Bionomic Design Countermeasures for Enhancing Cognitive and Psychological Functioning and Crew Performance in Isolated and Confined Habitats

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In the context of biomedical risk reduction and mitigation in future deep space missions, the need for effective behavioural and performance inflight support has been recognized as critical by psychologists, designers and mission planners alike. Research has shown that fractal structures of the natural environment ('bionomic') in the 1.3 – 1.5 dimensional range may enable the most effective linkages between cognitive and emotional processes and settings. Growing evidence strongly suggests that incorporation of these fractal dimensions into the design of habitat interiors (bionomic design) may assist the emotional, cognitive and perceptual processes associated with flexible, creative thought, stress reduction and personal emotional management. A discussion of the supporting evidence, study design, implementation requirements, measurement and application will be the focus of this presentation. Bionomic interior design elements can possibly serve as effective passive countermeasures to isolation and confinement stress as well as serve as a natural enhancement for performance and psychological functioning. Opportunities to collect efficacy data on the impact of bionomic interior design elements are proposed for multiple analog environments, e.g., Antarctica, NEEMO, HERA, MDRS, HiSEAS. Significance: The ability to bring nature into closed loop, artificial habitats is difficult. The possibility that critical features from such environments can be extracted and implemented in the form of textures, lighting, murals, decorative patterns, or colors, to support performance, cognition and psychological well-being represents an exciting efficient and effective passive countermeasure with little dependence on crew compliance. The development of portable design elements, e.g., murals, will enable testing in various analogs to validate their effectiveness across different settings characterized by intense demands for cognitive functioning in austere environments.

I. Introduction

In the context of biomedical risk reduction and mitigation in future deep space missions, the need for behavioral and performance inflight support infrastructure, particularly through meaningful habitat systems, has been recognized as critical by psychologists, designers and mission planners.[1-4] Yet, the area has received little systematic

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research attention so far,[5,6] and concrete habitability design interventions for in-flight support have changed little even with the advent of missions that have increased in duration in low earth orbit. In operations and design, habitability refers to the 'general acceptability of the environment to the user',[7] and aims to "promote optimal performance, physical and psychological health, and safety in long duration spaceflight."[8] The emphasis on *promotion* of positive effect through habitat design has recently intersected with a branch of ecology called bionomics which concerns 'the study of the mode of life of organisms in their natural habitat and their adaptations to those surroundings.'[9] Ecology, itself, is a branch of biology dealing with relationships and interactions between organisms and their environment.[10] This intersection between habitat design and bionomics has coalesced around a number of, heretofore, seemingly disparate findings as 'bionomic design'.

Growing evidence strongly suggests that habitat interiors might be expressly designed to assist innate natural emotional, cognitive and perceptual processes associated with flexible, creative thought, stress reduction and personal emotional management. Just as basic 'ergonomic design' directly supports physical functional performance, there appear to be pattern, color, texture and spatial characteristics of habitat interiors that facilitate more efficient cognitive functioning and performance as well as promoting stress reduction. The standard of design practice for operational environments has been towards minimalistic, patternless interiors where 'form follows function'. The argument is that such environments are not those in which we have evolved to perform at our mental best. The 'risk of incompatible vehicle or habitat design' has been identified by NASA as a recognized risk to human health and performance in space.[11, p 3] Therefore, the aim for the future in habitat design is to move from mere surviving and coping to thriving.

II. Habitability Design as Countermeasure for Human Behavior and Performance Decrements

A. Poor Environments as Stresssors

Historically, architecture and design in operational environments have been oriented to supporting physical functional performance of human activities. Yet, identified stressors by inhabitants of confined environments not only include problems with food, hygiene, temperature, odor, noise, but lighting, décor and interior space as well.[1] This is of interest in the deep space setting, as it suggests that the general reduction of situational stimuli (especially external cues) may not be as challenging as the monotony inside the vehicle environment itself. Suedfeld and Steel[12] put forward a threefold matrix whereby psycho-environmental, social and temporal factors determined well-being in capsule habitats. As Schultz[13] points out, it is not only the input of stimulus, but also its meaningfulness and quality that elicit an effect. Thus, sensory stimulation and environmental cues are vital to the satisfaction of basic human needs.

