International Journal of Digital Innovation in the Built Environment
Volume 11 • Issue 3

Evaluating Interior Architectural Elements That Influence Perception of Spaciousness in Isolated, Confined, and Extreme Environments

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ABSTRACT

This research aims to understand the factors that contribute to the quality of life within isolated, confined, extreme (ICE) environments by investigating the architectural elements that affect an individual's spatial perception, their manifestation in ICE environments, and how spatial confinement and isolation contribute to changes in an individual's perception of spaciousness. The researchers performed an in-depth examination on three different habitats, designed to simulate life in ICE environments, to identify which architectural elements were important contributors to positive and negative changes in spaciousness. For further explorations, 14 design professionals were asked to evaluate these habitats using the spaciousness and crampedness scale (SCS) and measuring the relative estimation in error of habitats' areas. Afterward, the evaluations were compared with the examinations. The results indicate that the environment's geometry, lighting, color, and texture significantly contribute to perceived spaciousness when evaluated through qualitative and quantitative methods.

KEYWORDS

Crampedness, Design Evaluation, Habitat Design, ICE Environments, Interior Architecture, Perception, Spaciousness, Spatial Perception

INTRODUCTION

Three characteristics define isolated, confined, and extreme (ICE) environments. The first one is the isolation of an individual from the typical social environment, like family or friends, for a prolonged duration. Second is the physical constraint of an individual's environment and the heavy restrictions on mobility. The third is the constant presence of significant physical dangers caused by external conditions of the environment (Carrère, 1990). These factors comprise an ICE environment's main stressors that could lead to unique living scenarios and coping mechanisms. Due to most ICE environments' intrinsic nature, especially those in outer space, most of the research on these issues is performed either on analogous environments (submarines, arctic stations) or in smaller-scale controlled experiments (HERA, HI-SEAS, SIRIUS/NEK).

There is a large body of knowledge exploring the effects of isolation and confinement going back almost 60 years, primarily focusing on team and individual effectiveness for given tasks.

DOI: 10.4018/IJDIBE.306255
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Certain psychological occurrences are commonly observed in individuals and groups exposed to ICE environments for long durations and are often among the main research areas in ICE studies. These occurrences are often negative and manifest themselves as lack of motivation, a decline in alertness and mental functioning, aggressive or depressed moods, social withdrawal, splintering and polarization among group members, or biological disturbances such as sleeplessness (Connors et al. 2005; Evans et al. 1988; Suedfeld and Steel 2000). The individuals in such environments reported depression, irritability, aggressive behavior, insomnia, absent-mindedness, lack of concentration, and memory problems (Strange & Youngmen, 1971).

However, there is a lack of research on the impact of the physical environment on people and the subjective experiences of those who reside in ICE environments. For example, in many cases, the lack of adequate living accommodations becomes a significant determinant and a stressor because of the inability of an individual to put the necessary distance between themselves and the others. At the same time, lack of space causes the users to invade each other's personal spaces, although unwillingly. Making apparent a characteristic one could not disregard is that people are territorial creatures and like to control their environment to achieve their desired level of privacy. That is one of the significant issues in such limited environments. An environment designed to increase the perception of available space could improve the well-being of both individuals and groups that occupy the environment. The two major obstacles of such a design are the feelings of isolation and confinement, which are also the key characteristics of an ICE environment; thus, they are, in almost all cases, inevitable outcomes and require extensive work to address. A design that avoids addressing such issues would be significantly less successful in improving well-being than one that does. Various design techniques were developed to address similar issues in different environments in the literature and identified various architectural elements that could influence an individual's perceived isolation and confinement to treat the negative effects that are bound to appear. However, the research on confined environments and their impact on spatial cognition is still a developing field and it requires much more experimentation.

BACKGROUND

Visual Perception

The reliance on vision is a significant part of this research; hence it is important to understand some of the influential theories of visual perception. Inquiries into modern visual perception began with the biological examinations done by Kepler in 1604, with him describing the formation of the retinal image and by many other scientists who have explored the anatomy of the eye further. Their explanations lead further generations to question how the raw data of visual information is interpreted through the eyes and how the seen objects are processed.

The fact that the information received through the eyes contained much less than what one could infer led to further development, from the anatomy of the eye to neurological aspects of the brain. As Gordon (2004) stated, Hermann von Helmholtz and Richard Gregory hypothesized that since the perceived visual information is not always enough, more is drawn unconsciously from our past experiences and memories to make general inferences about the immediate environment, and use these inferences to support the perceived environment and fill any holes. Their research showed us the importance of previous knowledge has when exploring visual perception. This means that when looking at an object, in addition to seeing its specific properties, it is expected to have certain others that are not immediately perceivable. These expectations played a significant role in the appearance of illusions, as the inferences could sometimes fail to match the scene as expected, which leads to discrepancies between what is seen versus what is there (Gordon, 2004).

Other theories, such as the prospect-refuge theory, were developed by Appleton (1975). He argued that preference towards specific environments and landscapes was rooted in biological and behavioral elements closely related to adaptation. The theory identified the perception of the environment as a key element of adaptation and that humans have evolved in a way similar to many other animals to store critical information relevant to their survival about the characteristics of an environment in a manner that is easily retrievable. People treat the environment as their habitat, and that information related to elements that pose a danger must be accessible for self-preservation. It is argued that to achieve this, there are two methods. The first one is to keep open one's senses to environmental information through observing or prospecting. The second one is to look for opportunities for shelter and concealment from ecological elements, take refuge. These factors lead to the argument that preferences for specific environments and living spaces are rooted in these adaptation behaviors and predict that environments that satisfy the ability to prospect and take refuge are more likely to be preferred.

