Astronaut-in-the-Loop: An Iterative Design Research Framework for Space Environments

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In order to sustain human life in space, designers and engineers must overcome many challenges unique to space environments and missions. While challenges such as life support, thermal control, and radiation are well researched and considered, space can alter systems and people in unanticipated ways. The effects of space environments are not always intuitive to Earth-based designers, due to a lack of experiential intuition that can only be gained through time spent living and working off-planet. While access to space is currently limited, we are at an inflection point for how humans will interact with space, particularly with low Earth orbit (LEO). Privately funded individuals have visited LEO since the early 2000s, and May 2020's launch of the first commercial rocket carrying astronauts to the ISS marks the beginning of increased access to LEO for more people and activities. This access indicates an emerging need for space environments that are designed to encompass a variety of experiences. Given the continuous twenty-year presence of humans in LEO, we have the opportunity to leverage the experiences of today's astronauts to envision a more human-centered approach to environmental design for space. This paper outlines how qualitative design research methods can be used to derive insights from astronauts and other individuals with unique, experiential knowledge of space, on topics from environmental design to crew psychology. We synthesize these insights into a series of design principles for future interventions in space environments. Leveraging both generative interview data as well as evaluative interview sessions with astronauts, we describe human-centered insights, develop design principles, and iterate on those principles using an astronaut-in-the-loop iterative design research framework. These design principles and framework also serve as vehicles to learn more about human needs when working and living in space.

Nomenclature

ECLSS	=	Environmental Control and Life Support System
HCD	=	Human-Centered Design
HCI	=	Human-Computer Interaction
HSI	=	Human-Systems Integration
ISS	=	International Space Station
LEO	=	Low Earth orbit

I. Introduction

OVERCOMING the technical challenges associated with designing closed systems for space is one of the central accomplishments of human engineering. Rigorous mission definition and planning, as well as advances in human-systems integration (HSI),[1] have enabled 20 years of human presence in low earth orbit (LEO) aboard the International Space Station (ISS). Spacefaring individuals also contribute to the growing body of knowledge on human spaceflight through a variety of channels, including on-orbit experiments, diary studies, oral histories, debrief interviews,[2-4] and as crew representatives at public and private space initiatives.[5] These contributions are extremely valuable, as they inform future designs and missions.

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However, it is clear that we are at an inflection point in the history of human spaceflight, moving toward what is sometimes referred to as "New Space."[6] The next generations of astronauts will be individuals with a diversity of training exposures, visiting space for a variety of reasons beyond the traditional structure of 'the mission.'[7] As the costs associated with spaceflight decrease, new industries and actors are approaching human spaceflight with motivations that differ from governmental space agencies, including space tourism and commercial lunar exploration.[6-8] Given these changes to the landscape of both space industry and exploration, there is a need to expand upon the foundational knowledge that has been developed about human life in space to date, as well as opportunities to learn from spacefaring individuals about the nuances of their experiences in space. These learnings are of value not only to space agencies, but also to the new, diverse group of actors now involved in design for space exploration, who will make decisions about future environments and missions but may not have an *embodied* experience of the microgravity environment.

In this work, we present the outcome and process used to develop a set of human-centered design principles for space, informed and iteratively developed from the perspectives of experienced astronauts, cosmonauts, and spaceflight participants (who we will collectively refer to as 'astronauts' in this paper, for simplicity). This contribution expands upon an ongoing research effort by the authors to catalog first-person perspectives of individuals who have been to space as part of an "astronaut ethnography," examining the implications of life in space environments while contending with confinement, weightlessness, and long-term presence in space.[9] In addition to a review of how astronauts have been and are currently "in-the-loop," as part of innovation, systems engineering and design, our contributions are:

- A series of design principles for environmental design in space, initially based on a retrospective analysis of 2020 astronaut interviews with $n = 9$ participants.[9]
- An iterative design research framework used to develop the content and structure of the design principles with evaluative design feedback from a validation group of $n = 5$ astronaut participants.
- The final set of design principles, along with examples and meta-principles developed during evaluation.