The main drivers for designing spacecraft interiors evolved from a primary focus with survivability to automation supervision,[15] followed by a 'humanization' of space hardware through designers, architects and psychologists in the advent of long duration missions in the 1970s.[16] More recently, habitability has been envisioned as a viable contributor to both active and passive countermeasures for certain stressors. Particularly for long duration, deep space mission scenarios, the aim is to reduce the stress of the mission through internal architecture and systems design.[17]

Areas where design has already been employed as a countermeasure include:

- Enhancing performance
  - E.g., inadequate lighting can lead to fatigue, irritability, and blurred vision. Appropriate lighting design can counteract degraded performance.
- Enhancing psychological functioning
  - E.g., confinement and isolation can lead to feelings of claustrophobia, lack of privacy, and lack of motivation. Flexible interior configurations allow for the introduction of novelty and change in an environment characterized by monotony and over-familiarity.
- Enhancing social cohesion
  - E.g., appropriate habitat layout can facilitate social interaction (e.g., events, group gatherings, and shared activities) and as well as provide for private interactions (e.g., communications with family and friends, small groups/dyads) which can counteract the negative effects of isolated, confined environments.
- Reducing stress
  - E.g., External views provide visual expansion of interior space, countering feelings of confinement.

B. The Habitability Design Challenge of Technical Environments

In extreme isolated and confined environments or ICEs (in space or on Earth) technology must substitute artificial aspects for many of Earth's natural conditions: breathable atmosphere, shirt-sleeve environments, artificial day/night cycles, processed foods, etc. The bionomic viewpoint would argue that these substitutions may not be equitable alternates for the entirety of conditions that they seek to mimic. Vladimir Gushin, a psychologist at Russia's Institute for Biomedical Problems stated in an interview, "Confinement on the space station isn't the problem, it's a lack of stimuli."[18] The interior of technical environments (or environments strongly depending upon technology, such as space vehicles or research stations in space) are often described as aesthetically neutral and functional, 'cold' in terms of the use of colors and, at the same time, visually crowded (stimulus overload). As the system life cycle of technological environments progresses, these minimal interiors (which are not really minimal, in fact) become totally cluttered, thus exacerbating the existing negative effects of impoverished habitability with visual crowdedness. Crowdedness is a term often used in Environmental Psychology and related to a number of behavioral, perceptual and psychosocial impacts. For instance, stimulus overload produced by visual crowdedness can lead to behavioral constraints, such as the inability to handle information and further contributes to stress and anxiety.[19, p 245]

At the intersection of systems design and the behavioral sciences, a study on habitability design interventions as countermeasures to monotony[20] recently used a model on information overload by Klapp.[21] Klapp proposed a matrix with two axes (variety-redundancy and meaning-entropy) and four quadrants. These are made up of *good redundancy* on the quadrant meaning-redundancy; *good variety* on the quadrant meaning-variety*; boring redundancy* on the quadrant entropy-redundancy; and *boring variety* on the quadrant entropy-variety. Klapp's interpretative model of how boredom arises may also hold the key to effective countermeasures in an extreme operational context, e.g. deployed military settings.[22] Too much 'boring redundancy' (banality, tedium, monotony, restriction, formalism) is disadvantageous. However, 'good redundancy' (codes, customs, rituals, traditions, tinkering, continuity, resonance, and 'social placebo' activities such as watching sports) mitigates boredom as much as 'good variety' derived from discovery, adaptation, invention, games of chance or bantering. Therefore, the nominal operational environment should strive for features found in these two quadrants. The challenge is how to accomplish that goal. One key approach to creating such beneficial features could be in appropriating natural design elements for interior habitat environments according to bionomic principles.