However, Gibson (1979) argued that visual perception did not occur as much as it was thought to be inferential but more direct. He emphasized the importance of examining visual perception not just in a laboratory setting but also in real-life scenarios. Hinting that the surrounding environment played a significant role in the perception of an object, as it was also a part of it. Later explorations in this theory led him to the theory of affordances in which properties of an object are there to be perceived directly from the stimulation of the object, further emphasizing the relationship between object and its environment, hence context (Gordon, 2004).

Hildebrand (1999) suggested that the prospect and refuge theory could also be applied to interior environments. He presented the idea that narrow and dark interior environments with solid walls without openings create appropriate environments for refuge. In contrast, bright and wide environments with lots of openings create environments for prospecting. He further suggested that as one moves from refuge to prospecting, moving from dark to light, there is an increase in the sense of security and thus pleasure. He also suggested that based on these considerations, interior environments that include natural materials, views of nature and water, and wide spaces would increase the comfort and pleasure of occupants. According to Stamps (2006), while these ideas were valid architectural criticism, they lacked scientific validation. To test Hildebrand's (1999) theory, he hypothesized multiple scenarios in which a person observes similar interior environments from various viewpoints (i.e., from dark to light, high to low, small to large, and vice versa). The experimental stimuli were made up of computer-generated images of Japanese rooms. The reasoning behind selecting Japanese-style rooms was based on Hildebrand's (1999) use of Frank Lloyd Wright as an example for their arguments, whose designs were heavily inspired by Japanese architecture. There were 14 participants, the images were shown one by one through a monitor, and they were asked to rate them between 1 (uncomfortable) and 8 (comfortable). Their findings suggested very little difference between comfort levels when looking from a small, dark and low room towards the opposite and vice versa. The only significant conclusion was the difference in the comfort of looking from a large room into a small room, which was the opposite outcome of the hypothesis.

In an attempt to validate the results, a second experiment was designed and conducted. This time images of stone buildings were used based on the fact that Hildebrand (1999) too used such examples in their work. The selection was made out of Roman Baths and Egyptian Tombs. While the hypotheses remained the same, the sample size was expanded to 83. This time, while the effects were more significant, the findings contradicted the hypotheses. While it was hypothesized that viewing large, bright, and open rooms from small, dark, and narrow rooms would be more comfortable, the opposite effect occurred. Stamps (2006) concluded that further validation with larger sample sizes might be required in addition to further exploration of scene properties such as airflow, colors, sizes and shapes, lighting.

Spatial Cognition

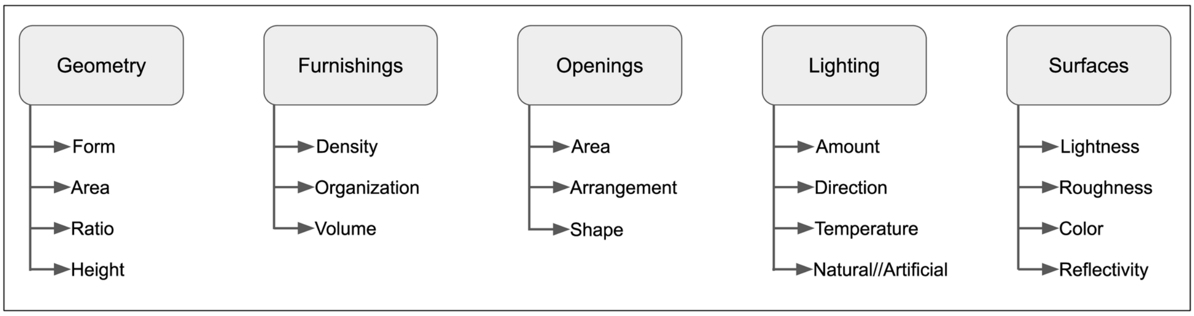
Spatial cognition is concerned with the acquisition, organization, utilization, and revision of knowledge about spatial environments. These capabilities enable individuals to manage primary and high-level cognitive tasks in everyday life. Furthermore, it is concerned with how humans and animals interact with the spatial characteristics of their environment (Waller & Nadel, 2013). There are various approaches to spatial cognition and how the brain processes the information acquired through the senses. One of these is the model-based approach, in which the brain creates a three-dimensional representation of the environment and its spatial layout. Individuals then replicate their planned actions on this model first before executing them. This saves valuable time and energy that one would otherwise waste on unsuccessful attempts at whatever action they wanted to perform. These cognitive models are created using environmental cues and internalized assumptions based on previous experiences (Loomis & Beall, 2004). The success and precision of an action performed in an environment are closely related to how well the cognitive model is constructed. Fajen and Phillips (2013) argue that there is an asymmetrical discrepancy between visual space and physical environment and that one could perform actions accurately with an 'accurate enough' cognitive model. They argue that the most important elements of a cognitive model are those that are immediately relevant to the action that is to be performed. They base this theory on the previous research done by Gibson (1979) and his ecological principles of vision. They later support their position with an experiment done by Warren and Whang (1987), where they demonstrate how the availability of eye-height scale information bypasses the need to use the knowledge of body dimensions when judging whether an obstacle could be passed.

