

Article

Space Habitat Resilience: Integrating Neuroarchitecture for Indoor Living in Extreme Environments

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Abstract

Moon and Mars mission architectures are shifting from short stays to longer surface stays in isolated, confined and extreme (ICE) conditions, where small crews live almost entirely inside pressurized habitats. As transit durations increase and lunar outposts evolve into more permanent bases, crews are exposed for longer periods to environmental hazards and non-terrestrial gravity that disrupt usual sensorimotor patterns. In this context, the habitat becomes the primary interface between human bodies and extreme environments, shaping how inhabitants perceive, move, orient themselves and sustain everyday routines away from Earth. This article develops a neuroarchitecture integrative model for indoor living in lunar and Martian habitats, treating space habitat resilience as a cognitive and experiential property of the human–habitat system. The model connects advances in space architecture and planetary science research with person–environment theories to show how interior form and indoor environmental quality (IEQ) influence attention, emotional regulation and social functioning under confinement. It distinguishes a macro scale, where planetary constraints compress human experience into Built Environments in Extreme Environments (BEXEs), from a micro scale, where habitability is organized into four functional clusters (somatic, operational, psychosocial and ludic-recreational). Conventional IEQ assessment addresses a small set of generic dimensions applicable to any building; here, these are reorganized into twelve cluster-specific dimensions, three per cluster, calibrated for confinement and for the absence of an accessible exterior. Focusing on room shape and proportions, degrees of enclosure and visual order as key interior variables, the model positions the habitat as an active co-regulator of cognition and argues for design agendas that move beyond minimum safety and volume standards toward evidence-informed cognitive habitability in emerging off-Earth settlements.



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Keywords: isolated, confined and extreme (ICE) environments; extreme environments (EEs); space habitats; neuroarchitecture; indoor environmental quality (IEQ); cognitive resilience

1. Introduction

In this new phase of manned spaceflight, exemplified by the Artemis II mission, which features a crew of both men and women, humans continue to test the limits of their ability to adapt to space, even as technological ambition advances faster than physiological resilience. On the one hand, this reveals a disconnect between rapid technological progress and the limits of the human body; on the other, the concepts and definitions of life off-Earth in

closed environments are often presented as if such limitations were, ultimately, easily solvable and could therefore be excluded from design considerations. Contemporary spacecraft and orbital infrastructures, such as ISS modules and Orion-class capsules, remain minimal habitats in which basic human needs are met in strictly functional and spatially compressed environments organized around life support and mission safety [1,2]. Looking ahead, however, space habitats will need to move beyond this paradigm of elemental sufficiency, providing environmental quality, cognitive support and psychosocial affordances even for short- to medium-duration stays and small crews to sustain performance, well-being and long-term mission viability [3–5]. In this article, “space habitat resilience” is understood not primarily as a structural or engineering property, but as a cognitive and experiential condition emerging from the interaction between human occupants and interior architectural environments. The habitat must therefore be understood not simply as a survival container, but as the primary environment through which inhabitants perceive, orient themselves, construct routines and maintain a workable sense of continuity away from Earth.

Unlike orbital missions, where Earth remains continuously visible and gravity is effectively absent, surface missions combine reduced planetary gravity with permanent exposure to a hostile exterior and prolonged occupation of compact, pressurized interiors [2]. While lunar stays may be relatively short, Martian missions may involve months of transit and year-long surface habitation, extending exposure to environmental hazards, non-terrestrial gravity levels and communication delays [3]. In both cases, habitation is temporary, but everyday life will unfold almost entirely indoors under extreme conditions that have no direct terrestrial equivalent [5,6].

Over the last decades, several theoretical approaches have redefined how the relationship between people and built environments is understood. Environmental psychology has demonstrated that spatial layout, density, privacy gradients and materiality systematically influence mood, cognition and social behavior in everyday settings [7]. Biophilic design research has argued that human cognition is evolutionarily attuned to natural patterns, rhythms and textures, and that built environments that ignore these affinities risk undermining attention, comfort and long-term psychological tolerability [8,9]. More recently, neuroarchitecture has brought these strands into a common field of inquiry concerned with how interior architectural form and sensory conditions shape perception, comfort and stress modulation [10–13].

In extreme environments, architecture is not a neutral backdrop to human activity. Interior space influences how inhabitants perceive, move, orient themselves, establish routines, and maintain a sense of temporal and spatial continuity under confinement. In space habitats, where stepping outside is impossible in Earth-like terms and the surrounding landscape is both visually compelling and physically hostile, the interior must mediate not only functional tasks but also the cognitive and emotional work of living at a distance from Earth [3,6].

Technological constraints still narrow the architectural repertoire for space habitats, even as design research begins to anticipate futures that may extend beyond current engineering limits, particularly through in situ resource utilization (ISRU) and subsurface construction [14–16].

At present, ISRU prospects remain markedly asymmetric between the Moon and Mars. While remote sensing data from the lunar south pole indicate accessible water ice in permanently shadowed regions near illuminated ridges, supporting near-term scenarios of regolith-shielded bases, this asymmetry has direct implications for habitat design: the Moon is increasingly framed as a technological and architectural testbed for resilient living in ICE environments, while Martian habitats remain more speculative and operationally constrained [17,18].

Within this perspective, Sherwood proposes a four-stage framework, Explore, Exploit, Experience, and Settle, that reframes space architecture as an evolving discipline, in which

design progressively shifts from enabling exploration and resource utilization to creating meaningful environments for human experience and ultimately permanent settlement [19]. Long-duration Mars mission and habitation studies then build on this logic by adopting conservative assumptions about drilling, in situ resource utilization and the construction and operation of surface habitats, reflecting the lack of ground truth evidence for readily exploitable near-surface ice and the technical limitations of large-scale life support and infrastructure [20,21].

These mission architectures and design studies frame the Moon and Mars differently: the Moon as a near-term technological and architectural testbed for resilient living in ICE environments, and Mars as a more speculative, operationally constrained arena in which habitat concepts remain tightly coupled to evolving systems engineering and human factors considerations [22,23]. Building on this trajectory, recent habitability and human factor research has begun to formalize integrated design processes and typologies of literature reviews that link methodological frameworks to concrete habitat concepts, providing tools to synthesize dispersed evidence on extreme environments into actionable guidelines for future lunar and Martian interiors [22].

In this context, the iconic Apollo 11 boot print and the first steps on the lunar surface (Figure 1) symbolize a trajectory that now moves beyond choosing between lunar or Martian destinations toward the broader ambition of inhabiting worlds beyond Earth. From the symbolic moment of the first steps on the lunar surface (Figure 1b), the focus shifts from arrival to long-term presence. In scenarios for the development of lunar habitats, two approaches tend to shape the debate: one favors the use of teleoperated and robotic systems in the initial phases, minimizing direct human exposure; the other assumes a more permanent human presence on the surface, despite the greater logistical and operational demands. Between these positions, hybrid models have emerged in which crews supervise robotic systems locally and intervene directly only when necessary. Framed in this way, the question is not about where humans go first, but how habitation is organized, distributed and supported in orbital environments in conjunction with habitats on the Moon's surface. This places the human factor—perception, safety, routine, autonomy and everyday living—at the center of space architecture, understood as a multi-nodal system of interdependent habitats, rather than a single habitat [24,25].

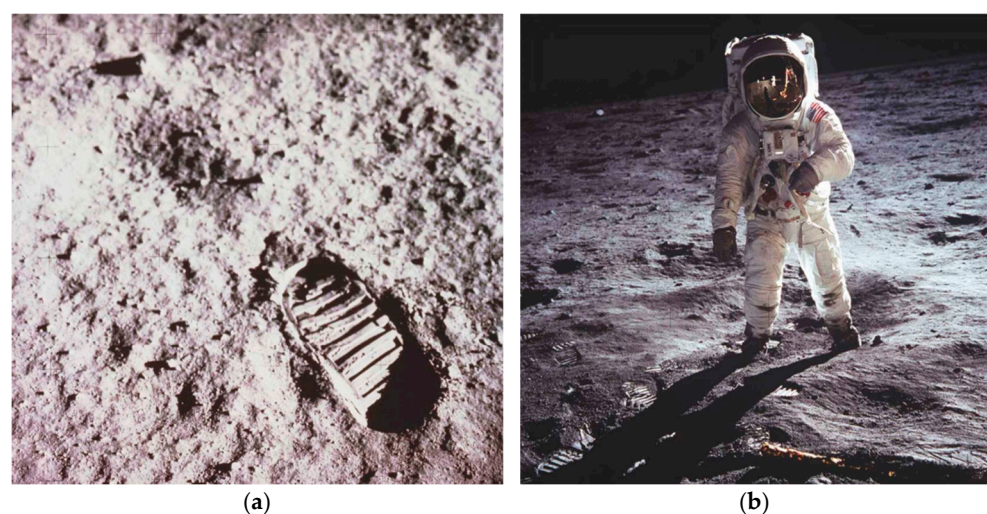


Figure 1. (a) Boot print on the lunar surface during the Apollo 11 EVA (AS11-40-5878); (b) Astronaut Buzz Aldrin on the lunar surface, Apollo 11 (AS11-40-5903). Image credits: NASA.

Against this background, the aim of this research is to develop a conceptual neuroarchitecture model that organizes theoretical and empirical contributions on cogni-

tive resilience in space habitats, with a specific focus on indoor living under extreme conditions, laying the theoretical groundwork for a more fully validated future framework. Building on environmental psychology, phenomenological architecture, biophilic design and neuroarchitecture, we address one central question, articulated in two complementary parts:

- Which interior spatial and sensory variables, including the temporal dimension of habitability in confined settings, are particularly relevant for sustaining cognitive resilience in extreme environments, and how can these insights be translated into an architectural understanding of cognitive habitability for temporary lunar and Martian habitats?

Although both destinations, Mars and the Moon, share severe intolerance and resource scarcity, their exploration differs: whilst the lunar footprint (Figure 1) marks the beginning of direct human presence and informs early discussions of lunar settlements and dust-related constraints [26–28], robotic images of Mars (Figure 2) reveal an extreme environmental profile shaped by planetary climatology and near-surface meteorological dynamics, where human presence has not yet been tested [29,30].

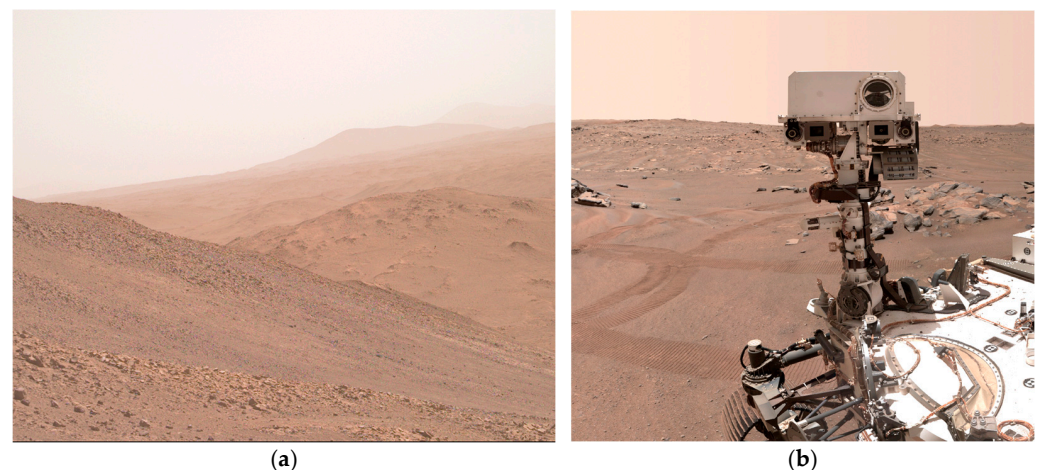


Figure 2. (a) Martian landscape showing extreme environmental conditions, selected by public vote as Image of the Week 208 (credit: NASA/JPL-Caltech/ASU); (b) Perseverance rover selfie at "Rochette" (credit: NASA/JPL-Caltech/MSSS).

