Habitability and the Golden Rule of Space Architecture

Sandra Häuplik-Meusburger[1]
TU Wien | space-craft Architektur, Institute for Architecture and Design, Vienna, Austria

Sheryl L. Bishop[2]
University of Texas Medical Branch, Galveston, Texas, USA

James A. Wise[3]
Neutra Institute for Survival Through Design, Pacific Grove, California, USA

The social, psychological and also spatial significance of living in an extraterrestrial environment place demands not only on the type of persons who would be 'best fit' to inhabit such environments but also on the living spaces that must be crafted to support human habitation in such environments. One of the critical characteristics for living and working in those environments is the dependency on the habitat. Its technological capability as well as the spatial and functional capacity to counteract the stress effects of a closed loop, extreme environment will be pivotal for mission success. Historically, such habitats have lacked all but the merest attention to such 'details' with a focus primarily on surviving rather than thriving. This is changing and the built environment is slowly becoming an accepted important factor to ensure both physical and psychological wellbeing.

The challenge for the design of off-Earth facilities is the trade-off between the need for resources to maximize performance and human well-being and the technological and spatial limitations inherent in closed loop environments. Designing for such environments must grapple with a scarcity model that allows for only what is absolutely necessary. The embodied practice of 'making use of what you have or making do without' has been the basic rationale of bottom-up survivability focused habitat design across all habitats in terrestrial extreme locations as well as space. When the focus is beyond mere survival, our list of critical 'necessary' elements grows and the struggle to provide more within the same finite capacity argues for an alternative top-down approach. The cold equations of resource limitations in extraterrestrial environments makes maximization of 'what you have' critical to mission success. This 'Golden Rule of Space Architecture' is fundamentally shaped by a design principle that differs in substantial ways from designing for terrestrial structures. To maximize performance, psychosocial and physical well-being in isolated, confined and extreme environments, every element must serve a critical functional role and be multi-purposive. Intriguing emerging evidence has provided new insights into essential characteristics of our habitats that, in essence, seem to require that we replicate critical characteristics of our terrestrial environments in order to provide passive supportive restorative benefits and peak neurocognitive functioning.

This paper highlights relevant concepts of the term Habitability for isolated, confined and extreme (ICE) environments from a perspective that extends beyond mere surviving to thriving. Application of the principles of necessity and multi-purposive are applied to examples for enhancing social cohesion and reduction of stress 'by design and built architecture'.

[1]Senior Lecturer, TU Wien, Institute for Architecture and Design, Department Hochbau 2, Karlsgasse 5/3, 1040 Vienna, Austria AIAA Full Member, haeuplik@hb2.tuwien.ac.at
[2]Professor Emeritus, School of Nursing, 5712 Highland Rd, Santa Fe, Texas 77517 USA. sbishop@tobey.org
[3]Retired Clinical Professor of Psychology and Environmental Sciences, Washington State University, Tri-Cities, 2432 Tiger Lane, Richland, Washington, USA 99352 <jamesawise@me.com>

Nomenclature

EE	=	Extreme Environment
EVA	=	Extra Vehicular Activity
ICE	=	Isolated, Confined, and Extreme [Environment]
ISS	=	International Space Station
ESA	=	European Space Agency

I. Introduction to an Inevitable Paradigm Shift

The main drivers for designing spacecraft interiors from an engineering psychology perspective evolved from a primary focus with survivability,[1] to automation supervision,[2] followed by a 'humanization' of space hardware through designers, architects and psychologists in the advent of long duration missions in the 1970s.[3] Historically, architecture and design in operational environments have been oriented to supporting physical functional performance of human activities over relatively short durations (i.e., 6 months or less). The challenge for the design of off-Earth facilities is the trade-off between the need for resources to maximize performance and human well-being and the technological and spatial limitations inherent in closed loop environments. Designing for such environments must grapple with a scarcity model that allows for only what is absolutely necessary. The embodied practice of 'making use of what you have or making do without' has been the basic rationale of bottom-up survivability focused habitat design across all habitats in terrestrial extreme locations as well as space.

When the focus is beyond mere survival, our list of critical 'necessary' elements grows and the struggle to provide more within the same finite capacity argues for an alternative top-down approach. The cold equations of resource limitations in extraterrestrial environments makes *maximization* of 'what you have' critical to mission success. A 'Golden Rule of Space Architecture' is fundamentally shaped by a design principle that differs in substantial ways from designing for terrestrial structures. To maximize performance, psychosocial and physical well-being in isolated, confined and extreme (ICE) environments, *every element must serve a critical functional role and be multi-purposive*.

Initially long-term sustainability of space exploration has been approached by extending short-duration bottom-up survival and coping habitat design approaches. As space design projects entail long time frames with many people involved wherein more "ideas are discarded than advanced"[i], simply extending the survivability approach to long duration needs led to the trade-out of features that would have improved habitability (e.g., as during the development of Space Station Freedom). While a focus on survival is necessary, it is not sufficient for long term crew health and well-being. Such tunnel vision actually represents a threat to mission success. It is time for a fundamental paradigm shift in how we approach long duration habitat design for extreme environments, especially those off-Earth. In order to successfully create a habitat that can promote thriving, we must *start at the top of any putative needs hierarchy, not the bottom*. We must start with the question of what we want to achieve (the vision) and not what we can achieve. What is it that a very successful house or dwelling allows a group to do that keeps them fully engaged with and enjoying it and each other? What environmental qualities does a habitat provide that humans have naturally sought out throughout history? A top-down space architecture design approach must be employed that *starts with* recognizing and including—even if only in surrogate form—the critical environmental, social and psychological qualities of our own natural Earth habitats in which the human species came of age and gained prominence on our own home planet. What we must not forget and recognize as we envision our first lengthy missions to other off-Earth bodies is that we are still tied, in our perceptual, emotive and cognitive neural processes, to environmental qualities of our own home planet. Earth, in many critically important ways, continues to *reside and abide* within our own biological processes and neural systems, and needs to be included in the design of any long-term space mission habitat.

This paper emphasizes habitat design as an absolutely critical element and outlines relevant aspects that must be addressed to design effective long duration habitats for space exploration. The intent is to outline a larger perspective that will hopefully stimulate creative solutions to the twin challenges of resource limitations and demand for maximization. There are no one-stop fixes. The need is for multiplicative integrated solutions in which the sum is

---

[i] Cf Häuplik-Meusburger S. & Bishop S. 2021. Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and In Space. Space and Society Series, Douglas A. Vakoch (Ed). Springer Nature: Switzerland. 250 pages. https://journals.open.tudelft.nl/spool/article/view/5267/5166

successful adaptation to the new environments of extraterrestrial living. To illustrate both the need for integrative solutions as well as application of the underlying principles, this paper will discuss examples for enhancing performance, psychological and physical functioning through elements directed at stress reduction and social cohesion.