According to previous research (Jager & Postma, 2003; Ruotolo et al., 2011), there are a certain number of cues that are inherent to us, which helps the brain create a cognitive map of an environment, a model. Cues could be described as elements within an environment that trigger a response to information only hinted at. These cues could be separated into two groups that are pictorial depth cues and dynamic cues (Gibson, 1979). Pictorial cues are connected to the information gathered through perspective, such as; relative size, horizon ratio, relative height in the field of view, as well as other properties such as contours, occlusion, and optical distortions caused by the light (shadows, highlights, reflections, etc.) The brain then estimates the spatial properties by integrating several of these cues alongside information gathered through other senses. These same systems also influence whether an individual is comfortable or not in a given environment. Spatial cognition also consists of a set of abilities that consist of; locating points in an environment, determining the orientation of lines and objects, assessing location in depth, appreciating geometric relations between objects, and processing motion (Colby, 2009). Theoretically, a purposefully created minor discrepancy among the perceived sensory information could lead to a false inference about the environment. This false inference could create negative or positive changes in the perceived environment in conjunction with the cognitive model.

In a regular interior environment, these cues are often manifested as architectural elements such as colored surfaces, windows and openings, lighting fixtures/modes, etc. In addition to creating a functional environment, these elements create a certain degree of stimulation and interest for the occupants. The interior environment, along with its elements, creates an interface with which a user interacts. These interfaces could be quantified with their organization, amount, and discriminability from each other (Miniukovich & Angeli, 2014). An excessive increase or decrease in the number of interactable interfaces could lead to a degradation of performance and quality of life (Rosenholtz et al., 2007).

Based on these elements, designers and researchers have established some 'tricks' that are commonly used when designing environments with restricted opportunities for spatial cognition. These tricks could be used to create a sense of spaciousness or reduce the sense of confinement. Some of these methods are commonly used when designing day-to-day environments with low square meters. Their main principles could be imported to the design of more controlled interior environments and tested. Simon and Toups (2014) summarized such methods used in 'tiny house designs', which could be applied to many different ICE environments. These methods are; clean and straight lines through an environment with minimal obstruction, uncluttered space above waist height, the proper ratio of ceiling height to the room area, use of light colors with dark accents, high levels of natural (or replicated natural) light, use of openings and windows, use of natural materials and scenery (biophilia). These methods could further be examined individually, and their impact on spatial cognition could be discovered through previous research and future experimentation. They can be categorized to explore further each variable that may impact the perceived spaciousness of ICE environments. This categorization can be done based on each architectural element of the interior environment and the use areas of these methods. Figure 1 demonstrates how this can be done alongside the sub-variables of each architectural element. The process consists of many layers starting from an environment's large and broad properties to smaller and specific elements.

Figure 1. Architectural elements alongside their sub-variables



To measure the impact of different architectural elements on spatial cognition, what is meant by the perception/feeling of spaciousness and confinement must be defined and quantified objectively. Imamoglu (1986) developed the Spaciousness and Crampedness Scale (SCS) to evaluate an individual's perception of spaciousness and crampedness towards an interior environment. The evaluations were done through three factors of spaciousness: appeal, planning, and space freedom, and four factors for crampedness: planning, physical size, clutteredness, and appeal. As the name implies, the appeal factor corresponds to the charm and appeal of an interior environment, such as its pleasantness and homeliness. The planning factor is related to the organization and fitness of an interior environment to its function, scale, and coordination. Space freedom refers to the perception of roominess or largeness of an interior environment as well as the crowding and clutter within an environment. Bipolar adjective pairs that were descriptive and representative of each factor were used to create the scale. The adjective pairs were scored from 1 to 7. Von Castell et al. (2014) measured perceived spaciousness through relative estimation error in their paper. First of all, was the accuracy of size estimations of the interior environment, which they formulated as:

$$EstErrorrel = \left(\frac{sizeest}{sizephys}\right) - 1$$

Geometry

This topic is closely related to the spatial or architectural properties of the interior environment, such as its spatial ratios, volume, etc. The most common variables of geometry include the form of the environment, its area, height, and spatial ratio. What is often meant by spatial ratio is the relation between the area of an enclosed space and its ceiling height. According to Stamps (2013), perception of spaciousness is closely related to the perceived 'boundaries' or the area that an individual could move in, and the horizontal area has a bigger impact on perceived spaciousness than the ceiling height. Their experiments showed that an increase in 'boundary height' caused the environment to be perceived as more confined than it was.

There is plenty of research on the preferences of objects and geometries. There has been evidence that people tend to gravitate towards curved objects and geometries (Bar & Neta, 2006; Silvia & Barona, 2009). This preference was demonstrated in the geometry of interior environments by

Shemesh et al. (2016), in which they experimented with different shaped interiors (square, round, sharp, and curvy). According to their findings, curvy surfaces were found to be the most pleasant in an interior environment. While these findings do not directly connect to the perceived spaciousness of an environment, the fact that the geometry of a room affects our preference towards it and our tendency to remain inside is an important subject to mention.

Furnishings

The key variables regarding the furnishings within an interior environment include the amount or density of furniture, their organization within the interior environment, and the volume they take up. The furniture organization is a significant determinant due to its effects on the occupants' line of sight. In confined environments, due to their volume limitations, the line of sight is often very limited and one of the major restrictions in the environment. Various elements could impact the line of sight in addition to the architecture of the environment; these could play a significant role in increasing the perceived spaciousness of a confined environment by increasing the distance an individual could see. Exploration from the largest elements to the smallest ones could be organized, which would lead to the subject of clutter.