In this sense, off-Earth habitats can also be understood as a specific architectural subset of construction in extreme environments, where extremeness results from the interaction of environmental hostility, technological dependence and the limits of human tolerability [31].

2. Methods

This article develops a conceptual neuroarchitecture model for cognitive resilience in off-Earth habitats by integrating empirical and theoretical contributions on isolated, confined and extreme (ICE) environments; indoor living in extreme environments; and off-Earth habitats, with a specific focus on Lunar and Martian missions. The aim is not to exhaustively map all publications, but to organize key concepts and findings that can inform an architectural understanding of cognitive resilience in artificial habitats. The literature review follows established guidance on narrative reviews, combining structured database searches with iterative citation snowballing to capture both peer-reviewed studies and influential conceptual contributions [23].

The keyword chains combined two main groups of terms. The first group addressed the context, using expressions such as "isolated, confined, extreme", "living in extreme

environments” and terms related to ICE and analogue environments, as well as recent work on human behavior and performance in deep space exploration, identifying next challenges and research gaps [24]. The second group dealt directly with architecture and design, including “Life in Interior Spaces”, “Indoor Environmental Quality” or “IEQ”, “space habitats”, “space architecture”, “neuroarchitecture”, “biophilic design” and “multisensory environments”. Publication date was not used as a strict exclusion criterion: post-2000 empirical studies were prioritized when considering evidence on behavioral and design outcomes in confined environments, while earlier theoretical and conceptual works were retained whenever their constructs remain central to current debates on person–environment relations, perception and architectural comfort.

This strategy was not intended as a systematic review in the narrow sense, but as a critical conceptual review designed to identify studies explicitly linking interior architectural variables with cognitive or affective outcomes in confined and hostile environments. Unlike bibliometric or systematic approaches, which quantify publication trends or synthesize empirical evidence through predefined protocols, a critical review is better suited to interpreting conceptual developments, comparing competing theoretical perspectives, and generating integrative explanations, an approach particularly appropriate to neuroarchitecture, a field only formally established in the early 2000s [32] but developed through longer-standing contributions from environmental psychology, phenomenology and architectural theory. The literature was therefore selected primarily for conceptual relevance rather than exhaustive coverage, prioritizing works that introduced influential concepts, redefined key constructs, or substantially reshaped the understanding of person–environment relations over purely descriptive or technical studies.

This choice is supported by the existence of a systematic review explicitly mapping the general intersection between neuroscience and the built environment [11]; however, that review, like the wider neuroarchitecture literature, does not address isolated, confined and extreme (ICE) environments or off-Earth habitats, precisely the gap this targeted search is designed to address.

The analysis also focused on the interior variables relevant to the design of off-Earth habitats. The literature was therefore selected based on the attention paid to spatial form, enclosure, room proportions, visual order, privacy gradients, multisensory atmosphere, materiality and nature-like stimuli, understood not as isolated parameters, but as components of a broader architectural question:

- How does interior space favor or hinder orientation, ease of perception and tolerable habitability under extreme conditions in off-Earth habitats?

The selected literature was then synthesized along two analytical axes: the macro-scale of extreme environments and the micro-scale of life in interior spaces and four recurring groups of interior functions that structure the neuroarchitecture model were developed.

These four functional clusters were identified through iterative thematic synthesis of the reviewed literature, grouping recurring outcomes reported across studies into functionally coherent categories; their theoretical grounding in ecological psychology and environmental affordances is developed in Section 3 (Conceptual Scope), and their definitions, together with the corresponding literature strands, are presented in Section 4 (Results). Consistent with the critical conceptual review approach outlined above, this reading evaluates, for each cluster, the core phenomenon its key literature explains, the specific contribution and limitation of that literature, and how it is proposed to integrate into the neuroarchitecture based conceptual model for indoor living in extreme off-Earth environments developed in this article.

3. Conceptual Scope

In the broader literature on human adaptation, extraterrestrial locations are typically classified as extreme environments (EEs), defined as settings that fall outside the optimal range for human survival and demand complex psychological and physiological adaptation [21]. Within NASA's Human Research Program, this line of work has been refined into the notion of isolated, confined and extreme (ICE) environments, which emphasizes physical extremeness together with social isolation and spatial confinement [24]. These two terms are used together in an operational sense for the conceptual model. Surface habitats beyond Earth, on the Moon and on Mars, are considered a specific subset of EE/ICE conditions, in which daily life is expected to take place almost entirely in indoor spaces and survival depends on artificially created pressurized environments [25,33].

3.1. Extreme Environments and Architectural Indoor Living

Two main strands of the literature inform the characterization of lunar and Martian habitats as extreme environments. One is the space architectural and environmental psychology work on habitability in ICE, where the interior of the habitat is understood as a key modulator of health, performance and social life [21,24,25]. The other is the planetary science and geoscience literature that characterizes the Moon and Mars in terms of gravity, radiation, atmosphere, dust, thermal regimes and cycles of light and darkness, thus defining the physical boundary conditions for any surface habitat. This section proceeds in four steps: it first establishes the criterion by which an environment is classified as extreme, then positions the lunar and Martian surfaces against that criterion using comparable physical data, then identifies the respects in which the two bodies differ from each other, and finally derives the conditions that these environments impose on interior architecture.

To relate these strands, we adopt the Environmental Extremeness Matrix (EXM) developed by Igarashi and Yashiro, building on Bannova's work on architecture in extreme environments [21,31].

The Environmental Extremeness Matrix (EXM) characterizes environments along two axes: intolerability and resource unavailability. Intolerability describes how rapidly an unprotected human body fails and is rated from 0 (tolerable) to 3 (death within minutes), while resource unavailability describes how difficult it is, even with protection, to access energy, water, food, goods, information and services, from 0 (possible) to 2 (effectively impossible). When plotted against these two axes (Figure 3), environments define a "degree of extremeness" as distance from ordinary conditions, further decomposed into phase (gas, liquid, solid), geometry (topography and meteorology) and measurable qualities such as temperature, dryness, radiation, pressure, oxygen pressure and gravity, drawing on NASA astrobiology criteria [24].

Positioned on this map, the lunar and Martian surface environments addressed here sit within the highest tier of intolerability (level 3, death within minutes without protection) combined with the highest tier of resource unavailability (level 2, effectively impossible without technological mediation), occupying the same extreme quadrant as the "Space" category (point A) and clearly separated from milder terrestrial analogues such as deserts, polar regions or high-altitude settlements, which cluster at markedly lower intolerability and resource unavailability levels.

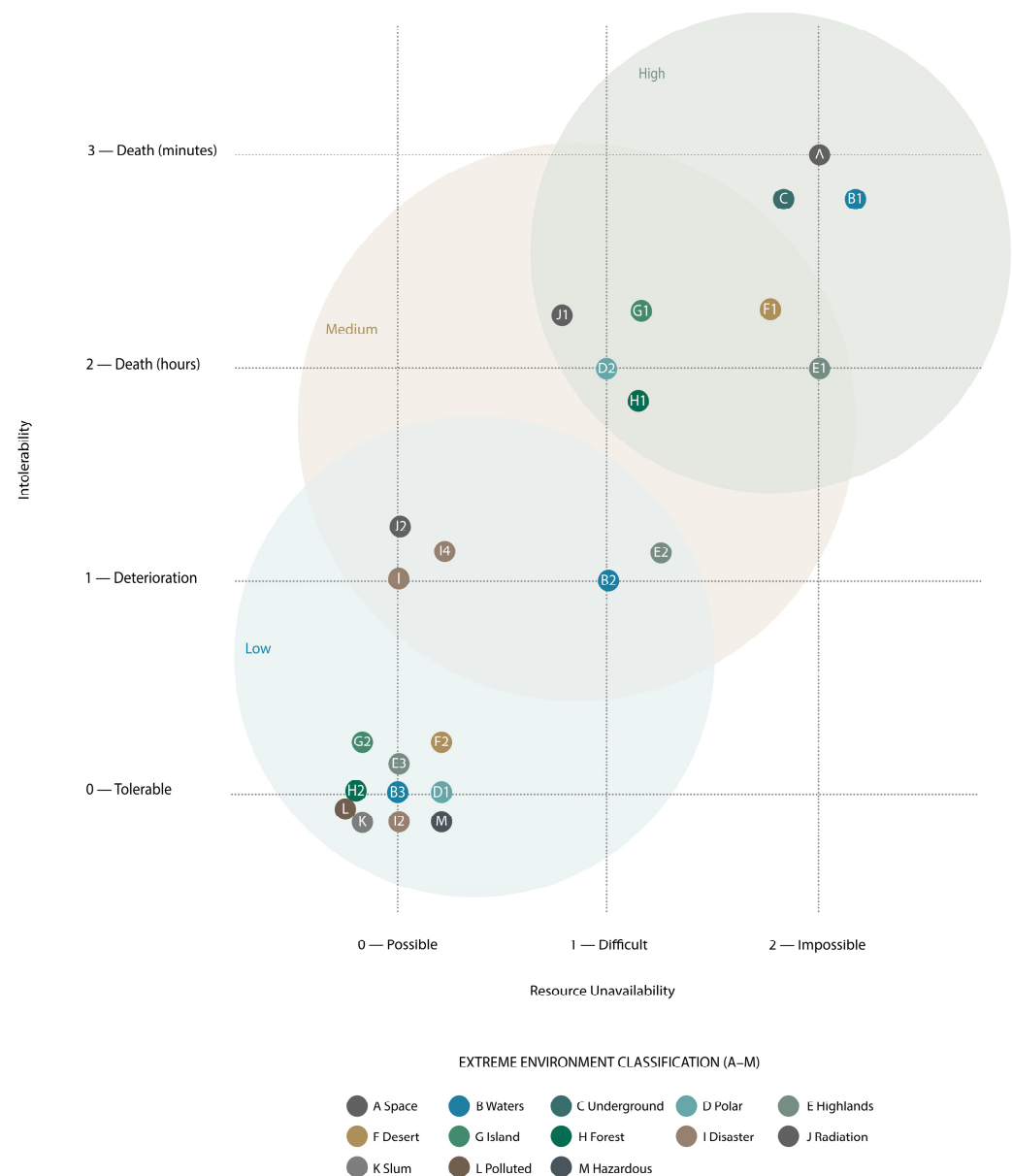


Figure 3. Dual-Criteria Environmental Map: Degree of Extremeness (DoX), constructed by the authors using the intolerability/resource unavailability framework proposed by Igarashi & Yashiro (2019) [31].

To address the interior scale, it is necessary to establish the physical boundary conditions that any off-Earth habitat must accommodate. Table 1 compiles the reference environmental parameters of Earth, the Moon and Mars in comparable units [14,30,34], so that the magnitude of divergence from terrestrial baselines becomes measurable rather than merely descriptive. Four parameters are particularly consequential for indoor living:

- Partial gravity alters posture, body movement and locomotion, and therefore the ergonomic logic of circulation, handrails, furniture and storage; its effects on the human body are generally adverse and become more pronounced in long-duration habitation [25,34].
- The light–dark cycle governs circadian entrainment: while the Martian solar day, or sol, remains close to the human circadian period [30], the lunar solar day of approximately 708 h, evenly split between two weeks of daylight and two weeks of darkness [27],

removes any natural cue for sleep–wake regulation, making artificial lighting a life support system rather than a comfort provision [24,35].

- The absence of a global magnetic field on both bodies raises annual radiation exposure to roughly 380 times the terrestrial baseline on the Moon and 204 times on Mars [34], which, combined with negligible atmospheric pressure [14], imposes shielding requirements that constrain volume, window placement and the very possibility of visual contact with the exterior [14,27].
- The near absence of ambient pressure requires the habitat to operate as a pressure vessel holding an internal pressure of approximately 101 kPa; the resulting outward load on the envelope, rather than gravity, governs its structural form [34].