We hope that the design principles presented in this work, which have been informed by an 'astronaut-in-the-loop' iteration and evaluation process, are accessible to a broad audience looking to learn more about human perspectives on life in space as they design the future of space habitation and exploration.

II. Related Work

A wealth of knowledge has been developed on human life in space, creating a firm foundation for understanding what it takes to keep human beings safe, healthy, and productive. Much of this knowledge has been informed by "astronauts-in-the-loop" contributing their experience as test subjects, crew representatives, consultants, and in many more roles. It is worth reviewing the ways in which astronauts are already a part of space design, testing, and in-situ function, in order to situate the contributions of this work within the broader landscape of space design and HSI.

A. Human Systems Integration

An early form of astronaut-in-the-loop interaction involved direct astronaut involvement with the spacecraft during launch, on orbit, as well as human-robot interaction during the mission.[2] During Apollo, human controls needed to be integrated into technology that was initially design for missile systems, and navigating this integration was considered "one of the biggest, toughest problems."[10] During the design process for Apollo spacesuits, astronauts wore and provided feedback on suit prototypes, advocating for flexibility and increased mobility.[11]As automation of space systems became more advanced, the participation of a "human-in-the-loop" during the design process became more common. The concept of Human-Systems Integration (HSI) is the contemporary model for considering astronauts as a component in larger technical and architectural designs for space.[12,13] This model broadly encompasses "all aspects of the system with human interactions"[17] including human factors, aiming to improve human system design, reduce operational costs, and optimize system performance.[12,14] HSI has been incorporated into the design process of many distinct efforts, including the integration of cognitive human factors in the design and applications of exosystems,[15] and the evaluation of comfort and mobility of prototype gravity loading countermeasure skinsuits (GLCS) with human participants during parabolic flights.[16]

B. Astronaut Feedback in Space Innovation

Astronauts are particularly well-suited to provide feedback about what does and does not work in the environment of space, both from a human and a systems perspective. For example, astronaut feedback led to experimenting with "walking on the ceiling" or reflecting on the experience of a "local vertical,"[17] both of which are challenging to identify and design for from a terrestrial frame. Station mockups and simulators have been built by multiple agencies for training and troubleshooting, providing a common ground for designers, engineers, and astronauts.[18,19] Interviews, debriefing sessions, and personal journals[2,3] provide opportunities for astronauts to reflect and comment on their experiences on orbit to space agencies. For example, the Skylab Experience Bulletins consolidated crew lessons learned from "air-to-ground transcripts, post-flight debriefings and in-flight films" into a series of reports that provided concrete recommendations on aspects of space life from the use of Velcro to sleeping quarters.[4] Qualitative research on human resilience in terrestrial extreme environments has been used to inform longitudinal journal studies of ISS astronauts, in order to gauge the differences between spacefarers and other explorers and make recommendations to improve behavioral outcomes.[3,20] Human-centered design (HCD) is becoming more commonplace within the space design community,[21,22] as more designs and design resources begin to address increasingly important human needs and activities during long duration missions.[23,24] These feedback-informed resources are the precedent that resemble our goals most closely, though there are still open questions associated with how best to weigh and incorporate astronaut feedback into complex systems engineering and design processes.[22]

C. Design Considerations for "New Space"

Longer missions and a continuous presence aboard the ISS have incentivized significant research into mental health, crew cohesion, and the psychological impact of space exploration.[12,25-28] This research also provides a foundation from which to consider many of the challenges associated with the shifting landscape of human space exploration seen in the past decade. Increasing numbers of space tourists have visited the ISS for short periods of time since the early 2000s, through enterprises such as Spaceflight Adventures.[29] As the ISS opens to both commercial activities and private astronaut missions,[30] private companies like Axiom Space are developing plans for all-civilian missions to LEO as well as "the first commercial space station" starting in 2024.[31] The privately-funded Inspiration4 mission plans to send an all-civilian crew to LEO aboard a SpaceX Dragon capsule. Crew selection from this mission differs significantly from current space agency methods – including a charity raffle and "shark-tank style" competition – though the crew will still undergo some training provided by SpaceX.[7] With new countries and private actors entering space with their own unique goals, new astronauts will have varying degrees of training and may need more from their environments.