Clutter directly impacts our perception of space through crowding, which is the inability to recognize objects in clutter. Our conscious visual perception has fundamental limits on the number of objects it could track, and an increase in objects beyond this limit causes us to perceive them in clutter and lead to crowding (Whitney & Levi, 2011). Clutter could be measured by the number of distinct items that could be seen on a single surface, the number of edges that are parallel or crossing each other, and the variances in the colors and textures of individual items (Bravo & Farid, 2004). Various elements could lead to clutter and are examined in two ways.

First is the surface clutter, often related to the surface properties of an object or an architectural component such as a wall with wallpaper. Surface clutter is two-dimensional; often caused by excessive use of materials with prominent patterns or features. The pattern introduces a new scale into the environment through constant repetition, and it could easily become overwhelming and overload the perception capabilities that make us feel confined. On the other hand, proper implementation of patterns on horizontal and vertical axes could cause us to perceive an environment wider or higher. The second type is object clutter, such as the number of three-dimensional objects present in an environment. Unlike surface clutter, the clever organization of objects could be a significant factor in reducing object clutter and freeing up the physical environment. This directly leads to both the perception and availability of more room for other activities. Furnishings could also contribute to object clutter if they are not planned and organized in an appropriate manner. For example, keeping the majority of objects under waist height (i.e., under counters) impacts our perception of clutter and improves the perception of spaciousness (Simon & Toups, 2014).

According to Samuelson and Lindauer (1976), neat rooms with little to no clutter are perceived to be more spacious than a similar room cluttered and disorganized. Even if the rooms contain the same objects, it is the organization of said objects that determines the room's spaciousness. They explained this as the fact that in addition to taking up less space, objects in a well-organized room create less visual stimulation and diversity, which then causes the occupant to focus more on other architectural elements such as walls, hence the room appearing to be emptier and larger. Imamoglu (1986) tested the impact of furniture density on the perceived spaciousness and estimation of room size within a scaled-down (1/10) conference room. There were three conditions; empty, normal, and over-furnished. These conditions were evaluated using the Spaciousness and Crampedness Scale (SCS). Their results indicated that there was not a significant difference in ratings of spaciousness between an empty room and a normally furnished room. On the other hand, an over-furnished room was rated to be much less spacious in addition to its lower appeal rating. The over-furnished room was also rated as more cramped compared to the other two conditions.

Von Castell et al. (2014) explored the effect of the furnishings on the perceived spaciousness of interior environments through two different experiments, first in a real true-to-scale room, where the amount of furnishing did influence the perceived spaciousness and room height. A second experiment was conducted in virtual reality (VR) environment, where the findings of the first experiment did not translate into similar results. Upon examining the VR environments they created for the experiments, a major lack of detail was noticeable. In order to control the variables, the rooms consisted of blank white surfaces and black boxes representing furniture. Possible use of furniture with minimal edges and surfaces or the use of transparent or reflective materials on certain faces of furniture could help increase the perception of available space in a confined environment.

Interior & Exterior Openings

Openings through an interior environment, connecting it to the exterior as well as other interior environments, have a more direct impact on the perception of spaciousness. Windows and doors are often considered architectural elements that connect both interior and exterior features of an environment. Openings make way for the eye to see further, as an increased line of sight leads to an increase in perceived spaciousness (Simon & Toups, 2014). These openings also help us define the physical boundaries of one room from another and define what is considered a confined environment. Vogler et al. (2004) argued that openings such as windows and doors have significant meaning and importance given to them based on our psychological and anthropological histories and that their existence in an extreme environment does a lot to humanize the existing environment. An important characteristic of many confined environments is the lack of any meaningful connection between the inside and the outside, often facilitated through windows. Key variables of openings that have an impact on the perception of spaciousness include the number of openings (their size), shape, and arrangement in relation to the rest of the environment. The size of a window, for example, has a direct impact on the perception of spaciousness, as demonstrated by Bokharaei and Nasar (2016), in which their experiments showed that the existence of larger windows increased the perceived spaciousness.

Natural & Artificial Lighting

Light is possibly the biggest contributor to the perception of space, as without any light, there would be no visual perception and thus not much to perceive. Three variables of light have been identified as valuable contributors to changes in perceived spaciousness. These are the amount of light (lux), the direction of the light source (direct/indirect/diffused), and its temperature (K). There has been plenty of research on how lighting quality, both natural and artificial, impacts the perception of an environment (Inui & Miyata, 1973; Kirschbaum & Tonello, 1997). The brightness of an environment causes it to be perceived as more spacious compared to another that is dimly lit (Bokharaei & Nasar, 2016). Full-scale room studies done by Matusiak (2004) showed that higher illumination through light sources, both artificial and natural (lamps, windows), as well as an increase in surface reflectance, showed an increase in the size impression of a room. The brightness of a room, or the availability of light, could be influenced either by the inclusion of light sources or by changing the properties of various interior surfaces to be more reflective, which will be explored in the next section. Light is a straightforward but effective tool when influencing the perceived spaciousness of an environment. Still, it requires careful and skilled manipulation as it has an even bigger impact on the health and psychology of individuals occupying the environment, especially a confined one.