A comparative overview of reference conditions across Earth, the Moon and Mars (Figure 4) illustrates the extent to which lunar and Martian environments diverge from terrestrial baselines [29,30].

Table 1. Comparative reference conditions on Earth, the Moon and Mars.

Parameter	Mars	Moon	Earth	Unit
Relative gravity	0.38	0.16	1.00	g
Effective weight of a 50 kg body	18.8	8.25	50.0	kg
Solar day (light–dark cycle)	24.67	708 (~29.5 d)	24	h
Mean surface temperature	−57	−30	13	°C
Surface temperature range	−143 to +30	−173 to +127	−89 to +58	°C
Atmospheric pressure	0.7 (0.7)	≈0 (≈0)	101.3 (100)	kPa (% of Earth)
Global magnetic field	No	No	Yes	—
Annual radiation dose (GCR)	204	380	1	mSv/year

These constraints operate simultaneously and cumulatively, and it is their combined effect, rather than any single parameters, that defines the extremeness of the environments addressed in this article [31].

Orbital habitats, the lunar surface and the Martian surface nevertheless present different environmental profiles. The International Space Station in low Earth orbit combines microgravity with vacuum, elevated radiation and large thermal gradients, so that unprotected exposure is fatal in minutes and virtually all resources must be transported from Earth [1].

On the Moon and Mars, the surrounding conditions differ in three respects that are directly relevant for architecture: gravity regime, envelope conditions and environmental dynamics. Regarding gravity, we have the following [33]:

- Terrestrial gravity (~1 g), as on Earth’s surface, where posture, movement and vestibular cues are familiar and architectural experience is tuned to this reference.
- Microgravity, as in low Earth orbit, where effective weightlessness removes a stable up–down direction; people and objects float, and any surface can become a “floor” if restraints and visual cues are provided.
- Partial gravity, as on the Moon (~0.16 g) and Mars (~0.38 g), where an up–down direction exists but mechanical loading, gait and balance differ significantly from Earth, influencing how inhabitants move, stop, change direction and stabilize themselves.

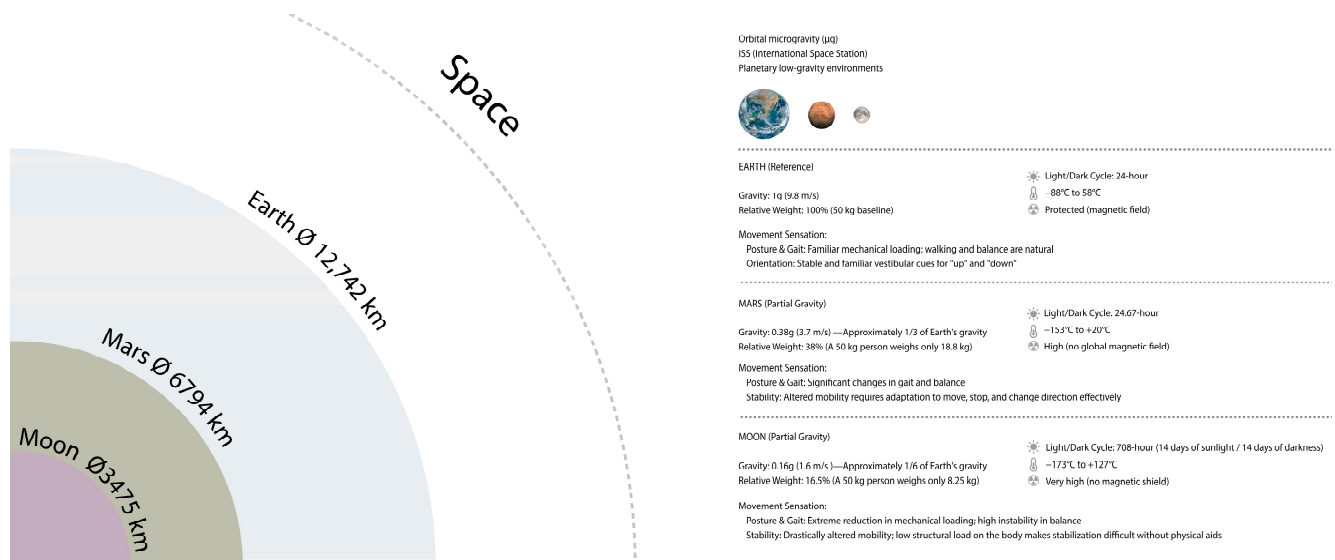


Figure 4. Reference environmental conditions on Earth, the Moon, and Mars, comparing radiation levels, gravity, atmospheric pressure, temperature ranges, and light availability.

For interior architecture, these regimes imply different demands on circulation patterns, floor–wall distinctions, posture support and the legibility of vertical orientation, reinforcing the need to treat gravity as an architectural parameter rather than a purely engineering constraint.

In terms of envelope conditions, the lunar surface is characterized by hard vacuum, lack of atmosphere and magnetic shielding, elevated solar and galactic radiation, and very large day–night temperature swings over a synodic cycle of approximately 29.5 days; recorded moonquakes and impact-related seismic events add an additional load case for structures [26,29]. The Martian surface presents a thin CO₂ atmosphere with low pressure, lower but still elevated radiation, and generally low temperatures. Dust dynamics are also distinct: lunar regolith is extremely fine, sharp and electrostatically charged, adhering to suits and penetrating seals, while Martian dust is mobilized in regional and sometimes global storms, reducing solar flux for days or weeks [29,30]. These are the material conditions behind the position assigned above on the EXM map: there is no direct access to air, liquid water, fertile soil or social infrastructure.

Long-duration orbital missions and terrestrial stations in polar regions and deserts show that, under such conditions, everyday life becomes organized around a very limited set of indoor spaces, from which every contact with the exterior departs and to which it returns [24,25]. Three design-driving conditions are particularly critical in lunar and Martian habitats:

- *Thermal and pressure regimes*—Large external temperature swings require compact, well-insulated volumes and favor partially buried or regolith-covered structures, limiting direct exposure to the landscape [27]. On Mars, in situ meteorological records show ground temperatures ranging from approximately 180 K (−93 °C) at night to around 260 K (−13 °C) during the day at mid-to-high-latitude sites, within the global range reported in Table 1, alongside a near-surface atmospheric pressure of 700–780 Pa [30]. These figures set the practical envelope for insulation performance and pressurization systems that interior architecture must accommodate.
- *Light and dust*—The dust dynamics described above make access to natural light limited and variable, both during Martian dust storms and in regolith-covered habitats and require dust to be excluded or filtered at every threshold [29,30]. Much of the responsibility for temporal structure, mood and orientation therefore shifts

onto artificial lighting, framed views and the organization of interior form. Detailed lighting design studies for Martian habitat units illustrate this trade-off in practice, combining simulated daylighting analyses across seasonal and orientation scenarios with concrete architectural responses such as light tubes, AI-controlled artificial lighting, interior gardens and framed views to greenery, explicitly justified by the established link between daylight, windows and mental health [35,36].

- *Geological instability*—Meteorite impacts and seismic activity together define a critical geological instability condition for off-Earth habitats: the Moon combines frequent micrometeoroid strikes with persistent low-level seismic activity, while Mars shows a lower impact flux thanks to its atmosphere but higher background seismicity in some active zones [27,29]. Recent reanalysis of Apollo-era seismic records has nearly tripled the number of documented moonquakes, from around 13,000 to over 35,000 events, with the most energetic (shallow) moonquakes concentrated in the Moon's northern hemisphere [37]. This substantially raises the estimated seismic design load for lunar surface habitats relative to earlier assumptions, reinforcing the case for flexible, non-brittle structural connections and site selection informed by regional seismicity.

What distinguishes these environments is not the absence of an exterior but the cost of reaching it. Contact with the lunar or Martian surface is possible only through mediation—suits, airlocks, rovers, shielded vehicles—and remains episodic, planned and bounded by consumables and radiation budgets [1,27,38].

The interior is therefore both refuge and interface: it must sustain orientation, temporal anchoring, perceived safety and psychological tolerability—the conditions on which cognitive resilience depends—and at the same time keep the outside present through framed views, transitional thresholds and the spatial sequences of egress and ingress [24].

3.2. Analytical Lens: Neuroarchitecture

The analytical lens adopted in this article builds on the long trajectory from environmental psychology, phenomenological architecture and biophilic design to contemporary neuroarchitecture, with a specific emphasis on how interior architectural form shapes perception and comfort in everyday and extreme settings, and on how it sustains the orientation, temporal anchoring, perceived safety and psychological tolerability on which indoor life in extreme environments depends (Section 3.1). Neuroarchitecture is used here as an integrative approach that connects research on people and their environments, architectural theory and multisensory accounts of dwelling, while directing attention toward variables that are especially relevant for indoor living under confinement: architectural form, enclosure, room proportions, material atmosphere and perceptual ease.

3.2.1. Precursor Traditions: Gestalt, Environmental Psychology, Phenomenology of Place and Biophilia

Architectural and psychological traditions developed in parallel from the early twentieth century onwards, treating form, perception and embodiment as inseparable. Gestalt psychology demonstrated that perception does not register isolated stimuli but organizes visual input into structured wholes through principles of proximity, similarity, continuity and figure-ground, which Arnheim [39,40] applied to the analysis of composition and visual order in buildings. Proportion, enclosure and alignment thereby shape perceptual comfort by determining how effortlessly occupants grasp spatial structure and avoid perceptual overload, a concern that becomes acute wherever visual information is dense, repetitive or, conversely, impoverished.

Since the mid-twentieth century, environmental psychology has progressively re-framed space as an active component of human experience rather than a neutral backdrop, showing that spatial layout, density, privacy gradients and material qualities systematically influence mood, cognitive performance and social behavior. The premise of this tradition is that behavior is a joint function of person and environment, a formulation of mid-twentieth-century field theory later consolidated in environmental psychology. Its transposition to spacecraft and to isolated, confined and extreme settings is already well documented [41–43].

This person–environment relation was given an ecological formulation by Gibson and Barker and subsequently systematized by Heft (2016), for whom experience, meaning and behavior emerge from multi-level environmental structures rather than from an isolated subject [44]. Two concepts from this tradition are load bearing for the present article. The first is the behavior setting, Barker’s higher-order ecological unit, in which the physical configuration of a place, the activities it hosts, and their temporal patterning form a single functional entity that co-organizes attention, arousal and interaction. The second is the affordance, the relational property by which an environmental feature offers a possibility for action to a particular organism. Read together, these concepts establish that architectural variables are not descriptive attributes of a container but the terms in which occupants perceive what a place allows, prevents or invites.

Early empirical work within this tradition already linked specific spatial features to comfort and strain. Stokols (1972) [7] distinguished physical density from crowding as a subjective, stress-related state, and Sommer’s (1969) [45] studies of personal space and spatial invasion showed that control over interpersonal distance is itself a determinant of well-being [7]; Hall’s (1990) proxemics established that these distances are culturally calibrated rather than universal [46]. Reviewing this body of work, Gifford (2001) reports that perceived density and lack of control over interpersonal distance correlate with stress and reduced satisfaction even when objective floor area remains constant, and that consequences differ under high social as opposed to high spatial density [13]. The corollary for confined habitats is direct: privacy cannot be secured by floor area alone, but depends on graded transitions, acoustic and visual separation and the possibility of regulating exposure [33].

Phenomenological approaches to architecture developed alongside this empirical tradition, emphasizing embodiment and multisensory experience rather than measurement. Eberhard’s *Brain Landscape* (2009) and Robinson and Pallasmaa’s *Mind in Architecture* (2015) explicitly articulate how architectural form and atmosphere participate in the co-construction of cognitive and affective states, and Gallese and Gattara (2015) ground this participation in embodied simulation, arguing that the perception of built form recruits the same sensorimotor resources involved in acting within it [32,47,48].

