. | Allows astronauts for the arrangement of their personal things, giving a soothing sense of control and order. |

### D | CHANGES IN VESTIBULAR SYSTEM

| | | |
|---|---|---|
| **1. SPATIAL DISORIENTATION AND VECTION** | **D.1.1** - Keep the established local vertical.<br>● Keep consistent orientation of every interior within a space module and the interface elements (e.g. by using different colours for 'vertical' and 'horizontal' surfaces)<br>● Apply furniture/fixtures layout according to established local verticals . | Enhances spatial orientation in the habitat, which helps with adjusting to microgravity environment (see D.2). |
| | **D.1.2** - Place the lighting system according to the established, consistent orientation.<br>● Place the lighting system on 'top'. | Increases 'up and down' orientation. |
| **2. SPACE ADAPTATION SYNDROME AND PROPRIOCEPTION** | **D.2.1** - Plan the use of smaller spaces.<br>● Design smaller, 'temporary areas' for new arriving astronauts, to help with adaptation to microgravity conditions. | Diminishes space sickness. |
| | **D.2.2** - Use colours and decorations to increase object finding in the habitat.<br>● Support an intuitive orientation, like darker 'floors' and lighter 'ceilings'. | Enhance spatial orientation in the habitat. |

### E| PERCEPTION OF SPACE THROUGH VISION

| | | |
|---|---|---|
| **1. NEUTRAL POSTURE AND ANGLE OF SIGHT** | **E.1.1** - Design spaces according to the change from the up-right to the neutral position.<br>● Design spaces so the user is oriented approximately 45 degrees. relative vertical | Enhance spatial orientation in the habitat and prevents fatigue. |

| | | |
|---|---|---|
| **2. DEPTH PERCEPTION** | **E.2.1** - Increase the number of scenes with linear perspective and familiar points of reference.<br>● Use visual elements that may enhance the perception of the perspective, e.g. patterns on the 'walls' following the orientation of the module (see Figure 5 for visual examples). | Enhance spatial orientation in the habitat. |
| | **E.2.2** - Design the lighting colour so it is compatible with the colour of the surfaces and does not affect the colour sensation.<br>● It is especially important for the external parts of the habitat (guide beacons, navigation signs, rover headlamps, etc.). | Makes the colour-coding more efficient, especially in the places where atmospheric absorption and optical scattering from dust may affect the colours. |
| | **E.2.3** - Design spaces, and especially EVA's according to their respective lighting.<br>● Design space in the way that the astronauts won't have to constantly move between sunlight and shadow. | Shortens the eyesight adaptation time. |
| **3. MYOPIA** | **E.3.1** - Give astronauts the possibility to focus on distant objects. | Answer to the demand for proximal sight and accommodation of the crystalline lens. |

**Table 1. Design suggestions responding to microgravitational environments.**

## V. Conclusion

The aim of this project was to investigate the role of human senses in how we shape our environment and the impact it has on human wellbeing in microgravity. It is a critical area to consider when planning for long-duration space missions but the field lacks concrete design guidelines. This paper is the first step towards senses centric-design guidelines for space missions.

The focus lies on understanding the mechanism behind human senses in space conditions and its relationship to architecture. The scope of this paper lies within the senses responsible for balance and orientation (visual, vestibular, proprioceptive) and for prevention of the sensory deprivations (haptics) which are all heavily affected by changing gravity. Based on the conducted research, design responses are developed for space habitats that address the main effects of microgravity. This research could form the scaffold for future interdisciplinary research between architecture and human performance of astronauts wellbeing in space. However, it is critical that the theoretical architectural aspects are tested in a microgravity environment to consolidate their effect on crew wellbeing. Thereafter, a set of technical guidelines should be developed based on both the theoretical aspects found in this study and the future microgravity tests suggested above. The research into technical design guidelines could lead to standardized designs for extreme environments that facilitate the transition between different gravitational environments. For example, following the suggestions D1.1, D2.2 and E.2.1 standard colours for floors and walls could be used to counteract the vestibular effects on the body. The use of colours could also be used to communicate vertical and horizontal distances within habitats by using a specific colour for a distance of 4,5 m and another specific colour for distances of 7 m between walls. If used as a standard system, this will not only facilitate perception in microgravity environments, but it will also facilitate the transition between different gravitational environments independently from the crew's background. Although this research is still in its conceptual phase, the authors believe that this paper highlights the importance of linking human senses to architectural design for microgravity environments.

## Acknowledgments

The authors would like to acknowledge International Space University for the support in conducting this research, as a part of the MSS Curriculum as well as the Hub for Biotechnology for the Built Environment (HBBE).

## References

1. Imhof, B. The Socio-Psychological Impact of Architectural Spaces in Long-Duration Missions. (2003) doi:10.4271/2003-

01-2537.