Color & Other Surface Treatments

Surfaces in interior environments have many properties. Interior architects often use various materials with unique surface properties to achieve the effects they desire. The wide range of surface properties includes lightness, roughness, color, and reflectivity. Often dependent on the material, color is one of the most common tools utilized by interior architects to influence the perceived size of an environment and has a significant body of research that has gone to it (Oberfeld et al. 2010; Oyama & Nanri, 1960). Many different surface treatments could be applied to interior environments to increase the perceived spaciousness. Surface properties have a direct connection to the amount of light present in the environment, and an increase in brightness leads to an increase in perceived spaciousness. Hence bright or reflective surfaces create the illusion of a bigger room due to their higher reflectivity than darker colors (Matusiak, 2004). According to Sundstrom and Sundstrom (1986), lighter colors tend to create the impression that the surfaces are receding from the observer, while darker colors cause the opposite effect. This technique is often used in small rooms to increase comfort levels. Kozicka (2008) divided the use of color in ICE environments into three categories as; backgrounds, large elements, and small elements. Findings indicated that backgrounds must be light and unsaturated to maximize the feeling of spaciousness, while large elements should be slightly darker and saturated to provide contrast. Finally, small elements should have high saturation and contrast, but not a large difference in hue, to help distinguish them without becoming overwhelming.

Wang et al. (2020) tested the influence of textured walls on the perception of space using virtual reality. They have conducted three separate experiments where they test the influence of wall texture on perceived spaciousness, the influence of wall textures on perceived spaciousness of different room dimensions, and whether an association of meaning towards a texture has an influence on the perception of spaciousness. Their results indicated that textured walls tended to cause the room to feel less spacious compared to a room with white walls in similarly sized rooms. The texture itself had an impact on perceived spaciousness. Wall texture had a bigger impact on perceived spaciousness in smaller rooms compared to larger rooms. Overall their results indicated that in smaller rooms, objective aspects of the textures were found to have a bigger impact on perceived spaciousness, while in bigger rooms, subjective aspects had a bigger impact. They associated these results with the fact that the observation distances are significantly shorter in smaller rooms and cause the occupants to focus more on the materials' physical (objective) properties. As the room size increases, the detail of observable information decreases accordingly. This causes subjective properties of the texture (such as its aesthetics) to fill in the blanks. Additionally, a factor that may not have been considered by the authors is that the use of VR headsets has its own drawbacks in large-scale environments. Due to the technological constraints on head-mounted displays, the image resolutions within the VR space can cause distant objects and surfaces to appear significantly blurrier than nearby objects. This could have caused the textured walls on large-scale rooms within the experiment not to be as sharp as they would be in their real-life counterparts.

METHODOLOGY FOR THE EVALUATION AND ANALYSIS OF I.C.E. ENVIRONMENTS

Based on these findings, the research hypothesis is that the presence of and changes in interior architectural elements could influence the perceived spaciousness of an ICE environment. The research uses mixed methods (both qualitative and quantitative data analysis) approach to habitat design in ICE environments by examining multiple experimental habitats that are built to simulate long-duration missions in extreme environments. As illustrated in Figure 2, the aim is to compare the findings within the literature with the architectural design of these habitats to uncover the relationship between the perceived spaciousness of these environments and interior architectural elements used within.

Three simulation habitats, seen in Figure 3, are selected for evaluation of their interior environmental characteristics. The selection was based on the functional similarities of these environments. All three environments are analogs of theoretical extreme environments such as Mars habitats, in which crews simulate various scenarios with maximum fidelity.

The Nazemnyy Eksperimental'nyy Kompleks (NEK) Habitat is located within the Institute of Biomedical Problems of the Russian Academy of Sciences, Moscow, Russia. Originally built in the 1960s, the habitat consists of multiple compartments and is primarily used for simulating isolation, confinement, and exploration scenarios at extreme and remote locations. The habitat can house crews of up to 8 people for longer than a year and has five interconnected modules. The selected module for this study, Module EU-100, is used to conduct medical and psychological experiments throughout