Given the inflection point we are nearing with respect to human space exploration, there is value in 1) developing a design resource that builds on foundational work and explores the personal, communal, and experiential sides of human life in space, and in 2) developing that resource in a way that is accessible to a broader audience of designers, engineers, and others newly involved in space exploration. In this light, the contributions presented in this paper outline the process and output of our attempt to produce such a resource—a set of human-centered design principles for both current and future space environments.

III. Approach

Design principles are artifacts from the human-centered design process that convert collections of human insights into a structured set of guidelines. They consist of a series of principles (i.e. high-level statements derived from synthesized insights to provide design motivation), an organizational system or taxonomy for the principles, and relevant case studies or examples to contextualize the principles.[32] In some cases, a series of meta-level principles are included as well, to provide an overview of the motivations and takeaways developed when creating the principles.[33] Design principles provide a few key benefits as an output for this research effort. They allow us to synthesize and present astronaut insights while protecting their privacy, they are intended to be generalizable, and their format is more accessible to broader audiences than traditional academic research. Design principles have been employed across domains, and Amershi et al.'s work in particular on human-AI interaction guidelines serves as precedent for our research methods.[32,34]

To develop these principles, we have drawn data from two sources. The first is a dataset of 430 astronaut insights developed from semi-structured interviews[35] with nine spacefaring individuals, conducted by the authors in 2020.[9] Astronauts in this cohort represented five space agencies and had spent time ranging from under one month to over one year cumulatively in space across multiple missions. Both data collection and synthesis were informed by Grounded Theory Method (GTM), which involves the systematic generation of a theory from qualitative data, rather than developing a prior research hypothesis to test.[36,37] Its central advantage as a method is to develop new theories from qualitative insights, reliant upon a distinctly 'human' approach to learning.[38] Similar coding methods have been employed previously in qualitative research conducted with explorers and astronauts.[3,20] Insights from this generative

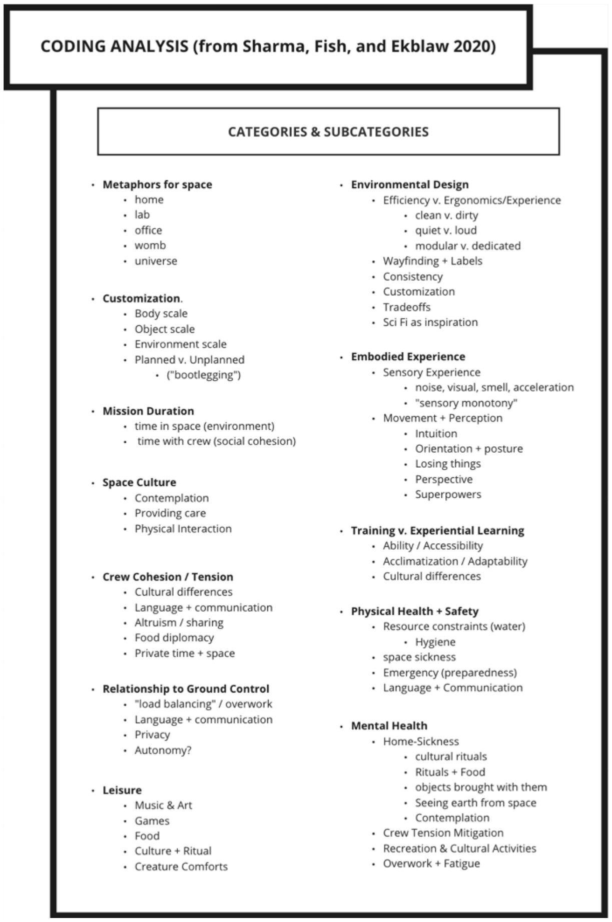

Figure 1. Categories and subcategories developed from generative dataset (*n* = 9 participants).[9]

dataset informed the development of 60 open codes (i.e. categories), which we organized into 12 high-level codes during synthesis, as can be seen in Fig 1. This generative dataset and its categories were used to seed the initial design principles prior to astronaut evaluation. Additional detailed information on the methods used to develop this dataset can be found in the authors' original publication on the generative dataset.[9]