A distinct contribution of this tradition concerns the scale of place. For Norberg-Schulz (1980), dwelling is not reducible to shelter: it requires orientation, the capacity to know where one is, and identification, the capacity to recognize the character of where one is [49]. That character, the *genius loci*, is not produced by the building alone but arises from the relation between the built form and the environmental setting that surrounds it, its light, ground, climate and horizon. The proposition is consequential for off-Earth habitats. A pressurized volume on the lunar or Martian surface acquires its character from a setting that cannot be inhabited directly, which means that the macro-scale conditions are not only structural constraints on the envelope but constituents of the place the interior comes to be.

Pallasmaa (2012) deepens this line of argument through a critique of the ocularcentric bias of modern architectural culture [50]. In *The Eyes of the Skin* and subsequent texts, he contends that the privileging of vision over the other senses has produced buildings that

are visually striking and experientially impoverished, and that architectural experience is in fact fundamentally multisensory and atmospheric: peripheral vision, touch, audition, the sense of temperature and even smell are primary mediators of spatial experience rather than secondary accompaniments to sight. Central to his argument is the notion that the skin reads the texture, weight, density and temperature of matter, so that materiality is apprehended haptically before it is judged visually. An environment lacking what he terms tactile plasticity and peripheral richness therefore leaves occupants in a condition of sensory deprivation that visual stimulation alone cannot compensate, however carefully composed. Pallasmaa further argues that atmosphere is perceived diffusely and pre-reflectively, as an overall ambience grasped before any element is identified in detail, which locates a substantial part of environmental well-being below the threshold of deliberate attention. This account provides the theoretical basis for treating multisensory atmosphere, alongside geometry and enclosure, as a primary architectural variable, and it bears directly on habitats where the sensory field is bounded by the envelope itself.

Robinson (2021) [51] extends the argument to the regulatory function of that envelope. Her notions of nesting and the skin mind propose that materials, textures and spatial enclosures constitute a second body that can support or disrupt a lived sense of security and tranquility. For occupants confined to a habitat for extended periods, the qualitative character of enclosure, the modulation of surfaces and the balance between openness and protection therefore become critical. A habitat composed entirely of hard, monotonous, visually flat enclosures risks becoming, in Robinson's terms, a traumatizing second skin, whereas carefully articulated forms and materials can help constitute a responsive nest that participates in stabilizing affect and bodily ease.

The biophilic turn generalizes this intuition by arguing that human cognition and emotion are evolutionarily attuned to natural environments, and that built settings which disregard natural patterns, rhythms and complexities risk undermining attentional engagement and psychological well-being [8,9]. Biophilic design translates this premise into spatial strategies that bring occupants into repeated, meaningful contact with nature and nature-like conditions across visual, tactile and spatial dimensions. Rather than simply adding plants, it treats features such as vegetation, water, natural materials, daylight and prospect-refuge relationships as variables that modulate attention, emotional tone and environmental legibility.

Pattern-based frameworks such as the 14 Patterns of Biophilic Design systematize these ideas by distinguishing recurring configurations associated with reduced stress, improved mood and enhanced cognitive performance in terrestrial buildings [52]. These patterns (Figure 5) organized into the three categories proposed by the framework and situates them in relation to the regulatory demands they address, positioning the habitat as a mediating membrane between the organism and its environment. The categories are distinguished by the kind of relation each establishes with nature:

- *Nature in the Space* addresses the direct, physical and ephemeral presence of natural elements and comprises visual and non-visual connection with nature, non-rhythmic sensory stimuli, thermal and airflow variability, presence of water, dynamic and diffuse light, and connection with natural systems.
- *Natural Analogues* addresses organic, non-living and indirect evocations of nature through biomorphic forms and patterns, material connection with nature, and complexity and order.
- *Nature of the Space* addresses spatial configuration rather than content: prospect, an unimpeded view over a distance for surveillance and planning; refuge, a place of withdrawal in which the individual is protected from behind and overhead; mystery,

the promise of further information through partially obscured views; and risk/peril, an identifiable threat coupled with a reliable safeguard.

The three categories are not equally transferable to a pressurized habitat, and the asymmetry is itself informative. Both Natural Analogues and Nature of the Space are matters of form, material and layout, and are therefore available to the designer without consumable or volumetric penalty. Nature in the Space is more constrained, though unevenly so: vegetation and water carry mass and life support costs, whereas dynamic and diffuse light, thermal and airflow variability and non-rhythmic sensory stimuli can be delivered through the environmental systems that already sustain the habitat rather than through living matter. Two of the definitions bear directly on the argument developed here. Refuge, understood as protection from behind and overhead within a shared setting, restates in perceptual terms the privacy requirement established above, where floor area alone proved insufficient. Risk/peril, understood as an identifiable threat coupled with a reliable safeguard, describes the ordinary perceptual condition of an off-Earth interior, in which the envelope is continuously read against what it excludes.



Figure 5. Conceptual diagram, constructed by the authors, based on the framework “The 14 Patterns of Biophilic Design” proposed by Browning, Ryan & Clancy (2014) [52].

Recent experimental evidence supports the underlying claim: a virtual reality study comparing biophilic and non-biophilic office environments found consistently faster physiological and psychological recovery from stress and anxiety in the biophilic conditions, indicating that even simulated nature cues can produce measurable restorative effects [53]. The study further differentiates between the biophilic conditions it tested. Tangible interior elements such as plants, water and natural materials drove the recovery of physiological stress, whereas a window with daylight and a distant view drove the recovery of anxiety. Two regulatory channels are therefore in operation, one working through the material substance of the enclosure and the other through visual access to a beyond. The distinction

is consequential for extreme environments, where the exterior is lethal and cannot be opened onto directly, while the second channel depends precisely on the perception of an outside. That the effect was obtained in a simulated setting is significant, since the window was itself a representation, which gives a preliminary warrant for mediated views where a direct one is impossible. The warrant remains preliminary, since exposure lasted minutes rather than the months of a mission.

When transposed to space habitats, the biophilic patterns cannot be replicated literally. They can, however, be translated into nature-like cues (light dynamics calibrated to a terrestrial or local diurnal rhythm, material atmospheres, framed views and multisensory complexity) that support cognitive resilience where exposure to genuine natural variation is minimal. Among these, dynamic and diffuse light carries weight, since it addresses directly the temporal dimension of habitability previously identified: in the absence of reliable natural *zeitgebers*, the interior must itself supply the variation that anchors occupants in time [41]. These findings establish that specific configurations produce measurable effects, but they do not specify how architectural form is processed, which variables carry the effect, or how such evidence can be obtained under conditions that resemble a mission: questions that neuroarchitecture addresses directly.

3.2.2. Neuroarchitecture: Consolidation, Evidence and Methodological Position

The belief that spatial configuration shapes psychological and behavioral outcomes long precede its scientific study. From Egyptian and Greek monumental design intended to structure experiences of the sacred and the afterlife, to twentieth-century functionalist architecture and its programmatic claims about health and efficiency, architects have consistently acted on the assumption that built form conditions states of mind [54]. What distinguishes the contemporary moment is the availability of methods capable of testing that assumption.

Neuroarchitecture builds on this accumulated foundation as an interdisciplinary field that makes the relationship between brain and environment explicit, combining neuroscience, environmental psychology and architecture to investigate the brain dynamics elicited by action in and interaction with the built environment [11]. Rather than representing a rupture with the traditions previously reviewed, it can be read as a contemporary consolidation and re-labelling of concepts developed across environmental psychology, Gestalt theory, phenomenology of place and embodiment, and biophilic design, with a sharpened focus on how built form participates in perceptual and emotional regulation [12]. Its core proposition is that architectural space operates as an active co-regulator of perception, affect and stress, in which variables such as spatial hierarchy, enclosure, complexity and sensory richness modulate how easily occupants orient themselves, feel at ease and sustain engagement over time.

Empirical work in the field has begun to specify these relationships. Abbas et al. (2024) show how specific architectural elements modulate neural and emotional processes, reinforcing that the built environment participates directly in cognitive and affective regulation [55]. Banaei et al. (2017), using mobile EEG combined with virtual reality, demonstrate that curved as opposed to angular interior geometries modulate activity in regions including the anterior cingulate cortex, indicating that elementary properties of room shape participate in stress regulation and in the affective appraisal of space [56]. Reviewing the wider evidence base, Coburn et al. (2020) report convergent psychological and neural responses to architectural interiors across studies [57]. More recently, the extension of this experimental paradigm through Mobile Brain/Body Imaging (MoBI) has been proposed, combining ecological psychology with state-of-the-art neuroscience methods to capture architectural experience as an embodied, exploratory process [54].

The field also sustains an active internal debate about its own scope and methods, and this debate is directly relevant to the approach adopted here. Higuera-Trujillo et al. (2021) caution against equating architectural experience with aesthetic experience alone, since aesthetics is only one component of a broader cognitive–emotional dimension that also includes ergonomics and functionality; they further identify a central methodological limitation of current neuroarchitecture research in the low ecological validity of established brain imaging methods, which typically require stationary participants viewing static two-dimensional representations of architectural spaces [10]. Addressing the same concern, Wang et al. (2022) argue that architectural experience is inherently embodied: people interact with space by moving through a building, opening doors or taking stairs, and architectural affordances are perceived directly only through such movement [54]. When an observer remains stationary, or when architecture is presented as a static image, this experience is reduced to a single fixed perspective.

This limitation informs the position adopted in this article. Neuroarchitecture is employed here as a conceptual lens rather than as a shorthand for a set of measurement techniques. The available experimental apparatus cannot yet reproduce the conditions under examination: prolonged confinement, altered gravity, absence of natural zeitgebers and the impossibility of unmediated egress. Transposing findings obtained from stationary participants viewing static images of terrestrial rooms to multi-year Martian habitation would compound the very ecological validity problem the field itself has identified. The lens is therefore used to organize and interpret converging evidence across traditions, not to substitute for the experimental validation that a future stage of this research will require.

A second gap reinforces this choice. The existing systematic mapping of the intersection between neuroscience and the built environment [11], like the wider neuroarchitecture literature, is conducted almost entirely in terrestrial, non-confined settings and does not address isolated, confined and extreme environments or off-Earth habitats. The lens must therefore be extended rather than simply applied, and it is this extension that the present model undertakes.

Within this lens, a defined set of interior variables forms the core of the analysis of indoor comfort for cognitive resilience in off-Earth ICE habitats: room shape and proportions; degrees of enclosure and privacy gradients; visual order and information load; and multisensory atmospheres and indoor environmental quality, including their modulation over the daily and mission-length cycles. These are architectural means, and they sustain the conditions identified as necessary for indoor life under extreme conditions: orientation, temporal anchoring, perceived safety and psychological tolerability. Curvature and angularity, degrees of enclosure, room proportions and the presence or absence of visual order influence how readily occupants attune to an interior, relax within it and maintain a tolerable relationship with confinement over time [55]. Within the conceptual model proposed here, these variables are organized into functional clusters of indoor living.

4. Results: Linking Macro EEs/ICEs and Micro Indoor Living

Building on the environmental characteristics established in the Conceptual Scope, this section integrates and re-evaluates that macro-level data on lunar and Martian conditions to derive their architectural implications for indoor living, connecting macro-scale extremeness to the micro-scale design responses discussed below. In this chapter, perspectives from space architecture and planetary science first enable us to characterize the extreme nature of these environments at the macro level; this macro context is then related to architectural issues concerning interior form and indoor environmental quality for daily life in space habitats—the micro level.

These macro-scale conditions are not mere background information but structuring constraints: the thermal and pressure regime already characterized for Mars surface habitats narrows the admissible envelope for insulation and pressurization that ultimately conditions somatic and operational comfort at the micro scale, while the substantially higher seismic design loads revealed by recent lunar seismicity reanalysis directly constrain the structural flexibility choices that, in turn, shape the circulation, workstation layout and privacy partitioning [30,37].