Figure 2. Evaluation Procedure

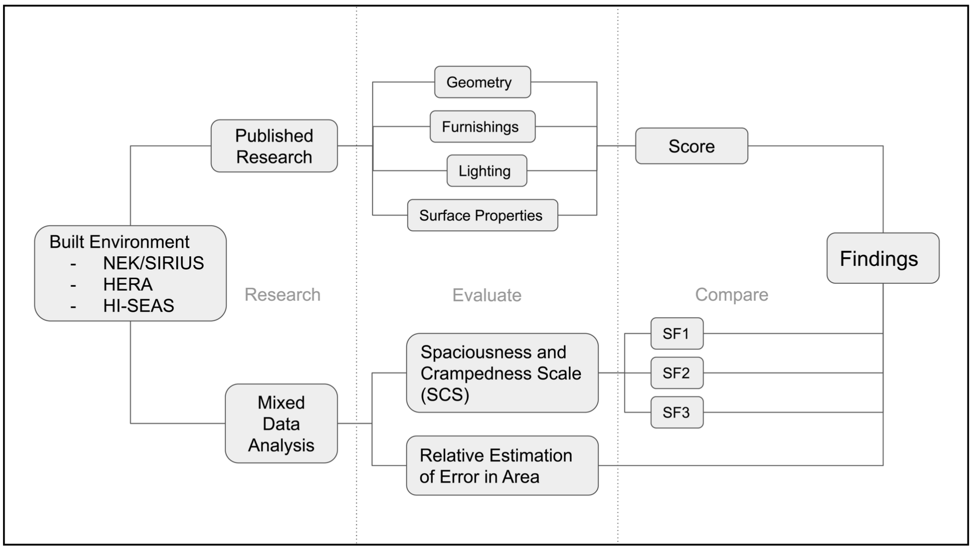
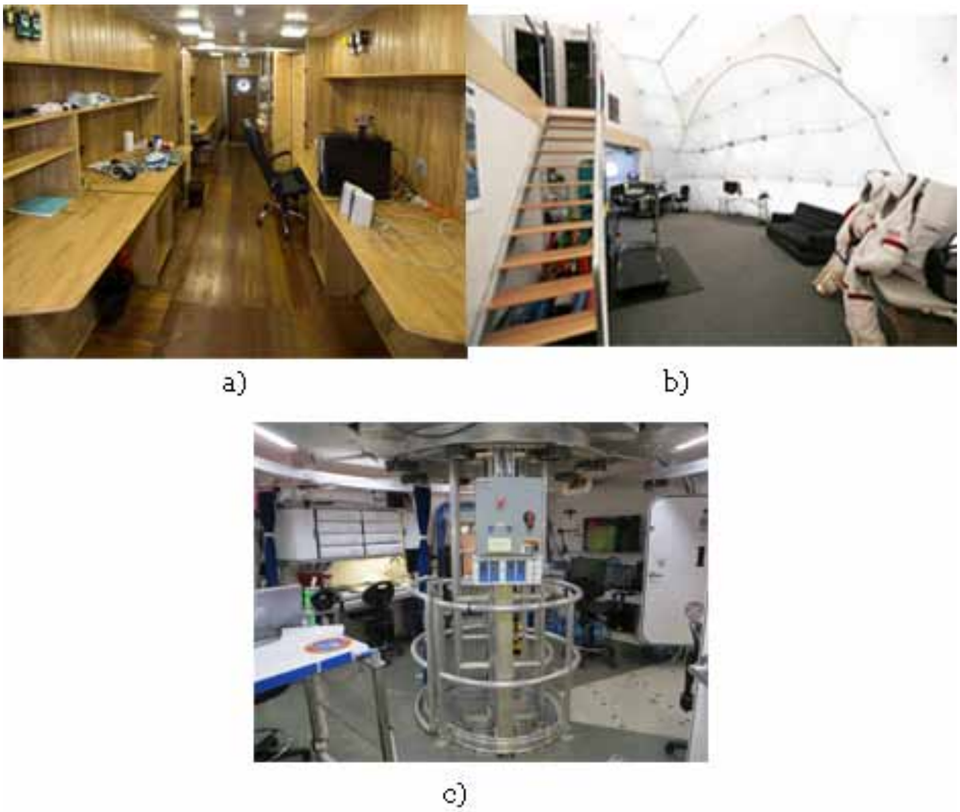


Figure 3. Interiors of the selected environments (a: NEK/SIRIUS Module EU-100, b: HI-SEAS, c: HERA Core Module)



the simulated scenarios. The module contains living quarters for two people, a kitchen, a washroom, and additional working spaces with medical equipment (Belakovsky et al., 2019).

The Hawai‘i Space Exploration Analog and Simulation (HI-SEAS) habitat is located on the Mauna Loa volcano on Hawai‘i Island. It is used as an analog for exploration missions on Mars and Moon. The similarity of the outside environment to the extreme conditions of Mars provides crews with high-fidelity scenarios for exploration. It is a semi-portable domed structure, able to house crews of six for durations of more than eight months. Inside the dome are two floors; the first floor contains the common areas, the kitchen, labs, bathroom, work areas, and a dining area. The second floor has individual compartments for the six crew members and a secondary bathroom. The dome provides a higher ceiling height for the habitat (Haeuplik-Meusburger et al., 2017).

The Human Exploration Research Analog (HERA) Facility is located in NASA's Johnson Space Center in Houston, Texas, United States. It is a three-story habitat designed to be used as an analog for isolation, confinement, and extreme conditions in exploration scenarios. Crews of up to four people simulate missions for up to 45 days. The first floor of the habitat consists of an airlock, a hygiene module, and a core area where the crews perform their daily tasks, experiments, and flight simulations. The second floor is used primarily for dining and recreational activities. The third floor contains individual sleeping quarters for the crew (The National Aeronautics and Space Administration, 2019).

The interior architectural features of the habitats are categorized as geometry, furnishings, lighting, and surface properties (materials). Exterior openings are not taken into consideration in this section due to their lack thereof in selected environments. Each habitat environment is evaluated based on these factors, as laid out in Table 1. Furthermore, the architectural elements with high and low values that are known to affect the perceived spaciousness are highlighted to determine which environments are more likely to score higher on the independent evaluations.

Fourteen interior designers were selected through focus sampling method and asked to perform evaluations by viewing selected photographs of each environment through a monitor. The viewing order was rotated to avoid any viewing biases. Upon viewing each environment, they were asked to fill out the Spaciousness and Crampedness Scale (SCS) (Imamoglu, 1986) consisting of 16 bipolar adjectives on a Likert-scale of seven for qualitative analysis and estimate the square meters of the area that is photographed for quantitative analysis, which would be used to calculate the relative estimation of error in an area (von Castell et. al., 2014). The SCS evaluations are examined and ranked under three factors as appeal (SF1) with four items (uncomfortable/comfortable; repelling/inviting; disturbing/restful; unlivable/livable), planning (SF2) with five items (poorly organized/well organized; poorly balanced/well balanced; poorly planned/well planned; poorly scaled/well scaled; uncoordinated/coordinated;), and space freedom (SF3) with seven items (cramped/roomy; small/large; restricted space/free space; tiny/huge; crowded/uncrowded; closed/open; narrow/wide). The mean scores are calculated for each factor and provide a qualitative measure of spaciousness using various positive and negative adjective pairs. A high score on the spaciousness factors indicates that the environment provides a sufficient degree of comfort and emotional satisfaction, in addition to being functional.