C. Nature as a Countermeasure to ICE Stressors

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.[23] The complex properties of nature are psychologically restorative. This is manifested by a tradition of building with and around nature from architects such as Richard Neutra, Mies van der Rohe and Frank Lloyd Wright who sought to reduce the threshold to the outside, or integrate both domains, especially through the careful configuration of windows or entries. Neutra's work on simply allowing exterior nature to penetrate some of a building's interior has been highlighted as one approach to biophilic (sometimes termed "biomimetic") human factors design.[24]

Other directions employed are the instilling of surprise, harmony and complexity. 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.[25] The key distinction in the latter is that complexity is different than 'complicatedness' or the aforementioned visual crowdedness. Complexity is what Klapp[21] might count as 'good variety', whereas complicatedness is information overload, sensorial or organizationally. Natural complexity is made up of abundance, variety, dynamics, growth and change, and, by definition, is embedded in the very relationships that bionomics and ecology have identified. These have a positive impact on our sensory system and challenge the intellect – whereas the complicated system, from the technical equipment to complicated procedures and visually cluttered environments, leads to frustration, and ultimately monotony. The cost of diverting attention from one stimulus to the next, for instance in a visually cluttered interior, can be substantial.[26] The difference between visually crowded and visually complex can be illustrated by the two examples below (see Figure 1).

Persistent astronaut reports underscore the importance of plants and living beings during their missions.[27] Astronaut Jeff Williams stated, that "*You can never tire of looking at the part of God's creation we call Earth. Travelling around the globe every 90 minutes provides lots of opportunity to view the geography, oceans, cloud formations, sunrises and sunsets, thunderstorms, city lights and many other things in vivid detail.*"[28] However, this resource will not be available for deep space crews where the receding visage of Earth will be replaced with dimensionless depths of space for long periods of time. Any positive stimulation must be inherent in the artificial environment crews bring with them.

To overcome the restriction and loss of natural stimuli, cosmonauts and astronauts have been creating their own (cf. Häuplik-Meusburger).[27] 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. During the Salyut missions (1971-82) cosmonauts experimented with plants and "designed" their own little greenhouse. After having recognized the psychological benefits of plants, the Soviets even designed a device "for the sole purpose of ornamental plant culture to provide psychological comfort to the cosmonauts in the station."[29]

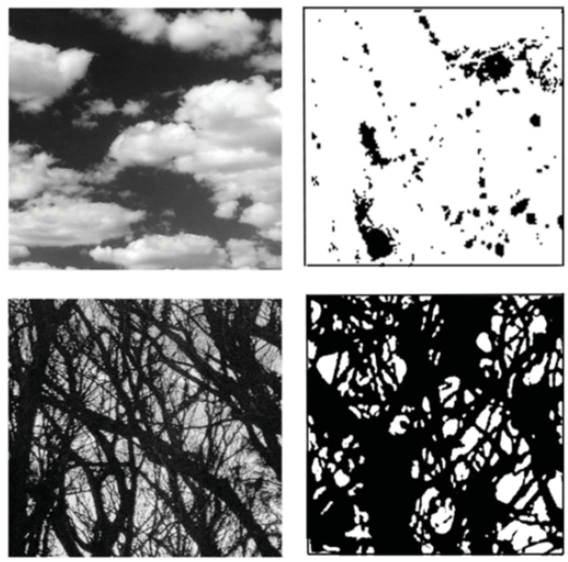
visually crowded	vs visual complexity
 appears: overloaded, unclear, difficult to orientate http://spaceref.com/international-spacestation/inside-columbus.html	 appears: geometrically complex, basic, natural and organic Figure 2: from Taylor et al, 2005, pg 93: Examples of natural scenery (left column) and drip paintings (right column). Top: Clouds and Pollock's painting *Untitled* (1945) are fractal patterns with *D* = 1.3 and 1.10 respectively. Bottom: A forest and Pollock's painting *Untitled* (1950) are fractal patterns with *D* = 1.89. (Photographs by R.P. Taylor).

Figure 1. Illustrating visual crowdedness versus visual complexity.