II. Habitat Design as Critical Element for Mission Design

In the context of biomedical risk reduction and mitigation in future lunar and deep space missions, the need for crew inflight support infrastructure, particularly through meaningful habitat systems, has been recognized as critical by mission planners, psychologists, designers and alike.[4-8] The '*risk of incompatible vehicle or habitat design*' has been identified by NASA as a recognized risk to human health and performance in space (NASA [Risk] 2013, p.3).[9] With the recognition of this criticality, habitability has been recognized as a viable contributor to both active and passive countermeasures for certain stressors. Yet, the area has received little systematic research attention so far,[10,11] and concrete habitability design interventions for in-flight support have changed little since the advent of long duration missions. In operations and design, habitability has become a general term to describe the suitability and value of a built habitat for its inhabitants in a specific environment and over a certain period.[12]

We are in a time where habitability as critical driver for space habitats is accepted, while at the same time, current missions are planned with the traditional bottom-up approach (what can be fitted in to a given volume, instead of what volume is needed). It is an ongoing process where space architects, designers and social scientists need to contribute.

III. Habitability as an Integrated System

When we talk about habitation in isolated, confined and extreme (ICE) environments, we're automatically talking about a complex and interconnected *habitation system* involving the individual as well as society in relation to the (built) environment. By looking at habitation from a socio-spatial perspective in a systematic manner, we can identify the following four main components:

- the Setting (the actual environment, mission length, tasks, type of habitat, and others),
- the Individual (physical and psychological conditions, experience, and others),
- the Group (composition, culture, and others), and
- Time (length, scheduling, and others).[13]

In contrast to more traditional models wherein humans are considered one undifferentiated element, the system model considers humans as individuals and humans as groups. The importance of both physiological as well as psychological needs is explicitly identified. Just as basic 'ergonomic design' directly supports physical functional performance, there appear to be pattern, color, form, texture and spatial characteristics of habitat interiors that facilitate more efficient cognitive functioning and performance as well as promoting stress reduction.[14] In the past, habitability models were primarily defined by ergonomics-derived habitability concerns such as those of atmosphere, temperature and vibration that can be traditionally quantified.[15] Growing evidence suggests it is the more 'intangible' aspects of the environmental factors inside and outside the habitat and their sensory, cognitive and emotional implications,[16] that should be the focus of a 'unifying systems design concept'.[17] This 'psychological habitability' (as opposed to/in extension of physiological habitability) refers to all aspects of habitability that have a direct or indirect engagement with the human psyche, especially for future long duration mission scenarios.[18] Psychologists Kanas & Manzey[19] point out that critical areas of psychological habitability include not only habitable volume, but also heretofore factors considered as 'nonessential', e.g., crew quarters, leisure applications, décor, and windows.

Habitability design requirements for all extreme environments are driven by human performance and interaction relationships: human-human, human-space, and moreover human-computer and human-technology. Over the years, it became evident that the interaction between the human and the designed product (technology) needed to be integrated to facilitate mission success. Those demands from environments that are largely closed loop technological 'worlds' were the driver for the expansion of the field of 'Human Factors' to encompass the interrelationships between technology and engineering.

Of particular interest were the persistent results from simulated long duration human missions where the dependence on an artificial closed loop environment would be total. Surprisingly, the general reduction of situational stimuli (especially external cues) may not be as challenging as the *monotony* inside the vehicle environment itself.[13] This suggests a concerted focus on habitability embedded solutions. Applications for long-term effective countermeasures need to provide ongoing, passively delivered, continuous mitigation through internal architecture and adaptive systems. Lessons learned from these theoretical and analogue experiments are that for long duration, remote mission scenarios, one primary aim needs to be reduction of the stress and deleterious impacts of isolation, confinement, and continuous immersion in a foreign dangerous environment on the mission and crew.

IV. What you Take is What you Have and The Golden Rule of Space Architecture

It is an unbendable fact about the logistics of space travel and habitation that **everything** is limited. Physical space, storage, air, water, food, power, fuel, medicine . . .**everything** - even people. Therefore, it seems logical that we must plan to make do with what we pack and bring. As such, those implications are one of the major design issues for ICE habitats. They are inherent in the design process and need to be considered in all phases. The design consequences of "what you take is what you have" are so pivotal that it could be characterized as a golden rule of space architecture (Figure 1). For instance, a corollary of limited resources is maximizing use of every possible 'item' that you bring. This results in demands for flexibility, capacity for repurposing, and multipurposive functionality for items, space and crewmembers. The challenge for the design of off-Earth facilities is conceptually illustrated with Figure 1.

Figure 2a exemplifies a real-life need for such adaptability and flexibility as a consequence of different air filters connectors for the Apollo CM module and the LM. Designing for ICE environments means largely doing without or making do with some kind of substitute. It means doing more with less. It means using resources in-situ to craft what you need. It means everything possible should have multiple functionality and utility. It means that every aspect of your physical living envelope is marginal and at risk.

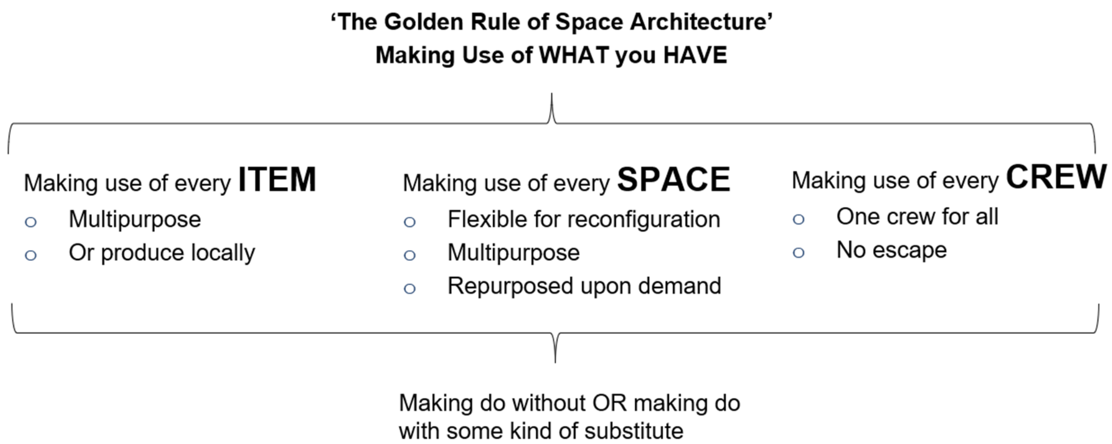

Figure 1. The Golden Rule of Space Architecture - underlying principle when designing working and living spaces off-planetary. (diagram by the Authors)

Every designed **element** must strive to be multipurpose, flexible for reconfiguration, and amenable to being repurposed upon demand. Solutions cannot take up too much room or power, generate temperature fluctuations, vibrations, or environmental disruptions. Solutions cannot require extensive maintenance or attention or interfere with the operation of other critical systems.