At the micro scale of indoor living, habitability research shows that off-Earth habitats must be understood as dense constellations of functions supported, or undermined, by indoor environmental quality (IEQ) rather than as neutral containers for life support hardware. IEQ is typically defined as the combined quality of thermal conditions, air, acoustics, lighting and visual environment as perceived by occupants, and it has been repeatedly linked to physiological homeostasis, cognitive performance and behavioral health in confined and extreme environments.

Synthesized in this way, Table 2 makes explicit that the four clusters share a single theoretical foundation, neuroarchitecture read through ecological affordances, rather than constituting four unrelated psychological sub-domains; what differs across clusters is the specific somatic, operational, psychosocial or ludic-recreational mechanism through which that shared lens is expressed. In combination with the macro-scale physical drivers discussed above, these results show that habitability in off-Earth ICE habitats cannot be reduced to a single variable or a single architectural lever, but emerges from the cumulative interaction of thermal, structural, gravitational and psychosocial constraints across the four functional dimensions.

In lunar and Martian surface habitats, where everyday life unfolds almost entirely indoors and exposure to natural environmental variation is drastically reduced, IEQ is not a secondary comfort parameter but a primary medium through which inhabitants experience, interpret and regulate the surrounding world. Within this frame, habitability, understood as the quality of life in the habitat and the equilibrium between human needs, mission demands and environmental conditions, is expressed through a recurrent set of indoor living functions. Across spacecraft, orbital stations, analogue facilities and polar bases, the literature converges on four interrelated clusters that are particularly relevant for cognitive resilience under EE/ICE conditions [47,51,52,57]:

- **Somatic functions** (sleep, circadian alignment, nutrition, hygiene, basal comfort)—Habitability studies show that misaligned light–dark cycles, inappropriate temperatures, intrusive noise and poor air quality systematically impair sleep and basic comfort, leading to fatigue, attentional lapses and mood disturbances in confined missions [1,57]. In lunar and Martian habitats, where natural *zeitgebers* are weak or absent, lighting spectra and dynamics, thermal zoning, acoustic absorption and ventilation patterns become architectural levers for sustaining somatic stability and, through it, cognitive performance [57].
- **Operational functions** (work, maintenance, locomotion, emergency response)—Lessons from terrestrial analogues highlight that layout legibility, net habitable volume, circulation clarity, workstation ergonomics and noise control are central to maintaining performance over time [25]. Here, habitability appears as usability: interiors that support efficient, low-friction action and minimize unnecessary cognitive load, allowing crews to execute complex procedures under stress without constant micro-decisions about orientation, access or local environmental comfort. This operational usability is itself gravity dependent.
- **Psychosocial functions** (privacy, crowding, social interaction, territoriality)—Long-duration ICE analogues report that insufficient privacy, perceived crowding and

monotonous social spaces foster interpersonal tension, demoralization and “psychological hibernation” [24]. Habitability here means livability: individual retreats, graded transitions between private and common areas, and socio-spatial cues that support cultural expectations of proxemics [45]. IEQ contributes via acoustic and visual privacy, differentiated lighting and color, and opportunities for personalization, letting inhabitants regulate social exposure where stepping outside is not an option.

Strategies from analogue and space habitat practice include multi-directional circulation to enlarge perceived volume, flexible partitions and adaptable furniture for varied privacy configurations, and color, lighting and texture calibrated against crowding [33]. These demands scale with mission duration: short-stay lunar outposts require accommodation for episodic crowding, whereas the multi-year isolation of Martian transits and surface missions demands privacy and territoriality provisions able to sustain equilibrium over far longer timescales. Room geometry itself carries affective weight: virtual reality and EEG evidence shows that curved boundaries elicit more positive affective and arousal responses than sharp-angled ones [58], making curvature and proportion further variables through which psychosocial comfort can be supported.

- **Ludic-recreational functions** (play, leisure, reverence and spirituality)—The concept of habitability goes beyond mere survival and the performance of tasks, encompassing restorative and recreational dimensions such as play, leisure, recuperation, and experiences of wonder and contemplation, as significant measures against monotony, under stimulation and existential fatigue in confined habitats. Research on recreational spaces in microgravity frames functional, social, constructive and imaginative play as recreational and restorative means to support adaptability, emotional regulation and group cohesion in space environments [51,59]. Qualitative accounts from space and analogue missions also highlight the restorative role of music, reading, shared meals, informal social spaces and framed natural or substitute views, all dependent on interior light, sound, texture and visual complexity. Beyond these sensory dimensions, restoration also involves how interiors sustain meaning, belonging and a felt connection to a larger order. Following Sarah Robinson’s phenomenological and biophilic reading of architecture, reverence can be understood as an architectural condition in which interior space fosters contemplation, emotional resonance and attunement to something greater than immediate operational demands. This aligns with the “live–work–play” framework in mission planning (ESA/NASA), which recognizes that long-duration habitats must support restorative and recreational practices beyond work and survival [25,52].

The four clusters (Figure 6) organize these indoor living functions into a single analytical structure, each with its associated indoor environmental quality dimensions. They were derived by cross-referencing the macro-scale physical constraints of lunar and Martian EE/ICE conditions with the neuroarchitecture and ecological affordances literature on how built environments shape cognitive and affective experience, a basis that the Discussion Section translates into architectural principles for cognitive habitability.

Table 2. Comparative synthesis of the four habitability clusters underlying the neuroarchitecture contributes.

Cluster (Functions)	Key Representatives	Core Explanation	Contribution	Limitation	Integration Proposed
Somatic	Coburn et al. [57]; Martínez et al. [30]; Amini et al. [35]; Amini et al. [36]	Accounts for how physiological regulation (sleep, circadian rhythm, nutrition, hygiene) sustains baseline comfort and cognitive performance in confined missions.	Establishes the physiological foundation on which cognitive resilience depends, directly linking lighting, thermal and acoustic comfort to circadian and homeostatic stability.	Evidence derives mainly from terrestrial analogues and orbital settings; direct empirical validation under partial gravity (Moon/Mars) is still lacking.	Establishes the physiological baseline of the neuroarchitecture model, mapping sleep, circadian and sensory regulation onto the lighting, thermal and acoustic dimensions of indoor living in EE/ICE.
Operational	Häuplik-Meusburger & Bannova [25]; Robinson & Pallasmaa [47]; Wang et al. [54]; Martínez et al. [30]; Onodera [37]; Benaroya [26]; Igarashi & Yashiro [31]	Addresses how layout legibility, circulation and ergonomics sustain task performance and reduce cognitive load under stress.	Introduces gravity dependence as a structuring variable, showing that ergonomic and spatial patterns must be recalibrated, not transposed directly from Earth.	Most usability findings come from terrestrial analogues or microgravity; partial gravity specific ergonomic data remain scarce.	Recalibrates layout, circulation and ergonomics through an affordance-based reading, showing that spatial patterns must adapt to gravity rather than transpose Earth-based standards.
Psychosocial	Browning et al. [52]; Pagnini et al. [24]; Häuplik-Meusburger & Bannova [33]; Shemesh et al. [58]; Onodera [37]; Sommer [45]	Describes how privacy, crowding, territoriality and proxemics regulate interpersonal tension and psychological equilibrium in isolated crews.	Adds a mission-duration scale (short lunar stays vs. prolonged Martian isolation) and links room geometry to affective/EEG response.	Findings derive mainly from small crew analogue studies; generalization to larger crews remains uncertain.	Translates privacy, territoriality and proxemics into a duration-sensitive design logic, linking room geometry and social exposure to psychosocial equilibrium.
Restorative & recreational	Robinson [51]; Robinson & Pallasmaa [47]; Liapi & Ackermann [59]; Häuplik-Meusburger & Bannova [25]; Häuplik-Meusburger & Bannova [33]; Browning et al. [52]; Yin et al. [53]	Explains how leisure, play and reverence counteract monotony and under stimulation over prolonged confinement.	Frames restorative functions as overlapping with the other three clusters rather than separate, drawing on a biophilic and phenomenological reading of reverence, contemplation and aesthetic experience within the interior.	Evidence is mainly qualitative, drawn from mission narratives and case studies, without systematic measurement of restorative outcomes.	Positions play, leisure and reverence as functions that overlap with the other three clusters rather than standing apart, counteracting monotony through multisensory and flexible space design.



Figure 6. Four habitability clusters in space habitats and their associated indoor environmental quality (IEQ) dimensions.

5. Discussion

5.1. Architectural Principles for Cognitive Habitability

Environmental psychology consistently shows that spatial layout, density, privacy gradients and materiality shape mood, cognition and social behavior, indicating that the built environment functions as a structured field of affordances rather than a neutral background. Gestalt-informed approaches underline that figure–ground relations, grouping principles and visual order determine how easily occupants understand complex scenes, anticipate continuities and avoid perceptual overload. In parallel, phenomenological and biophilic readings reinforce the view that buildings act as an extension of the body’s regulatory envelope, in which form, texture, sound, light and nature-like patterns participate in self-regulation and stress recovery. In EE/ICE contexts, where the habitat becomes the primary world, these strands converge on a central idea for this article: interior form and interior atmospheres are active regulators of perception, emotion and behavior, and therefore structural components of cognitive resilience.

Within this conceptual model, the neuroarchitecture reading proposed here focuses on four groups of interior variables, directly related to the functional clusters of indoor living identified earlier (Figure 6):

- **Somatic functions**—Variables such as bedroom shape, proportions, sleep configuration, circadian lighting, thermal/acoustic comfort and air quality support or disrupt sleep, recovery and homeostasis, with direct impact on attention and performance reliability.
- **Operational functions**—Layout legibility, net habitable volume, circulation clarity, workstation ergonomics, background noise and visual order condition the cognitive load required to navigate, locate functions and carry out tasks under stress.
- **Psychosocial functions**—Degrees of enclosure, privacy gradients, perceived density and the atmosphere of common areas determine opportunities for retreat and exposure, regulating social vigilance, relational effort and small-team cohesion.
- **Ludic-recreational functions**—Controlled complexity and variability, niches for leisure, opportunities for views, music and sensorimotor exploration depend on light, sound, texture and spatial patterns, and operate as countermeasures to monotony and under-stimulation.

The integration of the four clusters with IEQ dimensions may form the foundation for neuroarchitecture design in extreme environments, where interior space must actively support cognitive resilience across somatic, operational, psychosocial and ludic-recreational functions. In this perspective, four families of architectural variables become particularly salient for the cognitive habitability of lunar and Martian habitats:

- **Room shape and proportions**—These influence perceived enclosure, crowding and bodily comfort, as well as the speed with which spatial structure is grasped and trajectories are planned, especially in partial gravity conditions. Empirical evidence from virtual reality and electroencephalographic (EEG) experiments confirms this relationship: across a controlled comparison of four space geometries (square, round-domed, sharp-edged and curvy), curvature—rather than symmetry—was the geometric property most strongly associated with users' subjective preference, with non-expert participants showing a marked and statistically significant preference for the curved enclosure over sharp-angled alternatives; a parallel EEG analysis further showed that this same geometric distinction could be recovered directly from brain activity patterns, independent of participants' conscious reports [58].
- **Degrees of enclosure and privacy gradients**—These condition access to retreat and exposure and modulate regulation of proximity in small crews, directly engaging the psychosocial cluster.
- **Visual order and information load**—Alignments, symmetry, repetition and controlled variation, figure-ground clarity, which affect the effort needed to “read” the interior and anticipate continuities, with implications for error and attentional fatigue.
- **Multisensory atmospheres and IEQ**—Light intensity and spectrum, acoustic character, material tactility, olfactory cues and the presence of nature-like elements, which modulate arousal levels, stress responses and the potential for attentional restoration, supporting both somatic stability and the ludic-recreational dimensions of habitability.