The second data source informing this study is a series of five structured, evaluative interviews with spacefaring individuals conducted by the authors in 2021. Astronauts in this cohort represent four space agencies, and their sessions are used to evaluate and iterate on the content and structure of the design principles. We employed two methods traditionally used in qualitative design research for evaluation and iteration: participatory design practices and modified heuristic evaluation. Participatory design actively involves relevant stakeholders (in this case astronauts) in the creation of design artifacts and products. This process includes both interviewing participants and incorporating them into the iteration process of the principles.[39] Heuristic evaluation is a method employed in usability engineering that involves having a small group of experts evaluate a system or interface to assess its adherence to or violation of a set of design principles.[40] This method has been employed in multiple domains, including at NASA to evaluate novel interfaces and HCI more broadly.[41] Amershi et al. has modified heuristic evaluation in order to interrogate the design principles themselves, by asking experts whether the principles align with or are in contrast to their knowledge of a particular system.[34] In this paper, we refer to the use of these methodologies and the iteration of our principles as an *iterative design research framework.* An overview of this framework is shown in Fig. 2.

Due to the limited availability of our target population, we employ *purposive* and *chain referral* sampling[42] when recruiting participants, asking participants to recommend other astronauts to increase our ability to develop a larger participant pool. For this study, we treat the population of spacefaring humans we have interviewed as all belonging to a single population, and we have anonymized their contributions to ensure their privacy. In the results presented below, we step through the methods that make up our iterative design research framework in use and present the artifacts at each step of the research process. Our aim is to present not only the final outcome but the process itself, in the hopes that the methodology we employ is valuable in contexts beyond our research.

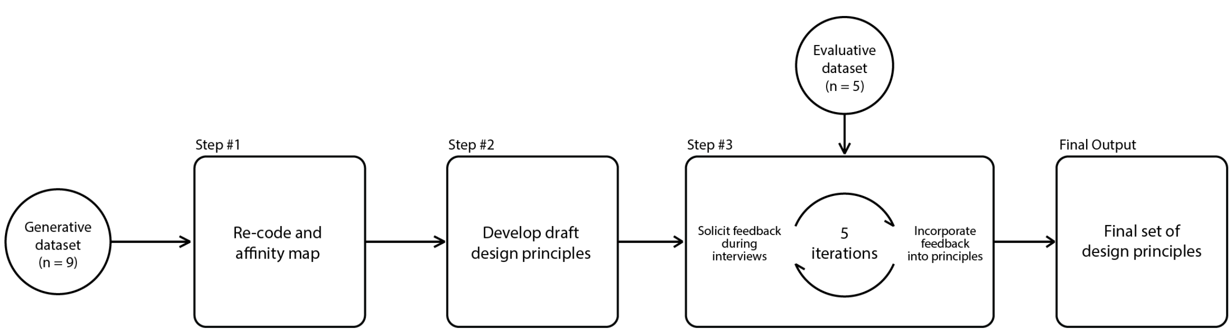

Figure 2. System diagram of iterative design research framework, illustrating study design.

IV. Results

A. Affinity Mapping & Initial Design Principles

The first step used to develop human-centered design principles is to seed the process with relevant human data. As described in Approach, we reviewed a series of generative astronaut interviews conducted by the authors in 2020 and used affinity mapping to develop organic themes and questions from the data. Affinity mapping organizes research insights around common themes, and consists of label creation, label grouping, and presenting grouped entities together.[43] During this exercise, we identified and grouped relevant human-centered insights about space habitation. The labels and themes that emerged from individual insights served as high-level observations that we would use to inform the taxonomy and structure of the design principles. While this process is subjective, it serves as an efficient way to stand up enough content for substantive interview conversations and evaluative review.