In the absence of real plants, astronauts and inhabitants of ICEs, including simulation environments, have put up images of landscapes and natural environments. The architect Kalil's conceptual interior configuration study[30] explored novel nature-inspired interior configurations. The notion of 'aesthetics as a function' later proposed by Clearwater and Coss[31] echoed the space architect Galina Balashova's earlier work on inclusion of natural scenes in Soviet long duration missions.[32]

III. Intervening Through Interior-Design-Based Countermeasures

A. Interior Design to Support Psychological Habitability

As built environments grow larger and more complex,[33] they often strive to become more and more 'Earth-like',[34, p 353] or indeed look for further or advanced design paradigms (i.e., beyond simply recreating Earth-like settings, both naturally and culturally).[35] Roger Ulrich's[36] psychoevolutionary framework proposes that affective responses towards environmental features are not just the result of deliberative cognitive information processing as proposed by Kaplan and Kaplan.[37] Instead those responses are, rather, rapid, automatic, and unconscious adaptive perceptual processing rooted in human evolutionary history in which different environments are immediately liked or disliked in order to facilitate responses that contribute to well-being and survival.

Studies demonstrating these rapid, immediate, and automatic affective responses to various environments[38,39] support psychoevolutionary models proposing that these emotional reactions saved precious time and energy spent learning which environments were beneficial or harmful.[36, 40, 41] Similar work in environmental psychology has also linked various qualities of natural environments to evolutionary beneficial characteristics contributing to survival and well-being. These preferences have been proposed to underlie the persistent incorporation of natural elements, either real or stylistically rendered, into built environment since the earliest human civilization.

In considerable disparate research, positive effects on cognitive performance, group dynamics, work stress, employee job satisfaction, employee productivity, recovery from surgery, and even reduced criminal recidivism have been linked to design elements that analogously or literally recreate environmental features and qualities of savannah environments where the human species evolved.[24,42-44] These bionomically valid elements are proposed to underlie the bases for many 'green building benefits' that have been widely reported in workplaces, and for genuine habitability improvements across different isolated and confined environments. Similarly, Parsons[14] argues that unrecognized negative stress reactions are genereated by post-modern built environments and could have important health effects.

Insight into the underlying mechanism for these differential affective responses to various environments, both positive and negative, has emerged from recent work linking the neural origin to subcortical areas, especially the amygdala, which are involved in modulating stress-related hormones. This association provides an explanation for why certain types of environments have a different influence on stress responses.[14,25] Natural settings have been demonstrated to produce restorative or rest directed attention[45] as proposed by attention restoration theory.[37] However, Ulrich's psychoevolutionary framework proposed that the restoration from natural environments is a product of much more than attentional capacities,[14,36,46] being grounded in stress *prevention* that came from the beneficial associations with perceptually benign, nonthreatening and supportive environments. His demonstration of accelerated healing in surgery patients exposed to a small tree group compared to a brick wall provided empirical evidence for the innate nature of the response.[47] Thus, Joye[25] proposed including elements of ancestral habitats in the built environment could counter potentially deleterious effects by producing more relaxed physiological and psychological states.

The types of environmental patterns involved in these processes suggest new ways that interior design may directly enhance habitability and the performance of 'Knowledge Work' in otherwise impoverished habitats such as those found in most extreme environments.[24] Specifically, bionomic studies of externalized cognition and evolutionary biology reveal how human mental and perceptual processes run some of their control loops through the surrounding environment. This is a common biological energy efficiency strategy that reduces the neural cost of cognition and emotion management to the organism. Such human neuro-environment linkages have undergone evolutionary selection and represent our genetically encoded 'ancient wisdom'. Subsequently, our minds and feelings are at their best in settings that recreate, in real or analogue form, certain aspects of our ancestors' preferred biological environments, specifically, those of savannahs, where such control loops were most successfully established.