Within this conceptual model, the relationships between habitability clusters and their associated IEQ dimensions are synthesized in a radial diagram (Figure 6), while the corresponding neuroarchitecture indicators for lunar and Martian surface habitats are summarized by cluster and IEQ dimension in Table 3.

The partial gravity condition noted above for room shape and proportions is not incidental. Ecological accounts of architectural affordances treat comfortable and safe use of space as a body-scaled, relational property rather than a fixed, universal measurement [54]. Under lunar or Martian gravity, altered gait, balance, reach and energy expenditure change these body-environment relations, so Earth-based anthropometric and ergonomic standards cannot be transposed directly. Room proportions, circulation clarity and workstation ergonomics must be recalibrated for each gravity regime. The behavioral and neural

evidence on room geometry reported above reinforces the phenomenological argument: geometric properties of enclosed space are not aesthetic variables but measurably shape affective and physiological state. Curvature proved more perceptually salient than symmetry, nuancing Gestalt accounts of spatial cognition, which have traditionally emphasized symmetry and regularity as primary organizing principles. Where interior geometry is constrained by structural and volumetric limits, modest curvature in wall or ceiling surfaces, rather than full formal symmetry, may therefore be a more cost-effective lever for psychological comfort under prolonged confinement [58].

Table 3. Neuroarchitecture indicators of Moon and Mars space habitats.

Habitability Cluster	IEQ Dimension	Moon	Mars
Somatic	Thermal/pressure	High-inertia compact cores; deeply embedded sleeping quarters.	Protected cores with some semi-transparent envelopes; sleeping quarters nearer mediated views.
	Air quality	Tight airlock/de-dusting chains; rest zones segregated from airlock circulation routes.	Airlocks sized for dust storms; rest zones segregated from storm-exposed transitions.
	Lighting/circadian	Fully artificial light cycles; controlled darkness and sunrise in sleep areas.	Filtered daylight and dynamic artificial cycles; mediated windows near sleep zones.
Operational	Visual/formal	Compact hierarchical plan; strong interior landmarks (colour, texture, light).	Plan articulated with terrain; framed external features as orientation aids.
	Layout and wayfinding	Short, low-branching routes; strong floor–ceiling continuity; high-contrast signage.	Compact routes and internal loops; wayfinding reinforced by mediated exterior cues.
	Air quality	Dust-shielded workstations; localized dust-control infrastructure.	Storm-robust air-treatment zones; work areas away from most exposed façades.
Psychosocial	Acoustic	High cabin–commons sound isolation; absorptive finishes.	Acoustic buffers between noisy tech zones and social areas; tuned reverberation.
	Visual/formal	High-enclosure cabins; small visual-refuge niches; virtual/mediated views.	Wider openness range; bays and commons framing Martian horizons.
	Privacy gradient and control	Short privacy chain; strong individual control of light/sound in cabins.	Longer privacy chain; semi-public enclaves with distinct identities.
Restorative & recreational (ludic)	Spatial flexibility and adaptability	Multi-use volumes with convertible surfaces; stowable furniture allowing work zones to be reconfigured as leisure zones.	Reconfigurable commons with movable partitions; dedicated ludic and contemplative niches sustained over year-scale stays.
	Lighting/circadian	Highly variable, expressive lighting in recreational zones.	Expressive lighting combined with subtle Martian day–night cues.
	Multisensory/material	Warm, soft, bio-mimetic textures; VR “Earth windows”.	Domestic-like textures; symbolic references to Martian context.

In space habitats, where external sensory input is limited and the same interior configurations are encountered daily over months or years, this model suggests that interior form and IEQ must be deliberately configured so that the four functional clusters of indoor living—somatic, operational, psychosocial and ludic-recreational—act as supports, rather than erosive forces, for cognitive resilience over time.

Rather than treating habitability as a residual comfort issue, this perspective frames cognitive resilience as an emergent property of the human–habitat system, shaped by how interior form and indoor environmental quality are designed under conditions of high intolerability and resource unavailability.

As a synthesis of the preceding analysis, Figure 7 integrates the physical drivers, biophilic patterns and IEQ dimensions into a unified conceptual model of space habitat resilience.

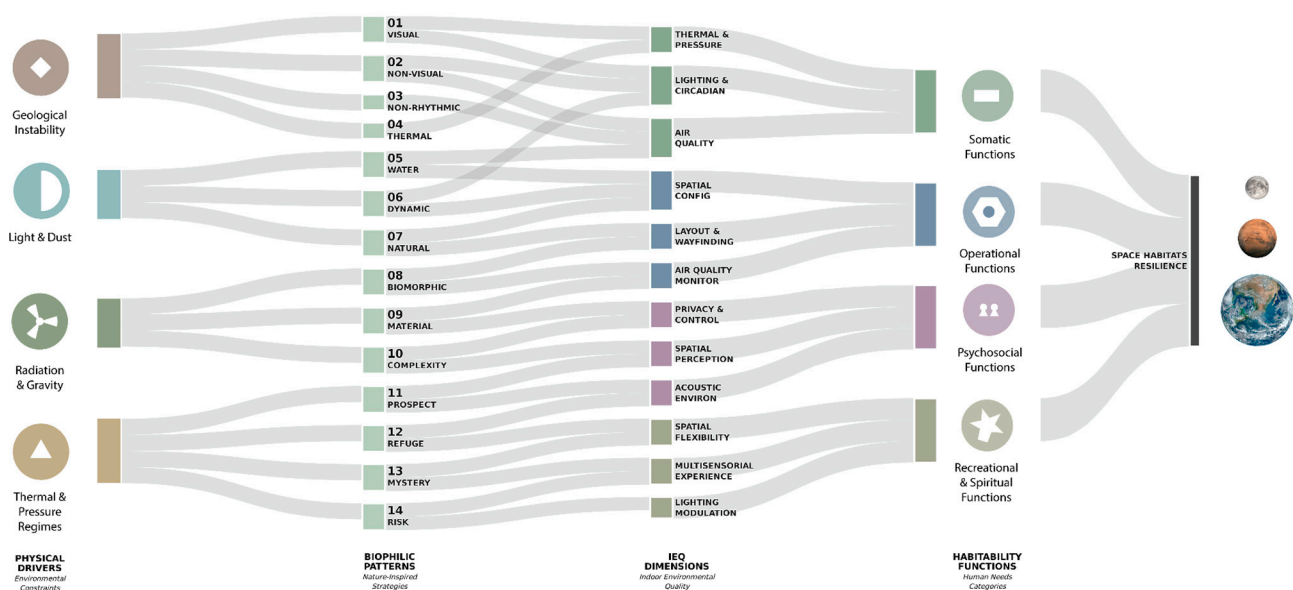


Figure 7. Neuroarchitecture conceptual model: dynamic flows converging toward space habitat resilience across macro-scale constraints and micro-scale interior variables.

The conceptual model in Figure 7 presents a directed flow across five columns. The first sets out the physical drivers of the macro scale: geological instability, light and dust, radiation and gravity, and thermal and pressure regimes. These converge on the fourteen biophilic patterns, which constitute the mediating repertoire available to the designer. The patterns feed the twelve IEQ dimensions, grouped in four triads, and these resolve into the four habitability clusters established in Section 4. The final node gathers the four clusters into space habitat resilience, referring to lunar, Martian and terrestrial settings.

The diagram is read as a chain of mediation. Planetary constraints do not act on the occupant directly, since the envelope excludes them. They act by determining which biophilic patterns remain available, which indoor environmental qualities can be sustained, and therefore which habitability clusters the interior is able to support. Each triad of IEQ dimensions is assigned to the cluster it primarily serves, while the crossing of flows in the central region shows that no pattern serves a single dimension and no dimension serves a single cluster. Dynamic and diffuse light reaches both circadian regulation and multisensory experience; refuge reaches both privacy control and spatial perception. The width of the flows is qualitative and carries no quantitative weighting.

The inclusion of terrestrial settings in the final column is deliberate. The same chain applies wherever the exterior is inaccessible or hostile, which extends the model to polar stations, submarines and other isolated, confined and extreme environments on Earth, and

allows for terrestrial analogues to serve as testing grounds for propositions that cannot yet be verified off-Earth.

The conceptual neuroarchitecture model developed in this article establishes three fundamental contributions that reposition interior architecture as a structural determinant of cognitive habitability in extreme environments:

- First, it formalizes the coupling between macro-scale planetary constraints and micro-scale interior experience. While lunar and Martian surfaces present comparable degrees of extremeness (intolerability level 3, resource unavailability level 2), their distinct gravity regimes (0.16 g vs. 0.38 g), dust dynamics and light/dark cycles translate into different architectural affordances for room proportions, circulation clarity and sensory stimulation (Table 3). This specificity challenges the prevailing assumption that space habitats can be designed as environment-agnostic pressurized containers.
- Second, the model demonstrates that cognitive resilience is architecturally structured through the systematic integration of four habitability clusters, somatic, operational, psychosocial and ludic-recreational, with the dimensions of indoor environmental quality. Conventional IEQ frameworks assess four to five generic dimensions, thermal comfort, air quality, acoustic environment and visual or lighting comfort, applicable to buildings in general. Under confinement these prove insufficient, since the same dimension operates differently depending on the function it serves. The model therefore redistributes them into twelve cluster-specific dimensions, three per cluster, so that air quality in a rest zone and air quality at a workstation are treated as distinct design problems rather than as a single performance threshold. No single IEQ dimension acts in isolation (Figure 7): circadian lighting supports somatic stability but also modulates psychosocial atmosphere; acoustic absorption reduces operational cognitive load while enabling privacy gradients for retreat. This cross-dimensional interdependence implies that habitat design cannot optimize functions sequentially and must instead treat interior form and IEQ as a coupled system in which architectural decisions propagate across multiple clusters simultaneously.
- Third, and most critically, the model identifies interior form variables—room shape, enclosure degrees, visual order and multisensory atmosphere—as primary mediators between environmental extremeness and human tolerability.

Evidence from Gestalt-informed studies, phenomenological frameworks and neuroarchitecture research converge on a decisive conclusion: perceptual ease, stress modulation and restorative potential are outcomes of deliberate spatial configuration rather than byproducts of sufficient volume or functional efficiency. Under EE/ICE conditions, where stepping outside without protection is impossible, interiors that fail to support effortless orientation, controllable exposure and sensory variation actively erode cognitive performance and psychosocial stability over time, well beyond any loss of comfort. This convergent architecture of resilience can be restated as a single chain: macro-scale extremeness (gravity, radiation, dust, light) constrains protective strategies (shielding, burial, compact volumes), compressing everyday life into limited interior configurations that define Built Environments in Extreme Environments (BEXEs). Within this constrained envelope, the four functional clusters and their associated IEQ dimensions structure how inhabitants experience confinement. Cognitive resilience emerges or fails at this intersection, determined by whether interior form and atmosphere function as regulatory supports or as chronic stressors.

Beyond these space-specific constraints, it should be acknowledged that neuroarchitecture as a field carries its own methodological limitations, particularly its predominant focus on architectural aesthetics rather than other dimensions such as ergonomics, affordances

or functionality, and the low ecological validity of many neuroimaging methods, which typically require stationary participants and therefore restrict naturalistic exploration of built environments [10]. These limitations are especially relevant when translating neuroarchitecture findings to extreme, non-terrestrial environments, where mobility, sensory access and long-duration exposure differ substantially from most laboratory settings. In particular, ergonomic and sensorimotor comfort parameters calibrated to Earth's normal gravity conditions cannot be assumed to transfer directly to lunar or Martian partial gravity regimes: floor material tactility, handrail and grip surface design, and spatial orientation aids would each need to be recalibrated and empirically validated for the specific biomechanics of walking, balance and reach under each gravity level, an open empirical question that falls outside the scope of the present conceptual model and remains a priority for dedicated partial gravity human factor research (e.g., parabolic-flight or analogue gravity testing).