Consider the other ways in which designing for extraterrestrial habitats are fundamentally different than terrestrial considerations. In an extraterrestrial environment, post-adaption to buildings and structures is challenging. Once everything is installed, structural and spatial reconfiguration may not be possible anymore, or only with extensive effort. If the base will be expanded at some point, it needs to be designed for eventuality. If a module needs to change its function, it needs to be so designed. If facilities need to be moved to another location or upgraded to another technology, it needs to be designed for that. If the crew size doubles, it needs to be designed to handle that demand. Overall the design needs to combine structural strength with mission-related flexibility. ALL utilization of space must be planned for - including needs for new space. This design approach is quite new and implies thinking in life cycles.

The same applies to resources. We can only take a finite amount of resources with us and must make those go as far as possible in as many ways as possible. Making do with what you HAVE or can produce locally (e.g., Figure 2 a.

and b.) will be an inflexible rule of space living. The same applies to the **PEOPLE** involved. You will be stuck with the same people in a confined environment for long durations of time. There is no ‘escape’ or ‘others’ to turn to. Thus, your space needs to proactively mitigate the deleterious effects of confinement, isolation, monotony, boredom, and loss of familiar stimuli.

Figure 2. (a) Apollo Command Module Box-shaped lithium hydroxide canisters were modified to fit into cylindrical holders of the LM. This was necessary to maintain safe carbon dioxide levels for the crew of three astronauts on their journey back home. (NASA, 1970)
Figure 2. (b) 3-D printing prototypes of dental and medical applications to maintain crew health on outbound journeys where fast return to Earth is not possible, such as to Mars. (Häuplik-Meusburger, Lotzmann and Meusburger, 2016 and 2015)

V. From Maxim to Application: Exemplary Habitability Design Applications

The implications of the Golden Rule for Architecture are both overt and indirect. The obvious challenges of making do with finite resources, space and crew are preceded by first deciding what is ‘necessary’. Carbon dioxide removers are necessary but should including actual plants to remove C02, provide psychological restorative benefits, contribute to food supplies, provide opportunities for leisure activities be considered? Is the capability to simulate terrestrial day/night cycles critical to human health and functioning? The identification of critical elements is rapidly expanding as intriguing emerging evidence from various fields change our list of priorities. Just as the identification of the atomic structure of matter radically change our view of fundamental particles, so is our understanding of the relationship between human functioning and the environment being rewritten. For instance, the field of bionomics (the study of organisms and their relationships to their environment) is providing new insights into critical characteristics of our habitats that, in essence, seem to require that we replicate certain features of our terrestrial environments to provide the same passive supportive restorative benefits and peak neurocognitive functioning we get from exposure to nature. The same line of evidence argues that traditional habitat design centered around Euclidian straight lines and dimensionality may actually be deleterious to human functioning. Similarly, a growing body of theory and convergent research from evolutionary psychology and externalized cognition has identified connections between sensed structural patterns of the physical environment and the work performance and equality of life experienced by its occupants. Roger Ulrich’s (1983)[20] psychoevolutionary framework proposed that affective responses towards environmental features are rapid, automatic and unconscious adaptive perceptual processes rooted in human evolutionary history in which different environments are immediately liked or disliked in order to facilitate responses that contribute to wellbeing and survival. Studies demonstrating these rapid, immediate and automatic affective responses to various environments[21],[22] provide supporting evidence that these emotional reactions saved precious time and energy spent learning which environments were beneficial or harmful.[20, 23, 24] Recent works on human activity[25] and isovists (the extent of space visible at eye position from a particular point) and isokin (a measure of the level and type of constraint that a confining space imposes on its occupant) approaches[27] analyzed the spacecraft environment in relation to architectural programming, and established design directions for central human activities that make a ‘home’ in a long duration mission. These domains are providing intersecting evidence for a far more complex understanding of the world and our relationship with it. As our understanding of what is essential for well-being, the list of critical needs expands and so does the challenge to provide for those needs within the strictures of the Golden Rule for Space Architecture. Luckily, technological advances have also enlarged our opportunities to meet those demands.

Translating the implications of the space Golden Rule requires a recognition of current approaches and how (and why) they fall short. For instance, in extreme environments (space and ICEs on Earth) technology has (had) to substitute artificial aspects for many of Earth's natural conditions: breathable atmosphere, shirt-sleeve environments, artificial day/night cycles, processed foods, or livable temperatures. The new evidence from bionomics would argue that the substitutions used to date may not yet be viable alternatives for the conditions that they seek to mimic. It may not be enough to just brighten and dim existing lighting on a specific schedule to mimic circadian rhythms. That single purpose bottom-up approach to addressing a specific issue (circadian schedules) is inefficient and minimally effective. A more effective approach could arguably be a top-down process where supportive elements in successful terrestrial ancestral habitats are identified and incorporated into our ICE habitats. A consideration of how lighting impacts all areas of human functioning needs would result in a multi-purposive approach in which the aim would be to introduce meaningful complexity through the use of geometry and proportions, lighting (diurnal/seasonal dynamics), shapes (fractal patterns, reduced clutter), and providing enhanced views, i.e., to recreate those elements that compose humankind's 'natural habitat' as proposed by bionomics.

The mindset and approach to replicate natural systems is not new. Figure 3 shows an example for a building based on the design philosophy by Richard Neutra,[28] a great modernist architect. His famous 1929 Lovell Health House, one of his early designs, exemplifies the concept of bringing an entire dwelling together around the concept of healthy living at all levels of scale and activity. Similarly, space habitats will need to be integrated dwellings where form and function are deliberately designed to mitigate against the stresses of ICE environments and provide for maximal psychological and physiological well-being.

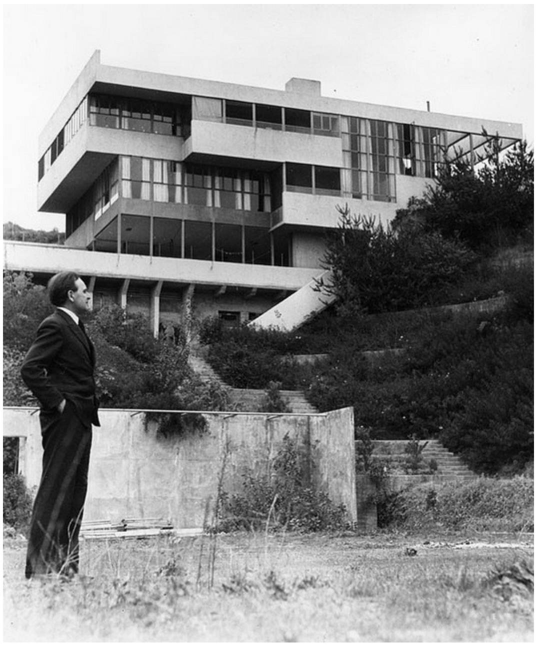

Figure 3. The architect Richard Neutra in front of his 1929 built Lovell Health House. [credit: Los Angeles Public Library Collection.]