B. Fractal Geometry and Bionomic Design

The overwhelming evidence that natural environments are, in general, preferred to built environments was slowly followed by intriguing evidence that some natural environments are more preferred than others.[48,49] The beneficial impact of various disparate natural environments prompted some researchers to suggest a "search for general characteristics of the patterns in nature that produce relaxation."[50] Various empirical studies demonstrated a preference for environments with savannah features.[51,52,53] Habitat theory proposed that savannahs, those low to intermediately complex environments where humankind first evolved, displayed an ideal mix of structural landscape features and natural contents.[49,54]

Since then, 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 quality of life experienced by its occupants. Purcell, Peron, and Berto proposed an intriguing hypothesis that the beneficial effects of natural scenes might be due to their fractal characteristics whereas built environments would be deficit due to their Euclidean geometry and lack of fractal properties.[55] Fractals are never ending patterns that are self-similar across different scales.[56] Fractal geometry is able to convey feelings of spaciousness by increasing density and optimizing space without expanding the topological dimension. Subsequent research has strongly demonstrated that preferences for natural settings can be predicted by underlying geometric, fractal properties which appear to be responsible for the associated affective effects.[57] Fractal patterns appeared to evoke associations of naturalness in humans and improve the ability to perceptually differentiate between highly similar patterns.[58] But there was initially no differentiation between the impact of *different types* of fractal designs.

Empirical evidence from multiple sources has subsequently suggested that the most effective linkages appear between cognitive and emotional processes and settings characterized by fractal structuring in the 1.3 – 1.5 dimensional range (*D*),[59-62] a parameter that quantifies a fractal pattern's visual complexity in any stimuli. For shapes containing no fractal properties, D=1 whereas a completely filled area with no fractal properties, D=2. For shapes with fractal properties, the *D* value ranges from 1 to 2. The more rich and complex the fractal, the closer the value is to 2. Early studies of 7824 computer images first identified an aesthetic preference for mid-range *D* values.[60,63] Yet, it was not recognized that the preference for mid-range fractal properties also underlay preferences for scenes of nature until later. Studies by Hagerhall et al exploring preference for landscapes found those most preferred scenes exhibited a *D* value of 1.3.[57] This preference for mid-range *D* values (1.3-1.5) was reinforced in subsequent studies by Taylor et al exploring 146 fractal stimuli from computer-generated images, human-generated drip patterns, natural objects and natural scenes.[44]

These later extrapolations of fractal properties in natural patterns provided the key to unravelling the (then) surprising superior effects for a savannah scene over a forest scene in a 1986 NASA study by Wise and Rosenbeg.[43] Test participants were continuously exposed to one of three different visual scenes (a photograph of a forest scene, a black and white reproduction of a savannah landscape and a pattern of scattered squares) and asked to perform three mentally stressful tasks (arithmetic, logical problem solving and creative thinking) to induce physiological stress, interspersed with one minute recovery periods creating high and low stress periods. The greatest effects (faster stress recovery as well as lower stress reactivity) were found for the black and white savannah image (44%) instead of the expected natural forest scene (3%). The investigators had no explanation for these dramatically different and unexpected results. In 2002, Wise and Taylor sought to explain those puzzling earlier results by exploring the relationship between fractal geometry and stress reduction.[24] The reanalysis included the calculation of *D* to quantify the visual complexity of the patterns in each stimuli. The pattern of squares was found not to be fractal at all, whilst the savannah reproduction and the forest photograph were both found to be fractal with *D* values of 1.4 (falling within the preferred mid-range) and 1.6 (falling outside the mid-range) respectively. It appeared that the savannah hypothesis was once again supported by these findings.

Taylor et al, noted that these results raise the intriguing possibility that the visual appeal of mid-range *D* fractals affects the physiological condition of the observer.[44] Whereas advocates of incorporating natural images into artificial environments are not new,[64] Taylor argued that a *pattern's fractal dimension, rather than it's naturalness, may be the determining factor for its impact on visual perception and stress-reduction* and that incorporating interior design elements characterized by the mid-range fractal properties into those environments where people are deprived of nature's fractals – e.g., in research stations in space and at the Antarctic,[65,66] could represent effective countermeasures to stress and promote well-being. ***Thus, a biologically based 'fractal hypothesis' of beneficial effects offers both an integrative explanation and a design strategy of significant power and flexibility.***

C. Applying and Validating the Bionomic Design Approach to Habitat Systems

The central 'bionomic-design hypothesis' proposes that the general spatial and (particularly) fractal structures of benign ancestral human environments act as a template for perceptual and cognitive processes which share controls of our perception, memory, and emotional management with the physical environment. Therefore, incorporating these elements into habitat design could provide passive, autonomous, cognitive and psychological supportive countermeasures.