5.2. Architectural Constraints, Mission Typologies and Research Directions

Indoor living (micro-scale) can support cognitive habitability under EE/ICE conditions, but several macro-scale and technological constraints inherent to these Built Environments in Extreme Environments (BEXEs) limit how far these insights can be implemented in first-generation lunar and Martian habitats. Radiation, micrometeorites, thermal extremes, vacuum or thin atmosphere, dust abrasion and non-terrestrial gravity all drive current design toward heavily protected structures, often with thick regolith shielding or partial/subsurface construction, compact pressurized volumes and constrained openings to the exterior. Under these conditions, opportunities for daylight, vistas, volumetric generosity and varied spatial hierarchies, the very qualities associated with perceptual ease and restoration, are structurally limited in the near term.

These constraints also bear directly on habitat geometry. Structurally, curved geometries, spherical and toroidal pressurized shells in particular, understood here as airtight envelopes capable of containing a habitable internal atmosphere, are favored because their near-isotropic stress distribution minimizes additional reinforcement, at the cost of unused internal volume caused by double curvature; the cylindrical shell is structurally less efficient but architecturally more favorable, since its walls curve in only one direction [34]. This structural preference coincides with the geometries associated with greater subjective preference among non-expert users and with distinct neural signatures of affective appraisal [58]. Toroidal geometries additionally allow for rotation about their own axis to generate artificial gravity by centrifugal force, an option that concerns orbital and transit habitats rather than the surface conditions addressed here. Rather than competing constraints on habitat morphology, structural and neuroarchitecture criteria converge here, suggesting curvature as a shared design parameter and a hypothesis worth testing directly in future habitat prototypes.

A further limitation of the present review is that it treats space habitats as a broad category and only implicitly differentiates between habitat types along the temporal spectrum from short-stay outposts to expandable settlements. In practice, macro-scale constraints and architectural possibilities differ markedly across at least three mission typologies:

- **Short-stay, high-constraint lunar outposts**

Small, mass-constrained, highly shielded shelters for days-to-weeks missions, likely relying on regolith berms or partial burial, with very limited volume and openings. Here, cognitive habitability research must explore how far micro-scale design and mediated environments (dynamic lighting, virtual vistas, material/color strategies) can compensate within extremely compact, protective envelopes.

- **Long-duration, temporary Martian bases**

Months of transit and year-scale surface habitation under thin atmosphere and partial gravity, with strong constraints on excavation and ISRU in the near term. For these bases, future work should examine trade-offs between structurally efficient, prefabricated shells and interior configurations that still allow for differentiated room shapes, enclosure gradients, social zones and ludic niches across both transit vehicles and surface habitats.

- **Prospective permanent/expanding settlements**

In longer-term scenarios, redundancy, local manufacturing and more advanced construction, such as robust subsurface complexes and larger pressure hulls, progressively loosen today's engineering constraints. Research can then shift from "minimum viable" cognitive habitability toward pattern languages for resilient neighborhoods in BEXE contexts, including distributed common spaces, layered privacy and diverse spatial typologies at multiple scales.

These typologies point to distinct research agendas. First, systematic studies are needed that explicitly couple macro-scale protective strategies, regolith shielding, subsurface or semi-buried construction and nested pressure hulls, with micro-scale interior configurations, testing how far cognitive habitability can be achieved within heavily shielded or windowless envelopes for each mission profile. Second, the structural and thermal efficiency of different habitat concepts should be analyzed together with their capacity to host varied interior forms (room shape, proportions, enclosure, privacy gradients) relevant for somatic, operational, psychosocial and ludic-recreational functions under confinement and partial gravity. Third, because most neuroarchitecture evidence still derives from terrestrial, gravity-bound settings with easy access to the outdoors, future work must adapt methods and metrics to long-duration confinement, altered sensorimotor cues and mission-specific temporalities (short-stay vs. long-duration vs. open-ended settlement), instead of relying on straight extrapolation.

Terrestrial analogs offer the calibrated intermediate step in this adaptation, since they reproduce confinement, isolation and operational autonomy while remaining accessible to systematic architectural analysis. The integrative model links the four functional clusters as a conceptual foundation, and its empirical validation in analogous habitats constitutes the natural continuation of this research. As a follow-up to this work, a systematic analysis is currently being developed based on a case study methodology and the application of the model, focusing on a corpus of analogous habitats spanning the last four decades of experimentation, from the earliest bioregenerative installations to the most recent simulation programs. This time frame will allow for the development of habitability in extreme environments to be read as a cumulative process, in which material solutions, operational protocols, and well-being strategies have been progressively reconfigured. The corpus is organized along two lines of analysis:

- The first concerns the nature of the terrestrial analog and the mission horizon, particularly regarding the Moon and Mars as destinations, with the terrestrial analog serving as a calibrated test bed. These comprise closed-environment analogs and autonomous ecological systems, characterized by full bioregenerative immersion; lunar surface analogs, typically set up in volcanic or polar environments or within lava tubes, which test expandable, insulating environmental enclosures that respond to conditions of extreme light and darkness; and Martian mission analogs, which focus on simulating intravehicular operations, communication delays, and extended autonomy within pressurized environments.
- The second axis concerns the duration of the missions and the degree of programmatic specificity of each habitat. Long-duration analogs provide longitudinal evidence on somatic, operational, psychosocial and ludic-recreational resilience during prolonged confinement. Medium-duration analogs conduct regular simulation cycles in

controlled and semi-controlled environments. At the extreme end of short-duration missions are cases involving typological or material specificity, such as foldable enclosures designed for Arctic conditions or inflatable habitats installed in lava tubes for emergency deployment.

This contrast between duration and specificity allows for the integrative model to be tested under very different conditions. The analysis centers on the issues arising from the model that will form the proposed conceptual framework: to what extent are somatic and operational clusters addressed systematically in analogous habitats; how the growing focus on psychosocial dimensions translates, or fails to translate, into spatial decisions; and to what degree the ludic-recreational cluster is incorporated into the design.

It is this last dimension that future research, within the scope of neuroarchitecture applied to life in extreme environments, will adopt as its agenda, reinforcing the model's contribution as a design tool for dimensions of habitability that are currently poorly specified.

Finally, while this conceptual model positions cognitive resilience as a property of the human–habitat system, three dimensions remain underexplored and warrant systematic investigation:

- Individual and cultural variability: Crew composition, prior environmental experience and culturally specific expectations of privacy, proxemics and sensory richness will modulate how the same interior configuration is experienced and tolerated over time. Design guidelines must account for these differences rather than assume universal thresholds.
- Mediation technologies: Emerging tools such as VR/AR environments, telerobotic extension into the exterior landscape and adaptive lighting and acoustic systems may decouple psychological experience from physical constraints, expanding the perceived repertoire of interiors without altering their geometry, though the long-term cognitive and emotional effects of such decoupling remain uncertain.
- Evolving construction and shielding capabilities: Advances in ISRU, 3D-printed regolith structures and subsurface excavation will progressively relax current volume and form constraints, enabling architectures that move beyond compact, heavily enclosed envelopes toward more spatially differentiated and atmospherically varied configurations.

As mission architectures evolve from short-stay outposts to permanent settlements, the principles established here, interior form as co-regulator, IEQ as experiential medium and habitability clusters as interdependent, provide a testable scaffold for adaptation across these moving frontiers: crew diversity, hybrid physical–virtual environments and in situ construction expansion.

6. Conclusions

A conceptual model of neuroarchitecture for habitation in lunar and Martian spatial contexts positions interiors as active co-regulators of cognition rather than as neutral containers for life support systems. By distinguishing between the macro scale of extreme environments (BEXEs) and the micro scale of life in interior spaces under EE/ICE conditions, the model links planetary-scale constraints to everyday experience and treats cognitive resilience as a property of the interrelated human–habitat system, thereby establishing the conceptual foundations for the future framework of this research.

At the macro scale, the Moon and Mars emerge as extreme cases of extreme environments, characterized by very high levels of intolerability and scarce resource availability that confine nearly all human experience to a small number of pressurized interiors, framed

here as Built Environments in Extreme Environments (BEXEs). Under these conditions, habitats become primary worlds that mediate perception, orientation, temporal anchoring, and social life.

At the micro level, habitability emerges as a multidimensional property realized through indoor environmental quality (IEQ) across four recurring clusters of functions: somatic, operational, psychosocial, and ludic-recreational. Sleep, work, privacy, social interaction, and recovery all depend on how the interior layout and IEQ are organized under ICE conditions. In lunar and Martian habitats, where going outdoors is impossible under conditions comparable to those on Earth and where exposure to natural environmental variations is drastically reduced, indoor environmental quality (IEQ) becomes the primary means through which inhabitants experience and regulate the surrounding world.

The model identifies four families of interior variables as particularly relevant to cognitive habitability: the shape and proportions of rooms, the degrees of enclosure and privacy gradients, visual order and information load, as well as multisensory atmospheres and indoor environmental quality (IEQ). These variables shape perceptual comfort, path planning, exposure regulation, somatic stability, and access to restorative activities, providing concrete reference points for architectural design under strict technological and volumetric constraints. Even in first-generation spatial habitats, interior design can systematically enhance perception and opportunities for recovery by explicitly configuring room proportions, confinement patterns, visual order, and multisensory atmospheres as cognitive resources to maintain performance, state of mind, and a tolerable relationship with confinement over time. In this sense, cognitive resilience in space habitats depends not only on the possibility of refuge and protection, but also on the ability of interior environments to symbolically and visually broaden and extend the relationship with the outside world and with a view of the landscape, and to support meaningful experiences of exploration, belonging, and continuity over time with the place.

Priorities will vary depending on the duration and types of missions, reflecting different time horizons, operational requirements, and risk profiles. The model translates this conceptual framework of cognitive habitability into design guidelines, which will initially be validated through the analysis of case studies involving terrestrial analogs from the past four decades. Once validated, the model can be applied from the earliest stages of habitat design, so that the interior layout is no longer a last-minute adjustment to the technological envelope but rather a design variable from the outset.