Our point is that an analogous approach of maximizing the broadest technological capabilities to replicate those terrestrial characteristics that our physical and mental health relies upon is what is needed now. The current bottom-up approach starts with designing a mechanistic technical envelope to provide for survival and defends against any 'nonessential' additional elements. The 'top down' approach espoused by Richard Neutra and other architects deeply concerned with health and well-being of their occupants begins with a clear understanding and vision of what humans *need to be at their best*, and then provides it. The Golden Rule of Space Architecture dictates that our resources are limited to what we bring and the solutions must be flexible, adaptable and multipurposive.

To illustrate the efficacy of a top-down approach bounded by the Golden Rule of Space Architecture, the following two examples illustrate how issues related to both group and individual factors identified using the habituation system outlined earlier can be successfully addressed.

A. Enhancing Social Cohesion by Design

Living with others is not easy in the best of circumstances. Social cohesion is challenging in all groups, but closed loop environments pose unique challenges. Remove the opportunity to get away when the inevitable irritations flare, shrink the shared space to something slightly larger than a medium-sized apartment and limit the opportunity to interact with anyone else for a protracted period (months or years) and suddenly there simply isn't enough room. Then there are the myriad nuances of social existence to deal with involving differing cultural norms and practices and individual differences.

1. First Consider the Overall Layout of the Habitat: Zoning out social Conflicts

On Mir, "for sanitary and privacy reasons, no one was ever enthusiastic about using a toilet two feet from the dinner table".[29] Clearly requirements of personal activities and social activities demand different spatial solutions in appropriate relationship to each other. Still, much of the tension between crewmembers observed in ICEs has been expressed through social (sometimes interpersonal) withdrawal, increased territorial behavior and the use of scapegoats or external others (e.g., Mission Control).[30-32] This interpersonal behavior has spatial consequences. It often leads to increased need for privacy across time. Designing for the inevitability of interpersonal conflict poses dual challenges - prevention and mitigation. Preventive measures would be those that minimize opportunities for potential conflict and irritations, e.g., multiple workstations with essential equipment, private areas for social distancing, automation for burdensome station-keeping duties, clearly defined personal space and the ability to control that space, restorative areas for relaxation. Mitigation measures would provide for effective means of countering rising tensions—engaging exercise, sports, or leisure activities, opportunities for positive social engagement, provisions that facilitated group fusion instead of group fission. On the habitability side, many features could address both needs. Retreat areas could be partnered along food production tasks in the greenhouse. Paths through a base could provide multiple routes to reach destinations allowing inhabitants some control over engaging others. Specific areas for various activities like exercise or other noisy activities could be separated from quiet areas to provide restoration. The ability to modify social spaces for different needs and events encourages group activities and positive interactions. We will be at both our best and worst and our living space must accommodate those extremes of our personality while consistently and relentlessly guiding and supporting us.

Figure 4. (a) The provision of sleeping bags is enough spatial provision for short-term missions. For long-term mission personal spaces, screened for privacy are the minimum requirement (NASA, 2007) (b) Joint dinners require space to accommodate all crewmembers. (NASA)

2. Design for All: Social Practices

When we design extraterrestrial environments, we don't design for an individual or a group of individuals. Astronauts are drawn from a large pool of professionals coming from different countries. It is a design challenge to design a universal space that fits many different personalities for many reasons. One is that social behavior, norms and rituals are very diverse in human societies. Moreover, most of our rituals and norms are expressed through our social and also spatial behaviors. Figure 5a just shows one example for a ritual that demands certain spatial conditions. It is also a reminder that everyday rituals can differ a lot within the range of astronaut personnel. As such an optimal habitat shall be able to reflect a wide range of individual and cultural rituals.

For example, on Skylab, astronauts had, for the first time, a large, dedicated area for food preparation and dining together on a specially designed table (Figure 5b). This enabled more 'normal' (Earth-like) group meals using knives, forks and spoons. From that point on, a table for having meals together has been considered vital by the crew and, eventually, became a requirement for subsequent habitats. Although mission task scheduling frequently makes it difficult to have dinner together, there is a wide agreement of its importance when possible for the crew. Eating daily main meal(s) in a group is a nearly universal behavior and common social practice. In all cultures, there is typically at least one main meal a day, with different etiquette and social rules attached to each mealtime. These group meals are not only related to nutrition intake, but also reflect norms and rituals of a society. They serve as powerful, oftentimes, unconscious and unrecognized influences on expectations and behavior. Astronauts are no exception to being influenced by their personal social norms. For example, on Skylab missions, observers noted that the crewmembers refused to travel over the table as they passed through the wardroom when traversing from one side of the module to the other (see also Fig 4b). When asked why they made the detour around the table, they confessed that they hadn't even realized they were avoiding using the space above the table for travel but it just didn't seem 'right' to be passing their bodies over the area where they ate.

Many of our social expectations are unconscious and unrecognized. Those not only represent demands on our habitats but pose opportunities for social discord and conflict when not shared by all. We must plan for and incorporate ways to accommodate varying norms since they will be present and operable as inherent needs of the humans that will be living in the spaces built.

Figure 5. (a) Dr. Sheikh Muszaphar Shukor Praying in outer space (from "Muslim in Space" DVD). https://www.youtube.com/watch?v=8rVpxyx8z3g. (b) Skylab crew's dining table. (Image credit: NASA)

B. Reduction of Habitability Stress by Design

As it became undeniable that many ICE psychosocial stressors can and did lead to degraded performance, the contribution of impoverished habitability went through a similar cycle of tacit recognition and similar disregard. As early as 1985, commonly reported habitat related experiences were "problems associated with interior space, food, hygiene, temperature, decor, odor, and noise".[5 p60] In 2004, M. Dudley-Rowley, M. M. Cohen and P. Flores conducted a comparison of a 1985 NASA space station crew safety study with the safety record on Mir (operational between 1986–1996).[33] Their findings highlighted the relationship between stressors and the architecture of the habitat and identified examples of stressors, their effects, as well as suitable architectural and design countermeasures. The overlap between negative outcomes from psychosocial stressors and those related to poor habitability argued strongly for treating these as interactive factors. Like many examples on Earth, appropriate and careful design can help reduce stress of the inhabitants. Extraterrestrial habitats need a least the same attention to combine form, function and appearance to mitigate against the stresses of ICE environments and provide for maximal adaptation. Several approaches to specific issues are illustrated below.