The relative estimation of error highlights the feeling of spaciousness based on how big of divergence is present between the estimated areas in square meters of an interior environment versus the real measured area of the same location. Afterward, the interior evaluations were compared with SCS scores and estimation errors for each habitat separately to uncover their degree of correlation.

Based on the architectural characteristics laid out in Table 1, HI-SEAS common area had the greatest number of characteristics known to affect perceived spaciousness positively. In addition to this, it has the highest ceiling height and overall volume available, although it has the least amount of area. On the other hand, the SIRIUS/NEK Module EU-100 has the largest amount of area available. Although, the amount of surface texture on the walls and floor, and the chosen color, are likely to be a negative contributor to perceived spaciousness in addition to the habitat's tubular shape, which restricts the field of vision by a large margin. Similarly, the HERA habitat has the elevator/ladder, which significantly restricts the line of sight and the highest number of objects within the environment, which negatively affects perceived spaciousness.

RESULTS

Spaciousness and Crampedness Scale

Mean spaciousness scores for each habitat were calculated (Figure 4), and a One-Way MANOVA test was performed on SPSS Statistics in order to investigate the changes in spaciousness evaluations

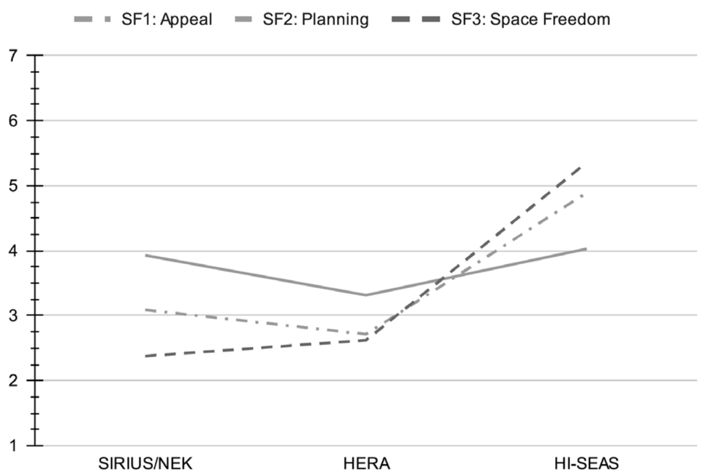
Table 1. Interior Element Characteristics of Selected Habitats

		NEK/SIRIUS: Module EU-100	HERA (Core)	HI-SEAS
Geometry	Form	Horizontal Cylinder	Vertical Cylinder	Domed
	Area	35 m^2	27.34 m^2	26.8 m^2
	Ratio (Area:Height)	17.272:1	12.716:1	4.872:1
	Height	2.20 m (d)	2.15 m (d)	5.5m at top(d=11m)
Lighting	Type	Downlight	Downlights + Task Lights	Downlights + Indirect Lighting
	Temperature	4000K-6000K (White)	4000K-6000K (White)	3000K-4000K (Warm White)
	Natural/Artificial	Artificial	Artificial	Artificial + Natural
Furniture	Type	Built in + freestanding	Custom Built-in	Freestanding
	Organization	Linear	Central	Central
	Density	Dense	Very Dense	Light
Surfaces	Type	Wood Planks	Metal	Carpet, Gypsum, Plastic
	Texture	Wood Grain	Flat	Flat
	Color	Light Brown	Grey, White, Black	White, Grey

among different habitats. Three dependent variables for evaluation were; SF1 (appeal), SF2 (planning), and SF3 (space freedom). The independent variable was the habitats.

There was a statistically significant difference between the habitats and their mean spaciousness scores, $F(6,74) = 16.96$, $p<0.005$, Wilk's $\lambda = 0.177$, partial $\eta^2 = 0.579$. Further investigations indicated that habitat type had a statistically significant effect on SF 1 (appeal) ($F(2,39)=17.9$, $p<0.005$, partial $\eta^2 = 0.48$) and SF 3 (space freedom) ($F(2,39)=74.34$, $p<0.005$, partial $\eta^2 = 0.79$) evaluations. Bonferonni Post Hoc test indicated a statistically significant difference between the SF1 and SF3 evaluations of HI-SEAS habitat versus HERA & SIRIUS/NEK habitats ($p<0.005$). On the other hand, no significant difference was observed between SF2 (planning) evaluations of all habitats ($p=0.318$).