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References

1. NASA (National Aeronautics and Space Administration). *NASA HANDBOOK*; NASA: Washington, DC, USA, 2014. Available online: https://www.nasa.gov/wp-content/uploads/2015/03/human_integration_design_handbook_revision_1.pdf (accessed on 28 June 2026).
2. Clément, G.; Buckley, A. *Artificial Gravity*; Springer: New York, NY, USA, 2007. Available online: <https://link.springer.com/book/10.1007/0-387-70714-X> (accessed on 28 June 2026).
3. Kanas, N.; Manzey, D. *Space Psychology and Psychiatry*, 2nd ed.; Springer: Dordrecht, The Netherlands, 2008.
4. Palinkas, L.A.; Suedfeld, P. Psychosocial issues in isolated and confined extreme environments. *Neurosci. Biobehav. Rev.* **2021**, *126*, 413–429. [CrossRef] [PubMed]
5. Palinkas, L.A.; Suedfeld, P. Psychological effects of polar expeditions. *Lancet* **2008**, *371*, 153–163. [CrossRef] [PubMed]
6. Evans, G.W.; McCoy, J.M. When buildings do not work: The role of architecture in human health. *J. Environ. Psychol.* **1998**, *18*, 85–94. [CrossRef]
7. Stokols, D. On the distinction between density and crowding: Some implications for future research. *Psychol. Rev.* **1972**, *79*, 275–277. [CrossRef] [PubMed]
8. Kellert, S.R.; Calabrese, E.F. *Nature by Design: The Practice of Biophilic Design*; Yale University Press: New Haven, CT, USA, 2018. Available online: <https://yalebooks.yale.edu/book/9780300214536/nature-by-design/> (accessed on 28 June 2026).
9. Wilson, E.O. *Biophilia*, 1st ed.; Harvard University Press: Cambridge, MA, USA, 1984. Available online: <https://www.hup.harvard.edu/books/9780674045231> (accessed on 28 June 2026).
10. Higuera-Trujillo, J.L.; Llinares, C.; Macagno, E. The cognitive-emotional design and study of architectural space: A scoping review of neuroarchitecture and its precursor approaches. *Sensors* **2021**, *21*, 2193. [CrossRef] [PubMed]
11. Karakas, T.; Yildiz, D. Exploring the influence of the built environment on human experience through a neuroscience approach: A systematic review. *Front. Archit. Res.* **2020**, *9*, 236–247. [CrossRef]
12. Attaianes, E.; Barilà, M.; Perillo, M. Exploring Neuroscientific Approaches to Architecture: Design Strategies of the Built Environment for Improving Human Performance. *Buildings* **2025**, *15*, 3524. [CrossRef]
13. Gifford, R. *Environmental Psychology: Principles and Practice*, 3rd ed.; Optimal Books: Colville, WA, USA, 2001.
14. Naser, M.Z.; Chehab, A.I. Materials and design concepts for space-resilient structures. *Prog. Aerosp. Sci.* **2018**, *98*, 74–90. [CrossRef]
15. Hayne, P.O.; Hendrix, A.; Sefton-Nash, E.; Siegler, M.A.; Lucey, P.G.; Retherford, K.D.; Williams, J.-P.; Greenhagen, B.T.; Paige, D.A. Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements. *Icarus* **2015**, *255*, 58–69. [CrossRef]
16. Li, S.; Lucey, P.G.; Milliken, R.E.; Hayne, P.O.; Fisher, E.; Williams, J.-P.; Hurley, D.M.; Elphic, R.C. Direct evidence of surface exposed water ice in the lunar polar regions. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 8907–8912. [CrossRef] [PubMed]
17. Leone, G.; Ahrens, C.; Kortenien, J.; Gasparri, D.; Kereszturi, A.; Martynov, A.; Schmidt, G.W.; Calabrese, G.; Joutsenvaara, J. Sverdrup-Henson crater: A candidate location for the first lunar South Pole settlement. *iScience* **2023**, *26*, 107853. [CrossRef] [PubMed]
18. Orosei, R.; Caprarello, G.; Cartacci, M.; Cicchetti, A.; Heggy, E.; Herique, A.; Kofman, W.; Lauro, S.E.; Noschese, R.; Pajola, M.; et al. Water Ice in the Subsurface and Polar Caps of Mars. *Space Sci. Rev.* **2025**, *221*, 126. [CrossRef]
19. Sherwood, B. Guest Statement: Space Architecture Education—Site, Program, and Meaning. In *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*; Häuplik-Meusburger, S., Bannova, O., Eds.; Springer/Springer International Publishing: Cham, Switzerland, 2016; Chapter 2.6; p. 42.
20. Simon, M.A.; Toups, L.; Howe, A.S.; Wald, S. *Evolvable Mars Campaign Long Duration Habitation Strategies: Architectural Approaches to Enable Human Exploration Missions*; American Institute of Aeronautics and Astronautics (AIAA): Reston, VA, USA, 2015.

21. Bannova, O. *Extreme Environments-Design and Human Factors Considerations*; Chalmers University of Technology: Gothenburg, Sweden, 2014. Available online: <https://publications.lib.chalmers.se/records/fulltext/204341/204341.pdf> (accessed on 28 June 2026).
22. Leach, N. *Space Architecture: The New Frontier for Design Research*; John Wiley & Sons (Architectural Design—AD): London, UK, 2014.
23. Paré, G.; Trudel, M.-C.; Jaana, M.; Kitsiou, S. Synthesizing information systems knowledge: A typology of literature reviews. *Inf. Manag.* **2015**, *52*, 183–199. [\[CrossRef\]](#)
24. Pagnini, F.; Manzey, D.; Rosnet, E.; Ferravante, D.; White, O.; Smith, N. Human behavior and performance in deep space exploration: Next challenges and research gaps. *NPJ Microgravity* **2023**, *9*, 27. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Häuplik-Meusburger, S.; Bannova, O. *Architecture for Astronauts: An Activity-Based Approach*; SpringerWien: New York, NY, USA, 2011. [\[CrossRef\]](#)
26. Benaroya, H. *Lunar Settlements*; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2010. [\[CrossRef\]](#)
27. Benaroya, H. Lunar habitats: A brief overview of issues and concepts. *Reach* **2017**, *7–8*, 14–33. [\[CrossRef\]](#)
28. Gaier, J.R. *The Effects of Lunar Dust on EVA Systems During the Apollo Missions*; Glenn Research Center: Cleveland, OH, USA, 2005. Available online: <https://ntrs.nasa.gov/citations/20050160460> (accessed on 28 June 2026).
29. Mackwell, S.J.; Simon-Miller, A.A.; Harder, J.W.; Bullock, M.A. *Comparative Climatology of Terrestrial Planets*; University of Arizona Press: Tucson, AZ, USA; Lunar and Planetary Institute: Houston, TX, USA, 2014. [\[CrossRef\]](#)
30. Martínez, G.M.; Newman, C.N.; De Vicente-Retortillo, A.; Fischer, E.; Renno, N.O.; Richardson, M.I.; Fairén, A.G.; Genzer, M.; Guzewich, S.D.; Haberle, R.M.; et al. The Modern Near-Surface Martian Climate: A Review of In-situ Meteorological Data from Viking to Curiosity. *Space Sci. Rev.* **2017**, *212*, 295–338. [\[CrossRef\]](#)
31. Igarashi, T.; Yashiro, T. Construction in extreme environments: Definition of extremeness and parameter analysis of case projects. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *294*, 012001. [\[CrossRef\]](#)
32. Eberhard, J.P. *Brain Landscape: The Coexistence of Neuroscience and Architecture*; Oxford University Press, Inc.: New York, NY, USA, 2009.
33. Häuplik-Meusburger, S.; Bannova, O. *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*; Space and Society Series; Springer: Cham, Switzerland, 2016. [\[CrossRef\]](#)
34. Caiazzo, A.; Casaburo, A.; Petrone, G.; De Rosa, S.; Franco, F. Structures for extraterrestrial habitat: A review. *Acta Astronaut.* **2026**, *238*, 471–493. [\[CrossRef\]](#)
35. Amini, K.; Janabadi, E.D.; Fayaz, R. Lighting and illumination investigation of long-term residence on Mars for the case of a set of designed Martian Habitat Units (MHUs). *Acta Astronaut.* **2022**, *192*, 210–232. [\[CrossRef\]](#)
36. Amini, K.; Moradi, M.; Vossoughi, B.; Janabadi, E.D. Space-technological and architectural methodology and process towards design of long-term habitats for scientific human missions on mars. *MethodsX* **2023**, *11*, 102270. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Onodera, K. Discovery of Repeating Shallow Moonquakes in the Apollo Lunar Seismic Data. *Geophys. Res. Lett.* **2026**, *53*, e2026GL122541. [\[CrossRef\]](#)
38. NASA. *The Artemis Plan: NASA's Lunar Exploration Program Overview*; NP-2020-05-2853-HQ; National Aeronautics and Space Administration: Washington, DC, USA, 2020. Available online: https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf (accessed on 28 June 2026).
39. Arnheim, R. *Art and Visual Perception: A Psychology of the Creative Eye*; University of California Press: Berkeley, CA, USA, 1974.
40. Arnheim, R. *The Dynamics of Architectural Form*; University of California Press: Berkeley, CA, USA; Los Angeles, CA, USA, 1977.
41. Connors, M.M.; Harrison, A.A.; Akins, F.R. *Living Aloft: Human Requirements for Extended Spaceflight*; NASA: Washington, DC, USA, 1985.
42. Sgobba, T.; Schlacht, I.L. Habitability and habitat design. In *Space Safety and Human Performance*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 653–719. [\[CrossRef\]](#)
43. Häuplik-Meusburger, S.; Bishop, S. *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*; Springer Nature Switzerland AG: Cham, Switzerland, 2021. [\[CrossRef\]](#)
44. Heft, H. *Ecological Psychology in Context: James Gibson, Roger Barker, and the Legacy of William James's Radical Empiricism*; Routledge: London, UK; Taylor & Francis Group: New York, NY, USA, 2016.
45. Sommer, R. *Personal Space: The Behavioral Basis of Design*; A Spectrum Book; Prentice-Hall, Inc.: Englewood Cliffs, NJ, USA, 1969.
46. Hall, E.T. *The Hidden Dimension*; Anchor Books: New York, NY, USA, 1990.
47. Robinson, S.; Pallasmaa, J. *Mind in Architecture: Neuroscience, Embodiment, and the Future of Design*; The MIT Press: Cambridge, MA, USA; London, UK, 2015. [\[CrossRef\]](#)
48. Gallese, V.; Gattara, A. Embodied Simulation, Aesthetics, and Architecture: An Experimental Aesthetic Approach. In *Mind in Architecture: Neuroscience, Embodiment, and the Future of Design*; Sarah Robinson, J.P., Ed.; The MIT Press: Cambridge, MA, USA; London, UK, 2015.
49. Norberg-Schulz, C. *Genius Loci: Towards a Phenomenology of Architecture*; Rizzoli: New York, NY, USA, 1980.

50. Pallasmaa, J. *The Eyes of the Skin: Architecture and the Senses*, 3rd ed.; John Wiley & Sons Ltd.: Chichester, UK, 2012. Available online: <https://www.wiley.com/en-gb/the-eyes-of-the-skin-architecture-and-the-senses-3rd-edition-p-9781119943501> (accessed on 28 June 2026).
51. Robinson, S. *Architecture Is a Verb*; Routledge: New York, NY, USA, 2021. [CrossRef]
52. Browning, W.D.; Ryan, C.O.; Clancy, J.O. *14 Patterns of Biophilic Design: Improving Health & Well-Being in the Built Environment*; Terrapin Bright Green, LLC: New York, NY, USA, 2014. Available online: <https://www.terrapinbrightgreen.com/report/14-patterns> (accessed on 28 June 2026).
53. Yin, J.; Yuan, J.; Arfaei, N.; Catalano, P.J.; Allen, J.G.; Spengler, J.D. Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environ. Int.* **2020**, *136*, 105427. [CrossRef] [PubMed]
54. Wang, S.; de Oliveira, G.S.; Djebbara, Z.; Gramann, K. The Embodiment of Architectural Experience: A Methodological Perspective on Neuro-Architecture. *Front. Hum. Neurosci.* **2022**, *16*, 833528. [CrossRef] [PubMed]
55. Abbas, S.; Okdeh, N.; Roufayel, R.; Kovacic, H.; Sabatier, J.-M.; Fajloun, Z.; Abi Khattar, Z. Neuroarchitecture: How the Perception of Our Surroundings Impacts the Brain. *Biology* **2024**, *13*, 220. [CrossRef] [PubMed]
56. Banaei, M.; Hatami, J.; Yazdanfar, A.; Gramann, K. Walking through architectural spaces: The impact of interior forms on human brain dynamics. *Front. Hum. Neurosci.* **2017**, *11*, 477. [CrossRef] [PubMed]
57. Coburn, A.; Vartanian, O.; Kenett, Y.N.; Nadal, M.; Hartung, F.; Hayn-Leichsenring, G.; Navarrete, G.; González-Mora, J.L.; Chatterjee, A. Psychological and neural responses to architectural interiors. *Cortex* **2020**, *126*, 217–241. [CrossRef] [PubMed]
58. Shemesh, A.; Talmon, R.; Karp, O.; Amir, I.; Bar, M.; Grobman, Y.J. Affective response to architecture—Investigating human reaction to spaces with different geometry. *Archit. Sci. Rev.* **2017**, *60*, 116–125. [CrossRef]
59. Liapi, M.; Ackermann, E. Microgravity playscapes: Play in long-term space missions. *Am. J. Play* **2016**, *8*, 157–177. Available online: <https://www.museumofplay.org/app/uploads/2022/01/8-2-article-microgravity-playscapes.pdf> (accessed on 28 June 2026).

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