2. Schlacht, I. L. Space Habitability - Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions. 295 (2012).
3. Imhof, B. An architectural approach to the design of a long duration human space mission. (Vienna University of Technology, 2006).
4. Cohen, M. M. Designing space habitats for human productivity. *SAE Tech. Pap.* **99**, 352–364 (1990).
5. Richard S. Williams, M. D. Nasa Space Flight Human-System Standard Volume 1, Revision A: CREW HEALTH. **1**, 83 (2015).
6. Russo, D. *et al.* NASA space flight human system standards. *Proc. Hum. Factors Ergon. Soc.* **3**, 1468–1470 (2007).
7. Martinez, V. Architecture for space habitats. Role of architectural design in planning artificial environment for long time manned space missions. *Acta Astronaut.* **60**, 588–593 (2007).
8. Thomsen, B. D. Body perception importance for wellbeing design. *Proc. 14th Int. Conf. Eng. Prod. Des. Educ. Des. Educ. Futur. Wellbeing, EPDE 2012* 549–554 (2012).
9. Piantadosi, C. A. *The Biology of Human Survival: Life and Death in Extreme Environments*. (Oxford University Press, 2003).
10. Imhof, B. The socio-psychological impact of architectural spaces in long-duration missions. *SAE Tech. Pap.* (2003) doi:10.4271/2003-01-2537.
11. NASA Lyndon B. Johnson Space, C. SKYLAB Experience Bulletin NO.17: Neutral body posture in zero-G. 68 (1975).
12. NASA Lyndon B. Johnson Space, C. SKYLAB Experience Bulletin NO.4: Design Characteristics of the Sleep Restraint. 67 (1974).
13. Nagel, O. *The evolution of the senses. Psychological Bulletin* vol. 5 (1908).
14. Alders, N. *Adaptive Thermal Comfort opportunities for dwellings: Providing thermal comfort only when and where needed in Dwellings in the Netherlands*. *A+BE Architecture and the Built Environment* vol. 13 (2016).
15. Nicol, F., Humphreys, M. & Roaf, S. *Adaptive Thermal Comfort: Principles and Practice*. *Book* vol. 53 (2013).
16. Du, X., Bokel, R. & van den Dobbelsteen, A. Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case. *Build. Environ.* **82**, 215–227 (2014).
17. Olgyay, V. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. (Princeton University Press, 1963).
18. Macpherson, F. *The Senses: Classical and Contemporary Philosophical Perspectives*. (Oxford University Press, 2011).
19. Nicogossian, A. E. & Robbins, D. E. Characteristics of the space environment. in *Space Physiology and Medicine* (Lea & Febiger, 1994).
20. Kanas, N. Psychosocial Stressors in Space and in Space Analogs. in *Humans in Space* 3–15 (Springer International Publishing, 2015). doi:10.1007/978-3-319-18869-0_1.
21. Kanas, N. *Humans in Space. The Psychological Hurdles*. (Springer, 2015).
22. Hodgetts, S. Hypo-Arousal. *Volkmar: Encyclopedia of Autism Spectrum Disorders* (2013) doi:https://doi.org/10.1007/978-1-4419-1698-3_181.
23. Merriam-Webster, M. Hyperarousal. *Merriam-Webster Dictionary* https://www.merriam-webster.com/dictionary/hyperarousal. (2021).
24. Arias, D. & Otto, C. Defining the scope of sensory deprivation for long duration space missions. (2011).
25. Franco, L. S., Shanahan, D. F. & Fuller, R. A. A review of the benefits of nature experiences: More than meets the eye. *Int. J. Environ. Res. Public Health* **14**, (2017).
26. Schlacht, I. L. & Birke, H. Space design: Visual interface of space habitats. *Pers. Ubiquitous Comput.* **15**, 497–509 (2011).
27. Almusaed, A. *Biophilic and Bioclimatic Architecture*. *Biophilic and Bioclimatic Architecture* (2011). doi:10.1007/978-1-84996-534-7.
28. Clearwater, Y. A. & Coss, R. G. Functional Esthetics to Enhance Well-Being in Isolated and Confined Settings. *From Antarct. to Outer Sp.* 330–348 (1991) doi:10.1007/978-1-4612-3012-0.
29. Watson, K. & Browne, D. What is Sensory Overload? *2018* https://www.healthline.com/health/sensory-overload#treatment.
30. Scheydt, S. *et al.* Sensory overload: A concept analysis. *Int. J. Ment. Health Nurs.* **26**, 110–120 (2017).
31. Cohen, M. M. Space laboratories. *SAE Tech. Pap.* (2001) doi:10.4271/2001-01-2142.
32. van Ellen, L. A. Hybrid habitat for Mars: Creating comfort with light. *Proc. Int. Astronaut. Congr. IAC* **2019-Octob**, (2019).
33. Caballero-Arce, C., Vigil-de Insausti, A. & Benlloch-Marco, J. Lighting of space habitats: Influence of color temperature on a crew's physical and mental health. *42nd Int. Conf. Environ. Syst. 2012, ICES 2012* 1–9 (2012) doi:10.2514/6.2012-3615.
34. Gander, P. H. *et al.* Flight crew fatigue IV: Overnight cargo operations. *Aviat. Sp. Environ. Med.* **69**, (1998).
35. Aarts, M. P. J. Changing perspectives on daylight: science, technology, and culture. Supplement to Science. *Science (80-. ).* 1–48 (2017).
36. WELL Building Standard, V. Circadian Lighting Design. https://legacy.wellcertified.com/en/explore-standard (2017).
37. Elsharkawy, H. & Zahiri, S. The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance. *Build. Environ.* **172**, 106676 (2020).