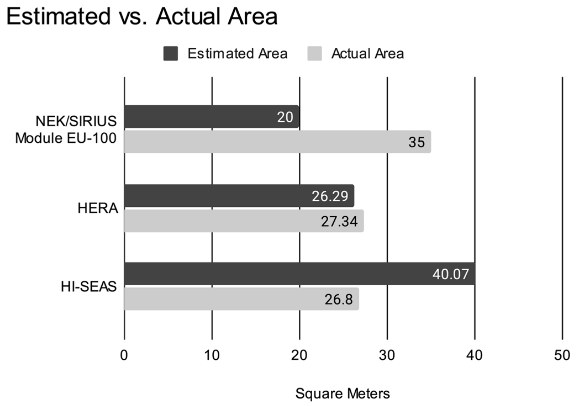
Figure 4. Mean Scores of Spaciousness and Crampedness Scale

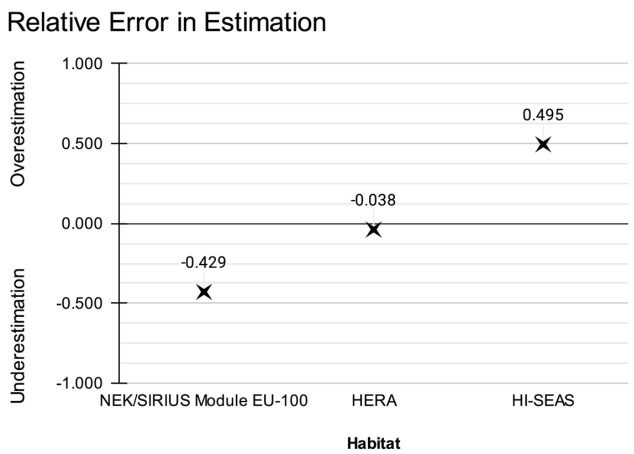


Relative Error in Estimation

Participants provided their estimations for each habitat area in square meters. Their responses were then compared to the actual area of the habitats; afterward, the necessary calculations were performed to acquire the relative estimation of error of all participants. Mean scores were calculated to visualize the data better, as displayed in Figure 5. The results indicated that the HI-SEAS habitat had the highest percent of overestimation, being perceived as 49.5% bigger than the real area of the habitat. On the other hand, the SIRIUS/NEK Module EU-100 was perceived to be 42.9% smaller than it is. The relative error in estimation was the lowest for the HERA habitat, with only a 3.8% underestimation of the habitat area.

Figure 5. Estimated area versus actual area of the habitats & relative estimation in error





DISCUSSION

The results of the SCS evaluation indicated that there was a significant difference between the evaluations of the three habitats. SF1 and SF3 factors of the Spaciousness and Crampedness Scale provided the most insight in the evaluations of the habitats, while the SF2 factor did not provide a significant contribution. This may likely be due to one of the unique characteristics of such ICE environments, in which the overall planning and functionality of the habitat are prioritized due to the limited resources, volume, and restrictive mission requirements.

The (HI-SEAS) habitat with the largest available volume, light, least amount of furniture density, and least amount of color/texture were also ranked the highest on SF1 and SF3, meaning that it was the most appealing compared to the other two habitats, and had the most space available for living. On the other hand, the SIRIUS/NEK habitat ranked the worst on SF3 evaluations, although it had more area and volume than the HERA habitat. This is likely due to the geometry and the use of color and texture within the environment. However, the effects of the line of sight seem to be contradictory to what was expected. Although the HERA module contains an elevator shaft in the middle of the habitat, which blocks the occupants' line of sight, it was evaluated to have more space freedom than the NEK/SIRIUS habitat. Field of vision may also be a contributing factor since the tubular shape of the latter habitat is more restrictive compared to the open cylindrical geometry of the latter. HERA habitat was evaluated to be the least appealing out of the three. This is likely due to the more mechanical, machine-like appearance of the habitat and its overall brightness being the lowest.

The results of the relative error in the estimation test indicated that the SIRIUS/NEK habitat was perceived to be the least spacious, while the HI-SEAS habitat was the most spacious. The perceived spaciousness of the HERA habitat had unexpected results, in which the relative error was smallest. This seems contradictory to the expectations at first since it ranked the overall lowest score on SCS evaluations. However, when looking at the SF3 evaluations, HERA habitat ranked second. This may indicate that the relative error in estimation has a higher degree of correlation to SF3 than to the rest of the items or the overall spaciousness evaluation. The rest of the estimation directions were as anticipated.

CONCLUSION

The study aimed to approach the architecture and design of various ICE environments, in this case, the habitat simulations, through the use of mixed methods data analysis that will increase the overall perceived spaciousness and provide a higher degree of comfort. The various architectural elements explored in this study have a large background of research and testing across multiple building scenarios but often were not considered for ICE environments studies. For example, future architects of such isolated and confined environments can take advantage of the curved structures often preferred due to their structural advantages, while avoiding the formation of narrow volumes that heavily constrict the field of view, or become disproportionate. In addition to the use of geometry, reducing surface clutter and excessive furnishings as well as providing cleaner surfaces with fewer textures can cause the habitat to be perceived as larger than it actually is. Similarly, the effects of providing a variety of light sources and increasing overall illumination levels carry over to these environments and could be the most cost-effective way of increasing perceived spaciousness.

With the utilization of qualitative and quantitative evaluations of such environments, enough awareness can be raised to take into consideration the more nuanced aspects of an interior environment that is not immediately apparent. Although limited in its scope, this study attempts to establish these evaluation methods for further analysis in the future. With the use of immersive viewing technologies, higher data accuracy can be achieved, and more in-depth explorations into how the occupants perceive spaciousness in various ICE environments can be explored. This, in turn, would provide more tools and techniques for designing new environments for uncharted territories.

CONFLICT OF INTEREST

The authors of this publication declare there is no conflict of interest.

FUNDING AGENCY

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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