To translate our affinity mapping output into draft design principles, we next developed a series of categories, based on those developed for the generative dataset, to provide sufficient structure for evaluation. We sought inspiration from human-AI interaction for this categorization exercise, which provides useful precedent due to the complex interplay between humans and technology in HCI as a field. In particular, Horowitz's and Amershi's design principles are organized from a human-centered point of view, describing learnings at each step of an individual's interaction with a machine system.[34,44] We similarly chose to organize categories around concepts like human senses, personal needs, and communal interactions rather than around technical systems or spatial functions to emphasize the human-centered nature of this resource. The initial categories we used to organize insights were *sound, sight, touch, taste, proprioception, intuition, privacy, collaboration, social behavior,* and *connections to home.* In the end, our first pass at design principles resembled a series of insights organized by human-centered category rather than recommendations, but they provided enough content and structure for evaluation and iteration.

B. Participatory Evaluation & Iteration

We next conducted a series of five interviews with astronauts to workshop the principles' content and structure, using the participatory design and heuristic evaluation methods described in Approach. For each of the interview sessions, we presented a draft of the design principles document and asked participants to identify what elements stood out to them as particularly true, what elements we mischaracterized or were missing, and if any anecdotes or context came to mind as they reviewed the document. Following the interview, we modified the content and structure of the design principles in order to incorporate the participant's feedback. We then repeated this two-step evaluation and iteration process for each of the remaining interviews (see Fig. 2). Overall, the evaluation and iteration process enabled us to expand and develop our design principles. Having started evaluation with a set of categories and related insights, astronaut feedback helped identify new insights and categories, develop those insights into recommendations, and create overall principles per category based on recommendations. We provide an example of iteration and principle development to illustrate this process in detail.

Stabilizing the Body in Space. In our first draft of the design principles, we included an insight derived from an affinity map group on the challenges learning to stabilize oneself in microgravity and needing an additional contact point to prevent rotation, under the category "Proprioception"—

CATEGORY: Proprioception
INSIGHT: Stabilizing oneself when floating in space requires three points of connection or contact.

After our first interview, we broadened "Proprioception" to "Orientation & Movement" in order to capture additional related insights and recommendations associated with the category. Based on feedback, we also modified the insight slightly to read more like a recommendation.

CATEGORY: Orientation & Movement
INSIGHT: Stabilizing oneself when floating requires three points of connection or contact, an important interior surface consideration.

Between our second and third interviews, we developed principles associated with each of the categories that synthesized the insights associated with them. This was an effort to make the substantial content of the document easier to parse for our participants, by providing an overall principle with associated examples.