Recommendations for habitat design that specifically address behavioral and performance challenges in ICEs include: the interior design of crew quarters, windows, opportunities for personalization, and social interaction.[12,67,68] The practical environmental aspects of capsule co-habitation such as privacy, culture or territoriality have also been pointed out as critical in reviews of capsule environments.[1,12,69] Those considerations have been included in the design of conceptual habitats.[70-73] Recent works on human activity 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 (especially deep space missions).[74]

Integrating bionomic fractal properties into the current paradigm of habitat design is the logical next step in interior design evolution. The goal is to introduce *meaningful* complexity through the use of lighting (diurnal/seasonal dynamics), geometry (fractal patterns, reduced clutter), and providing wide views, i.e., to recreate those elements that compose humankind's 'natural habitat' as proposed by bionomics.

IV. Testing the Efficacy of Bionomically Designed Habitats on Performance and Stress

There is a need to demonstrate the efficacy of bionomically designed (habitation) elements for the reduction of and mitigation of stress and the enhancement of cognitive performance before we can take the next steps. Recent grant proposals in response to NASA NSPIRES calls have been submitted to this end. In addition, initiatives are being explored to integrate such studies into other analog environments, e.g., the upcoming Poseidon Project in the NEEMO underwater facility, the HiSEAS facility in Hawaii, the Mars Desert Research Stations in Utah. Other possibilities of high interest would be Concordia, other polar bases, and facilities where long duration missions are involved.

These proposed studies would evaluate 1) improved cognitive functioning, 2) psychological functioning (mediated stress and faster stress recovery), and 3) task performance in the analog environments while enriched with interior design elements, e.g., murals or large posters that incorporate bionomic fractal properties in the range of 1.3-1.5 suggested by prior research.[24,43] Ideally, assessment on these parameters will occur during a period without the bionomic enhancements present and then post implementation to provide a comparison across pre-post periods. Variations could also include assessing the impact of those 'natural' stimuli (e.g., forest scenes) heretofore thought to be highly effective but that fall outside the optimal 1.3 *D*-1.5 *D* range into the suboptimal 1.6+ range.

Assessment would include performance on tasks characterized by intense cognitive demand that requires a period of training and skill acquisition. In the Hera facility, for instance, crew members have tasks to perform on the Robotics On-Board Trainer (ROBoT), a high fidelity training simulation task that allows crewmembers to practice maneuvering the Canadarm2 to grapple or capture an incoming resupply vehicle to the ISS. There is a period of training and practice before actual 'mission' tasks are scheduled. Comparison across pre-post installment on cognitive functioning, stress, and task performance (using a ROBoT task) will be conducted using various proven performance and cognitive assessments employed in previous missions or their equivalent. The pre-post design provides within-group control to counter small sample sizes typically encountered in most analog environments. Stress during the task performance challenge can be measured through skin conductance which has been shown to be a reliable indicator of mental performance stress with higher conductance occurring under high stress[46] as well as salivary sampling for specific stress biomarkers (cortisol and DHEAS) as indicators of stress in general and in particular before and after the performance task challenge scenarios characterized by increased cognitive demand.

V. Conclusion

The validation of a set of flexible bionomic enhancements will provide NASA and other agencies a new set of passive countermeasures to improve crew functioning and performance via optimized habitat design. This could include design elements that can be installed in various spaces in the habitat, personalized, adapted to different color schemes to provide variety, integrated with operational features, implemented in various modalities (e.g. virtual reality panels, computerized renderings, 3D printed), used to enhance crew training strategies, and/or as countermeasures for use during a long-duration/deep space mission. Just as important is the probability that such enhancements will have similar utility in any environment characterized by high performance cognitive demands and stress. Generalization of findings into other situations outside the ICE condition represents an exciting extension of this line of research.

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