38. University of Connecticut. Neutral Posture. *Connecticut: Occupational and Environmental Health Center* http://oehc.uchc.edu/ergo_neutralposture.asp. (2011).
39. Jay C. Buckey. *Space Physiology*. *Oxford University Press* (2006).
40. Clément, G. *Fundamentals of Space Medicine*. (Springer, 2005).
41. Melchiorre Masali, Marinella Ferrino, Monica Argenta, M. M. C. Anthropology: Physical and Cultural Adaptation in Outer Space. in *Lunar Settlements* (ed. Benaroya, H.) (2010).
42. Clarke, A. H., Grigull, J., Mueller, R. & Scherer, H. The three-dimensional vestibulo-ocular reflex during prolonged microgravity. *Exp. Brain Res.* **134**, 322–334 (2000).
43. Clément, G. Alteration of eye movements and motion perception in microgravity. *Brain Res. Rev.* **28**, 161–172 (1998).
44. Kanas, N. & Dietrich Manzey. *Space Psychology and Psychiatry*. (2008).
45. Khan, S. & Chang, R. Anatomy of the vestibular system: A review. *NeuroRehabilitation* vol. 32 437–443 (2013).
46. van Veen, H. A. H. C. & van Erp, J. B. F. Tactile information presentation in the cockpit. in 174–181 (2001). doi:10.1007/3-540-44589-7_19.
47. Iaria, G., Burles, F. & Duchesne, S. Wayfinding: How space flight affects astronauts' brains. *Canadian Space Agency* https://www.asc-csa.gc.ca/eng/sciences/wayfinding.asp (2017).
48. Harris, L. Bodies In the Space Environment (BISE) - Which way is up in space? *Canadian Space Agency* http://www.asc-csa.gc.ca/eng/sciences/bise.asp (2013).
49. Kornilova, L. N. & Kozlovskaya, I. B. Neurosensory Mechanisms of Space Adaptation Syndrome. *Hum. Physiol.* **29**, 527–538 (2003).
50. Van Erp, J. B. F. & Van Veen, H. A Multi-purpose Tactile Vest for Astronauts in the International Space Station. *Proc. eurohaptics* 405–408 (2003).
51. Howell, E. Weightlessness and Its Effect on Astronauts. https://www.space.com/23017-weightlessness.htm (2017).
52. NASA. Mixed Up in Space. https://science.nasa.gov/science-news/science-at-nasa/2001/ast07aug_1/ (2001).
53. Jones, E. M. *One small step. Apollo 11 Lunar Surface Journal*. http://www.hq.nasa.gov/alsj/a11/a11.step.html (2009).
54. Damann, V. *Brain in Space Effects of Space Flight on the Nervous System*. (2019).
55. Courtland, R. Zero-gravity may make astronauts dangerous drivers. *NewScientist* https://www.newscientist.com/article/dn14779-zero-gravity-may-make-astronauts-dangerous-drivers/ (2008).
56. G. Clement, C. Lathan, A. S. & Lorigny, E. Mental Representation of Spatial Cues During Space Flight. (2008).
57. Messerschmid, E. & Bertrand, R. *Space Stations, Environmental Control and Life Support System*. (Springer-Verlag Berlin Heidelberg, 1999).
58. Delombard, R. *et al.* Microgravity Environment Description Handbook. (1997).
59. Sveiven, M. AD Classics: Endless House / Friedrick Kiesler. *ArchDaily* https://www.archdaily.com/126651/ad-classics-endless-house-friedrick-kiesler (2011).
60. Connors, M. M., Harrison, A. A. & Akins, F. R. *Living Aloft*. (NASA, 1985).
61. Franco, L. S., Shanahan, D. F. & Fuller, R. A. A review of the benefits of nature experiences: More than meets the eye. *International Journal of Environmental Research and Public Health* vol. 14 (2017).
62. William Browning, Catherine Ryan, J. C. *14 Patterns of Biophilic Design*. *Terrapin Bright Green, LLC* (2014).
63. Loe, D. L. Light, colour and human response. *Colour Des. Theor. Appl. Second Ed.* 349–369 (2017) doi:10.1016/B978-0-08-101270-3.00015-1.