Design Principles		Recommendations & Observations
P1	**SOUND:** **Addressing comfort while maintaining safety is important when designing acoustic environments such as noisy systems and social spaces.**	• Partitions and material choices may help lessen the constant high and low frequency noise generated by fans, ECLSS, and other equipment, but must still allow warning sounds to permeate. • Consider separating systems that produce loud noises from both quiet and communal areas (e.g. exercise equipment and hygiene procedures v. dining and sleeping) • Reduce the amount of incidental noise that may be produced in private and quiet areas (e.g. bunk cabin doors, air circulation fans). • Allow for personalization of one's own acoustic environment (e.g. music, podcasts, nature sounds) to provide moments of respite and reset. • Interiors should allow for communal acoustic enjoyment (e.g. concerts, movies) and account for the need to get close to one another to hear.
P2	**SIGHT:** **Varying the visuals in space environments through windows, color, and lighting connects viewers to Earth and mitigates sensory monotony.**	• Leverage visual standards and lighting to aid in orientation, and consider variation in hue and temperature to delineate between different areas. • Including windows or other ways to connect and communicate with Earth can help reduce feelings of separation from Earth and humanity. • Keep in mind that windows provide 90-minute light/dark cycles and views of Earth's seasons, creating dynamic lighting conditions and a sense of visual timekeeping. • Currently, crews coordinate activities to avoid disturbing each other. Customizable lighting and other interventions could allow individuals to choose different working, leisure, and quiet hours.
P3	**TOUCH:** **Touch is an important sense for both comfort and navigation in microgravity environments, and can provide positive psychological impact.**	• Incorporating softness into key elements—including clothing, sleeping bags, and handrails—increase comfort and sensory variety. • When choosing materials, including Velcro and fabric, one should consider flammability, ease of use, cleaning and maintenance, comfort, and impact on sensory variety. • Interiors should take into account that relationships to surfaces are renegotiated as individuals use walls to move through space. • Interiors should take into account the fact that individuals help each other move through touch.
P4	**SMELL:** **Activities that generate smells—both positive and negative—should be considered when designing layout and adjacent usage of enclosed spaces.**	• Ventilation is needed to dry clothes, manage smells, and circulate air. Consider vent positionings that don't expose crewmates to unpleasant smells in key areas (e.g. dining, sleeping). • Consider separating activities/systems that produce strong smells (e.g. exercise, waste management) from activities that rely in part on smell. • Current station designs produce a "stale" smelling environment. Exceptions include cooking processes, food waste, ECLSS/sanitation systems Incorporating pleasant, fresh smells may provide sensory variation and mental refresh, in addition to providing a feeling of connection to Earth.
P5	**TASTE:** **Planning for variety in taste, texture, and intensity of food can counteract monotony, provide reprieve, and cultivate a sense of home.**	• Some individuals describe their tastes evolving during long periods in space, increasingly favoring spicy, sour, or sweet flavors. • Consider that a reduced sense of smell along with the design of food packaging can limit the experience of taste in space. • Developing new methods of cooking and renewable food production (e.g. fermentation) increases the variety and healthiness of long-term diets. • Current serving, eating, and food storage methods are worth innovating on to expand possible flavors, foods, and experiences of eating.
P6	**ORIENTATION & MOVEMENT:** **While orientation and movement in microgravity is a learned skill, certain mission activities and social cues benefit from a shared orientation.**	• When designing wayfinding, consider that while one's own personal sense of "up" continually changes with respect to the ISS and Earth, most adjust over time and rely less on written signage. • Consider designing communal work spaces (e.g. lab environments) with a consistent orientation to facilitate equipment use and group interaction. • Consider a single orientation for spaces designed for important decisions, as it can be hard to read facial cues on an upside down face. • Stabilizing oneself when floating requires one to counteract torque. The positioning of handrails and other aids can help alleviate related fatigue. • Pushing, pulling, or bouncing objects off surfaces is needed to move through space, which is an important interior surface consideration.
P7	**INTUITION & ACCLIMATION:** **Force and momentum in microgravity play out in unexpected ways, and there is no single acclimation strategy in space that works for all individuals.**	• One needs considerably less force to move in space than one initially anticipates, and acclimation comes with exposure to zero-g. • Mass is still important in weightless environments: pushing something with force will make it hit something else with force. • Acclimation can take a few days to a few weeks, and is facilitated through experiences that simulate space environments (e.g. parabolic flights, analog missions on Earth). • For some, simulating the feeling of gravity can help with certain behaviors (e.g. strapping yourself to a pillow or sleeping bag when you sleep).
P8	**OBJECT & SPACE ORGANIZATION:** **Organization, cleanliness, and stowage are all perennial challenges to living in space, and terrestrial conventions may not provide ideal solutions.**	• The use of the full volume of a space is possible due to lack of gravity but is limited by storage and adjacent use constraints. • Stowage design considerations should take into account that objects packed in non-rigid containers on Earth will redistribute and float in space. • Losing objects in microgravity is easy as things tend to float away; designs that mitigate this issue reduce inconvenience and cognitive load. • Any flat surface can act as an extra "table" space or as a partition, including fabric, but requires a method of adhering, like Velcro. • Consider Velcro-like solutions to attach objects that won't be disturbed, and bungee-like solutions to hold objects in place securely. • Designers should be aware that organization and cleanliness are considered 'perennial issues' in space, as it takes time to find equipment, set up, and reset an area. • To increase the amount of habitable space available, updated stowage organization and disposal methods should be developed.
P9	**PERSONAL NEEDS & PRIVACY:** **Accounting for personal needs beyond life support (privacy, personal space, leisure) significantly impacts quality of life.**	• Consider adding areas that separate work and non-work activities and provide space for multi-sensory refresh. • Exercise has value for both mental and physical wellbeing, but also produces loud noises, sweat, and smells that need to be addressed. • Control over one's personal environment is valuable, as is adjustment of personal spaces and items, such as workstations and sleeping areas. • The ability to wash clothes would allow for the reuse of personal garments, rather than disposal.
P10	**SOCIALIZATION:** **Long-term and mixed-use environments need to balance optimizing spaces for productivity and creating space for social life outside of work.**	• Consider adding dedicated spaces and objects for communal, non-mission interactions (e.g. dining, small experiments, creative activities). • Make sure that environmental layouts and CO2 management are easily adjustable and can handle social gatherings in communal areas. • Organize paths through space to productively intermingle private and social areas, encouraging moments of both gathering and recharge. • Consider spaces and technologies for leisure and entertainment, particularly for long-haul and non-research spaces. • If including non-research activities in spaces primarily designed for research, consider ways to separate research and non-research activities.
P11	**COMMUNICATION & COLLABORATION:** **Designing communication strategies that promote both safety and effective collaboration can ease isolation and improve crew cohesion.**	• Environments that foster better communication — between crew, Ground Control, and people on Earth — improve working and living conditions. • Consider systems that improve communication between individuals without a clear line of sight, to promote safety and effective collaboration. • Real-time communication and data exchange greatly improve connection, but will need to be fundamentally rethought for long-distance voyages. • Meals can be communal focal points or moments of solitude for the crew, and there is value in designing for both cases. • When crews are able to train together, there is significant opportunity for building rapport and familiarity. As the nature of training changes, new ways of facilitating crew cohesion should be developed.
P12	**SPACE & EARTH CULTURE:** **Food, music, and other touchstones from home can be used to bridge cultural gaps. Designs that facilitate these activities can promote cultural exchange and altruism.**	• Music is important at an individual and group scale. Consider spatial and material design that allows for the creation and enjoyment of it. • Include windows or other ways to view Earth to provide a clear connection to home and potential impetus for global contemplation. • Consider the inclusion of diverse media resources and systems that can incorporate multiple languages, as hearing and speaking in one's own language provide an anchor point to one's own home and culture. • Including improvements to how we photograph, record, and immersively communicate the experience of space will help us better connect and share that experience with others.