1. Pushing the Boundaries Outward

One factor leading to increased stress is the limitation of actual physical living space. This is, perhaps, the most recognized characteristic of all closed loop habitats. Combined with isolation, it leads to feelings of confinement and associated feelings of claustrophobia, lack of privacy and lack of motivation. Yet confinement is not simply a result of square meters per person. The psychological experience of too little (perceived) volume, behavioral constraints associated with a particular volume or too much chaos leads to feelings of 'crowdedness', a term used in Environmental Psychology and related to a number of behavioral, perceptual and psychosocial impacts from both the individual as well as cultural perspective.

Given the high resource demands to physically add to volume, employment of methodologies to expand the *experience* of existing volume must be actively incorporated into all designs. For instance, use of configurations that avoid narrow spaces which are often perceived to be unpleasant and cramped and the use of larger open spaces or those with proper isovist characteristics will foster perceptions of spaciousness. Utilizing multiple compartments provides opportunities to create environmental variety and segregated activities. Architecturally, use of long views can be incorporated inside the habitat as well (Figure 6a and b).

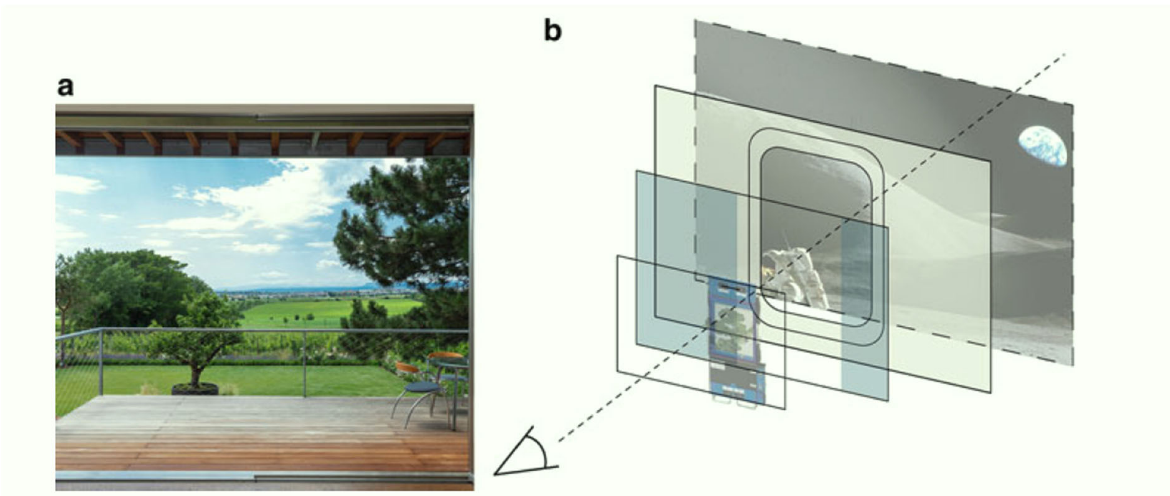

Figure 6. (a) Borrowing the view. House and garden designed to 'borrow the view' of the neighboring vineyard, as such the vision is prolonged and the whole plot looks larger and spacious (Credit: space-craft Architektur, Ernst Kainerstorfer). (b) Sightline Design, Principle illustrating the incorporation of a distant and natural vista into the composition of a natureless technical interior.[34, 35]

Spaciousness is also generated through paths that offer alternatives to travel to the same destination, supporting individual choice, alternatives to use different routes, increasing occasions to expand social distance and privacy as well as opportunities for greater interpersonal interaction. The 1985 Human Spatial Habitability (HuSH) model developed by James Wise and his students at the University of Washington shows how occupant movement, visual, and social practices relating to sense and use of space can be combined into a single quantitative framework for habitability design. As they concluded, "*It's not how large you make it, it's how you make it large*."

Supportive use of color and lighting can be employed to reduce feelings of crowding and promote physiological synchronization with sleep/wake cycles. Windows and window analogues have long been recognized as effective architectural elements conveying psychological as well as functional benefits in ICEs and space habitats.[36] Windows, digital displays or art can be used to counter feelings of monotony and confinement by providing visual depth.

The design and integration of windows is a good example of the interrelated system aspects of habitability. They combine the aspects of the mission related requirements with the environmental constraints and human behaviour issues. Since the famous discussion on the inclusion of the window between the designer Raymond Loewy and NASA associate administrator for Manned Space Flight George Mueller, the incorporation of windows has long been recognized as desirable. We would argue that the psychological and physiological benefits windows provide make them a habitability necessity. It has become widely acknowledged, that 'window gazing' is the number one leisure activity for space crews, and that astronauts and cosmonauts spend a lot of time in front of windows looking at the Earth. While we cannot argue that the placement of a window is a pure engineering requirement, we have ample evidence that windows (or their surrogates) serve critical functions for human psychological health and well-being.

However, recognizing that a need exists and providing effective solutions for that need has generated numerous challenges for space designers. It is not enough to simply ADD an architectural element; consideration of how that element will be used is critical. Human behavior must be integrated into the design. For example, Skylab astronaut Gerald Carr stated in 1974, that "*if something is going to stick out and make a nice handhold, it's going to be used for a handhold*".[37] True to his prediction, thirty years later, in 2004, a poorly designed flexible air hose began leaking air on the International Space Station. The hose was located in the Destiny science module, close to an optical window for earth observation. Due to a lack of appropriate handholds, the astronauts repeatedly held onto the air hose when looking out of the window. This unplanned practice finally resulted in a leaky hose, through which internal air left the station. This is a wonderful example of the gap between engineering functionalism (what is needed, where and when) and human behavior (what will people do with it and how is it going to be used). We must deal with the fact that people (the so called 'wetware'), do not always follow use specifications. Rather than planning on the human user to follow engineering use directives, designers should be designing for how humans will naturally tend to use engineering systems.

Of course, space provides unique new issues surrounding human behavior and windows. We have yet to deal with external views that may lack depth cues or do not provide changing vistas (e.g., a star field), or whose presence may pose a health risk (e.g., higher radiation exposure on the Moon). In such cases, the substitution of virtual 'external' displays may be necessary or even the better solution. The addition of external views to look out 'at another world', whether actual physical windows or digital 'ports' displaying real-time actuality or augmented reality will be a psychological benefit for the crew. Surrogates for windows where the inclusion of windows to the outside is limited (e.g., Lunar facilities covered in regolith) should also be utilized. For instance, plant growth facilities and integrative greenhouse designs could be used, to an extent, as an interior view, or to make up for a lack of visual complexity obtained from windows. In this case the design integration of the activity of 'looking in and looking out' provides a variety of sightlines within a compact and limited habitat. By design, available space can be psychologically increased through sightline design and relations between the different interior functions (Figure 7).

2. Bringing Nature with Us: Greenhouse Design Integration

Aside from the obvious nutritional and life support system applications, there may be additional compelling reasons to ensure the inclusion and integration of green spaces into extraterrestrial habitats. Abiding by the Golden Rule for Space Architecture to provide for multiple uses and applications of all spaces, the inclusion of plants into extraterrestrial habitat design can provide critical noninvasive, passive countermeasures for the deleterious effects of confinement and monotony through sensory and spatial enhancement of the otherwise technical and monotonous space environment.[38] Natural settings have been demonstrated to produce restorative or rest directed attention[39] as proposed by attention restoration theory.[40] Ulrich's psychoevolutionary framework proposed that the restoration from natural environments is a product of much more than attentional capacities,[14, 41, 42] being grounded in stress *prevention* that came from the beneficial associations with perceptually benign, non-threatening and supportive environments. However, not only is greenery restorative but a convergence of several lines of research has produced compelling evidence that we have been evolutionarily primed for optimal cognitive functioning in environments of particular botanical complexity through the *fractal* characteristics of environmental patterns that surround us.[43] This neural efficiency has been demonstrated to produce improvements in cognitive performance.[44, 45] The prospect of countering the ennui, loss of motivation and subsequent detriments to performance in a highly dependent technological environment through the inclusion of natural characteristics represents an exciting opportunity. ***In a real sense, Earth abides in all humans as an evolutionary derived template for effective functioning. This means that we must provide for those critical terrestrial linkages in our built environments in space, even though the original environments cannot be reproduced as such.***

Bringing our own greenery can also address the monotony and boredom that are inescapable outcomes from the confinement and over-familiarity of ICE environments. Outside the space exploration field, there is ample thought on the inclusion of natural properties in building and interior design as a strategy for psychological and sensory integration.[46] The complex properties of nature have been shown to be psychologically restorative in a myriad of studies due to its infinite variability, evolutionary association with beneficial resources, and associations with relaxation and stress reduction activities (Figure 8a). Many studies have shown that "natural contents and, in particular, landscape configurations" have positive effects on human functioning, representing sources of desirable visual complexity rather than undesirable visual crowdedness.[47] The time-based qualities of plants (i.e., change through growth) and their distinct color range make them a sensorially stimulating addition to the environment inside the spacecraft. The theory of 'Biophilia' or the urge to affiliate with other forms of life, applied to interior environmental qualities argues that this drive is as old as the human species' relationship to the natural environment that nurtured our evolution (Figure 8b).

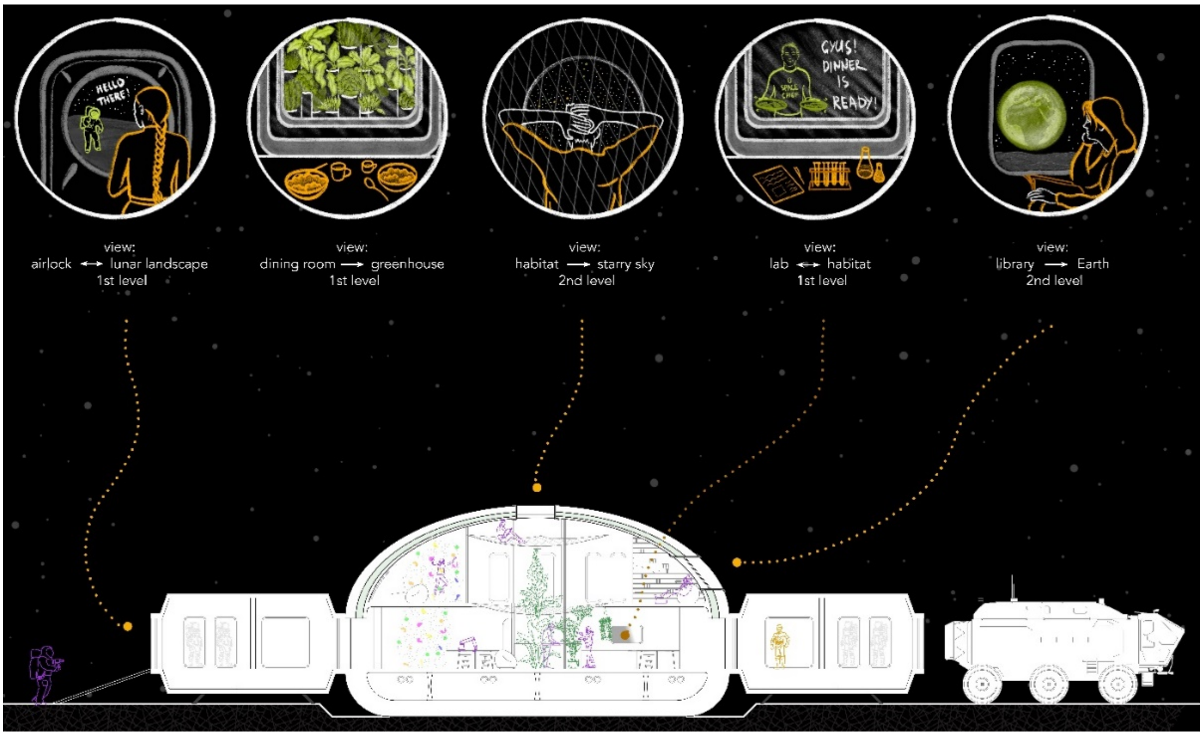

Figure 7. Diagrammatic section showing visual connections within a lunar habitat. From left to right: View from the airlock out to the lunar landscape, from the dining area to the technical greenhouse, from the habitation area to the stars, from the laboratory to the social area of the habitat, from the library to Earth. (From the design studio Lunar Oasis 2021 (TU WIEN & ADU), project by Team Lunarshell: Flora Münzer, Sara El Masri, Iman Al Husseini, Rawan Al Solh, Manal Hamdan, Fardous Al Akrabi)

Figure 8. (a) Integrated greenhouse design. As a 'window to something living', an integrated greenhouse can provide this surrogate view in all mission scenarios where the inclusion of windows or the view outside is limited: (1) Physical real-time interaction with plants, (2) visual integration into interior, (3) individual plant systems, and (4) virtual window integration (Credit: space-craft Architektur). (b) Expedition 5 Cosmonaut Victor Savinykh with 'his' plants on board Salyut 6, 1977 (Credit: TASS, courtesy of Victor Savinykh).

VI. Summary

The Golden Rule of Space Architecture succinctly summarizes the realities of designing for living off-Earth. We will only have what we bring, what we can create from what we bring or find in-situ. What we can bring is severely limited given the constraints of vehicle capacity and engineering capability. Therefore, we must maximize everything that is makes the selection cut as 'necessary'. Deciding what is truly necessary must go beyond mere survivability and include those psychosocial elements needed for human health and well-being. Substitutes or surrogates for various factors need to be thoughtfully planned. If we don't have natural elements like blue skies and greenery, what can we substitute for those features? If we don't have long views providing depth perception when looking at star fields, what would be a viable technological alternative or substitute? The answers to these questions lie in the close examination of needs versus resources and our technological capabilities to find alternatives. In all circumstances, the limitations of extraterrestrial environments enforced by the dependency on closed loop environmental systems will continually reinforce adherence to the golden rule of space architecture. As shown by the examples in Table 1, there are myriad approaches to effective countermeasures. How these are enacted under the strictures of the constraints of extraterrestrial environmental demands will depend on how creative we can be in maximizing what we bring.