Figure 3. Final set of design principles for space habitation, developed through an iterative design research process incorporating evaluative feedback from *n* = 5 astronauts. Categorical principles are numbered, and recommendations are associated with each principle to provide more detailed examples.

CATEGORY: Orientation & Movement
PRINCIPLE: While orientation and movement in microgravity is a learned skill, certain mission activities and social cues benefit from a shared orientation.
INSIGHT: Stabilizing oneself when floating requires three points of connection or contact, an important interior surface consideration.

Our final two interviews provided additional context that helped refine the insight into a more generalizable recommendation. The first was a clarification that while three points of contact are helpful, the broader challenge was accounting for torque and rotation, which one could do with their wrist (and its degrees of freedom) if needed. The final interview highlighted the fatigue that stems from holding oneself in position for long periods and described the value of handrails to alleviate the strain, thus informing our final design principle and related recommendation:

CATEGORY: Orientation & Movement (P6)
PRINCIPLE: While orientation and movement in microgravity is a learned skill, certain mission activities and social cues benefit from a shared orientation.
RECOMMENDATION: Stabilizing oneself when floating requires one to counteract the effects of torque. The positioning of handrails and other aids can help alleviate fatigue.

In this way, the evaluation and iteration process used to create these principles allowed us to take multiple passes at content, language, and organization. The final result of this iterative process can be seen in Fig. 3.