Table 1a Examples of Effective Countermeasure Design Considerations - Enhancing Performance

Goal of the (counter) measure: **ENHANCING PERFORMANCE**		
Problem	Means to achieve the goal	Examples of enactment through habitability
Artificial and inadequate lighting can lead to fatigue, irritability, inattention and blurred vision. A potential safety hazard is mistaken perception. Monotony and boredom results in inattention, loss of motivation, disengagement, tension and conflict.	Appropriate lighting design can counteract degraded performance. Use of lighting to enhance attention and cognitive processing. Provision for independent exploration, research and personal work. Provision of equipment used for operational as well as personal provisions. Multi-functional spaces provide needed change in stimuli, adaptable spaces, variety and utility.	Use of color and lighting to regulate mood and attention Adequate resources reduce conflict and provide opportunities for independent work, e.g., telescopes, cameras, rovers, drones, etc. available for surface exploration. 3-D printers could produce machine parts, tools, craft pieces as well as personal clothing or items. Greenhouse provides restoration, fresh produce, raw materials for crafts and

		production processes (e.g., 3-D printers), maintenance of atmospheric elements (CO2 removal, 0^2 contribution). Exercise spaces can also be used for crafting spaces or combined with storage spaces such that available volume increases as supplies are used.

Table 1b Examples of Effective Countermeasure Design Considerations – Enhancing psychological functioning

Goal of the (counter) measure: **ENHANCING PSYCHOLOGICAL FUNCTIONING**		
Problem	Means to achieve the goal	Examples of enactment through habitability
Constant confinement and isolation as well as the decrease of privacy can lead to feelings of claustrophobia, loneliness and impaired judgment. Over-familiarity and lack of variety in stimulation leads to boredom, ennui, depression, alienation and loss of motivation. Lack of exposure to natural elements and fractals undermines efficient cognitive processing and produces stress.	Flexible interior configurations allow for social group activities and change in an environment characterized by monotony and overfamiliarity. Modular sections can be differently themed to provide environmental variety. Multiple pathing to destinations provides variety of movement and social regulation. Use of color and lighting to regulate mood and attention. Incorporation of biofractal/ natural elements to support restoration, effective cognitive processing and stress reduction.	Adaptable spaces that can be repurposed easily for situational needs. External views to habitat exteriors provide visual expansion of interior space. Use of configurations that are perceived as more spacious and/or provide visual depth (e.g., long corridors, windows, external views. Exposure to growing plants provide restoration and connection to terrestrial evolutionary needs (Earth abides). Bring our own green-multipurpose greenhouses.
	Robotic Pets	Fulfills affiliative needs, facilitates shared ties with crewmembers, can assist in robotic exploration.
	Communication and monitoring technologies/modalities independent of real-time information exchanges.	Use of computer games and virtual/ augmented reality to facilitate 'external' relationships. Provide for alternative experiences, challenges, environments and training to maintain or gain skill sets. Use of AI support and monitoring systems for personal psychological and physical health and well-being. Varied communication protocols with family & friends, colleagues and Mission Control back on Earth.

Table 1c Examples of Effective Countermeasure Design Considerations – Enhancing social cohesion

Goal of the (counter) measure: **ENHANCING SOCIAL COHESION**		
Problem	Means to achieve the goal	Examples of enactment through habitability
The withdrawal from the normal social matrix and dependence on a small community can lead to depressed mood, social withdrawal or group splintering.	Aim is to counteract the negative effects of isolated, confined environments.	Appropriate habitat layout can facilitate social interaction (e.g., events, group gatherings, shared activities). Can provide for private interactions (e.g., communications with family and friends, small groups/dyads). Multiple paths offer options for control over social encounters. Provision of private spaces whether permanent (e.g., bedrooms) or situationally created for specific circumstances, enhances control over social interaction. Greenhouse access enhances opportunities for hand-made, unprogrammed meals and opportunities for personal cooking skills and sharing of cultural or personal specialties. Participation in food production represents a group-oriented contribution.

One undeniable characteristic of humans is that they WILL apply creativity to problem-solving. We demonstrated this throughout humankind's evolutionary history. It's the single most decisive reason for sending humans for exploration rather than robotics. In situations where you cannot possibly foresee all the unknowns, you need the creative flexibility of human imagination to fill in the gaps between what you have and what you need. Designing for extraterrestrial habitats means the focus should be on malleability, flexibility and technology to enable residents to create what they need from what they have. It is the challenge to consider the human in a particular environment that has yet to be characterized or experienced.

References

[1]Parsons, H.M. (1996) Engineering Psychology. In: Raymond J. Corsini, and Alan J. Auerbach, (Eds), *Concise Encyclopedia of Psychology* (pp 300-303). 2nd Ed. New York: John Wiley &Sons.

[2]Loftus Jr., J.P. (1984). *An Historical Review of NASA Manned Spacecraft Crew Stations*. In: G. P. Carr, & M.D. Montemerlo, (Eds.) *Aerospace Crew Station Design* (pp. 3- 22).

[3]Harrison, A.A. (2001). *Spacefaring: The Human Dimension*. Berkeley, CA: University of California Press.

[4]Bell, S. T., Brown, S. G., & Mitchell, T. (2019). What we know about team dynamics for long distance space missions: A systematic review of analog research. Frontiers in Psychology, 10, 811.

[5]Connors, M., Harrison, A.A. & Akins, F.R. (1985). *Living Aloft: Human Requirements for Extended Spaceflight.* Mountain View, CA: NASA Ames Research Center.

[6]NASA (1989). *NASA Lunar Architecture. Report of the 90-Day Study on Human Exploration of the Moon and Mars*. NASA-TM-102999. Washington, D.C.: NASA.

[7]Williams, R.S. & Davis, J.R. (2005). A critical strategy: Ensuring behavioral health during extended-duration space missions. *Aviation, Space and Environmental Medicine*, 76, B1-2.

[8] Kanas, N., Manzey, D. (2008). *Space Psychology and Psychiatry*, 2nd Edition, Microcosm Press, El Segundo, California, and Springer, Dordrecht, The Netherlands.

[9]NASA [Risk]. (2013). *Evidence Report: Risk of Incompatible Vehicle / Habitat Design*, Human Research Program, Space Human Factors and Habitability Element, National Aeronautics and Space Administration, Houston, Texas.

[10]Whitmore, M., Adolf, J.A. & Woolford, B.J. (2000). Habitability Research Priorities for the International Space Station and Beyond, *Aviation, Space and Environmental Medicine*. 71(9) Section II, 122-125.

[11]Fiedler, E.R. & Harrison, A.A. (2010). Psychosocial Adaptation to a Mars Mission. *Journal of Cosmology*, 12, 3685-3693.

[12]Häuplik-Meusburger, S. (2011). Architecture for Astronauts: An Activity-based Approach. Springer Science & Business Media.

[13]Häuplik-Meusburger S. & Bishop S. (2021). Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and In Space. Space and Society Series, Douglas A. Vakoch (Ed). Springer Nature: Switzerland. 250 pages.

[14]Parsons, R. (1991). The potential influences of environmental perception on human health. *Journal of Environmental Psychology, 11,* 1–23.

[15]Peacock B., Novak-Blume J. & Vallance S. (2002). An Index of Habitability. Proceedings of the 32nd International Conference on Environmental Systems, San Antonio, Texas, USA, July 15-18, 2002.

[16]Fraser, T. M. (1968). The intangibles of habitability during long duration space missions. Retrieved May 18, 2020, from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19680017230.pdf.

[17]Celentano, J., Amorelli, D., & Freeman, G. (1963). Establishing a habitability index for space stations and planetary bases. Retrieved May 18, 2020, from https://arc.aiaa.org/doi/abs/10.2514/6.1963-139.

[18]Collet J. & Novara M. (1992). Global approach to simulation: A gateway to long-term human presence in space. Advances in Space Research, Volume 12, Issue 1, p. 285-299.

[19]Kanas N., & Manzey D. (2003). Space psychology and psychiatry. Dordrecht: Springer/Microcosm Press.

[20]Ulrich R.S. (1953) Aesthetic and affective response to natural environment. In I. Altman & J. F. Wohlwill (Eds.), *Human behavior and the environment: Volume 6* (pp. 85–125). New York: Plenum Press.

[21]Hietanen, J. K., & Korpela, K. M. (2004). Do both negative and positive environmental scenes elicit rapid affective processing? Environment and Behavior, 36(4), 558–577.

[22]Korpela, K. M., Klemettila, T., & Hietanen, J. K. (2002). Evidence for rapid affective evaluation of environmental scenes. Environment and Behavior, 34(5), 634–650.

[23]Kaplan, S. (1987). Aesthetics, affect and cognition. Environment and Behavior, 19(1), 3–32.

[24]Kaplan, S. (1988). Perception and landscape: Conceptions and misconceptions. In J. Nasar (Ed.), Environmental aesthetics: Theory, research, and applications (pp. 45–55). Cambridge: Cambridge University Press.

[25]Häuplik-Meusburger, S. (2010). My home is my spaceship – An investigation of extra-terrestrial architecture from a human perspective. In 40th International Conference on Environmental Systems. AIAA 2010-6021.

[26] Craven, J. (2019). The meaning of 'form follows function'. ThoughtCo. Retrieved August 15, 2020, from https://www.thoughtco.com/form-follows-function-177237

[27]Wise J. (1985) The Quantitative Modelling of Human Spatial Habitability. NASA Contractor Report No. NAG 2-346. December. The University of Washington, Seattle, Wash.

[28]Neutra, R. (1954) Survival Through Design, Oxford University Press, NY

[29]Burrough, B. (1999). Dragonfly: NASA and the crisis aboard Mir. London: Fourth Estate.

[30]Kanas N., & Feddersen W. E. (1971). Behavioral, psychiatric, and sociological problems of long duration space missions. NASA TM 58067. Houston, TX: NASA Johnson Space Center.

[31]Kanas N., Sandal G., Boyd J. E., Gushin V. I., Manzey D., North R., Leon G. R., Suedfeld P., Bishop S., Fiedler E. R., Inoue N., Johannes B., Kealey D. J., Kraft N., Matsuzaki I., Musson D., Palinkas L. A., Salnitskiy V. P., Sipes, W. Stuster, J. & Wang J. (2009). Psychology and culture during long-duration space missions. Acta Astronautica, 64(7–8), 659–677.

[32]Sandal, G. (2002). Individual and group adaptation in space: Evidence from analogue environments. In Proceedings of life in space for life on earth, 8th European symposium on life sciences research in space, 23rd annual international gravitational physiology meeting, Karolinska Institute, Stockholm, Sweden, 2–7 June, 2002.

[33]Dudley-Rowley, M., Cohen, M. M., & Flores, P. (2004). 1985 NASA-Rockwell Space Station crew safety study: Results from Mir. Aviakosmicheskaia i Ekologicheskaia Meditsina, 38(1), 15–28.

[34]Häuplik-Meusburger, S., Aguzzi, M., & Peldszus, R. (2010a). A game for space. Acta Astronautica, 66(3–4), 605–609.

[35]Häuplik-Meusburger, S., Peldszus, R., & Holzgethan, V. (2010b). Greenhouse design integration benefits for extended spaceflight. Acta Astronautica, 68(1–2), 85–90.

[36]Al-Sahhaf, N. A. (1987). Contributions of windows and Isovists to the judged spaciousness of simulated crew cabins. Thesis for the Master of Science in Engineering, University of Washington.

[37]NASA [Bull.1] (1974). Skylab Experience Bulletin No.1: Translation Modes and Bump Protection. Houston, Texas: NASA, Lyndon B. Johnson Space Center, 1974. JSC-09535.

[38]Häuplik-Meusburger, S. (2014). Astronauts orbiting on their stomachs: The needs to design for the consumption and production of food in space. Architectural Design, 84(6), 114–117.

[39]Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., & Garling, T. (2003). Tracking restoration in natural and urban field settings. Journal of Environmental Psychology, 23(2), 109–123.

[40]Kaplan, R., & Kaplan, S. (1989). The experience of nature: A psychological perspective. Cambridge: Cambridge University Press.

[41]Ulrich, R.S. (1993) Biophilia, Biophobia, & Natural Landscapes. In: Kellert, S.R. and Wilson, E.O., Eds., The Biophilia Hypothesis, Island Press, Washington DC, 73-137.

[42]Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

[43]Purcell, T., Peron, E., & Berto, R. (2001). Why do preferences differ between scene types? Environment and Behavior, 33(1), 93–106.

[44]Wise, J. A., & Rosenberg, E. (1986). The effects of interior treatments on performance stress in three types of mental tasks. Technical Report, Space Human Factors Office, NASA-ARC, Sunnyvale, CA.

[45]Wise, J. A., & Taylor, R. P. (2002). Fractal design strategies for enhancement of knowledge work environments. Paper presented to the human factors and ergonomics society meeting, Baltimore MD, October 2002.

[46]Kellert, S., Heerwagen, J., & Mador, M. (Eds.). (2008). Biophilic design: The theory, science, and practice of bringing buildings to life. Hoboken, NJ: Wiley.

[47]Joye, Y. (2007). Architectural lessons from environmental psychology: The case of Biophilic architecture. Review of General Psychology, 11(4), 305–328.