C. Findings

While the majority of our findings are integrated into the design principles (as seen in Fig. 3), overall learnings emerged from the iterative design research process that we discuss here. One benefit of the iterative evaluation process is the ability to identify and flesh out gaps. For example, insights focused on cleaning, organization, and garbage were initially spread throughout the early design principles document, under “Smell” and “Communication.” However, they were aggregated and grouped together early in the iteration process due to the number of related insights suggested by participants. When added as a distinct category, “Object & Space Organization” (P8) received the most consistent positive feedback among participants. Another benefit of our approach was the ability to iterate on the language used for our principles. Of our five participants, four were non-native English speakers, and so their feedback helped us identify confusing sentences and simply our principles to be more accessible. While participant feedback was instrumental in converting insights into recommendations, some of the content within the design principles are still read as descriptive statements rather than guidelines, most notably in the “Intuition & Acclimation” and “Taste” categories. Despite their descriptive nature, we decided against removing these insights as they were consistently described as important to our participants and provide valuable motivation for design decisions.

Additional themes emerged during the evaluation and iteration process that are worth addressing. For instance, we observed that certain categories, including categories covering senses and intuition, received more varied feedback, while others, including communication and organization-focused categories, received very consistent feedback. Participants also expressed preference for certain senses over others during the interviews. For example, one individual commented that their memories of space were associated with sight and smell more so than touch, while another emphasized the importance of touch to how they remember space. This sensory preference may have impacted the variation of experiences described by participants during interviews, as well as which categories participants provided significant feedback on. We catalog these instances of commonality and variance within the design principles directly, by making note of where diversity of experiences appears within the recommendations.

Some of the astronaut feedback we received related to the process of designing for space as a whole, rather than to any individual category. We consolidated this feedback into three meta-principles that are applicable across the design principles:

Meta-Principle 01. Involving individuals who have an embodied experience of life in space in the design process for space environments will allow for more productive, livable outcomes.

This meta-principle was derived from conversations with participants about the ways astronauts were involved in the design process, including the selection of items for personal use in space and positive collaboration experiences when contributing to space design. It also stems from less positive descriptions of "afterthoughts" associated with the space environments they experienced, as well as challenges of unanticipated and unintended uses of spaces and objects.

Meta-Principle 02. Improvisation should be encouraged and facilitated, as crews enjoy the opportunity to improve their environment and generate their own in-situ solutions.

Descriptions participants provided of valuing moments of agency and creative innovation initially motivated this meta-principle. Creative problem solving was also connected with 'feeling human,' which mirrors earlier findings that "meaningful work" can help with transition and adaptation to space environment.[3] However, it is important to note that one participant raised an important caveat—the experience and intent of the person improvising matters, as well as what they are creating, given the high-stakes nature of space environments. How much a space tourist should improvise in space, and whether there are ways to allow for safe improvisation in the initial design of habitations, is an open question worth investigating.

Meta-Principle 03. Planning for the life cycle of a space habitat requires knowledge of what needs to remain consistent, what should be updated over time, and what should be flexible and personal.

This meta-principle arose from three pairs of themes and their interactions, as identified by a majority of participants. *Flexibility* and *preference* were strongly suggested when considering aspects of human life in space that vary considerably due to differences between people and mission needs. However, participants often juxtaposed these themes directly with an emphasis on the use of *standards* and *guidelines* to make similar elements on the ship consistent across modules and agencies. These themes all relate to a better understanding of the life cycle of a space environment, and the need to account for *updating* and *maintenance* of certain systems. In particular, updating hardware was cited as a challenge, but software-based solutions and planned interoperability were proposed as ways to instill enough standardization to allow for future flexibility and modularity.

While overall findings were consistent within the cohort, due to the small sample size further study is needed to test the generalizability of these findings in a broader context. However, we believe that these themes may serve as useful hypotheses to explore in future research. Qualitative research as a methodology is often strongest for mechanism discovery and hypothesis generation, seeding deductive research goals.[42] The sample size of our study maps to the broader challenge of balancing specificity with coverage in both selecting and consolidating insights into recommendations. It is worth noting that some details were 'left on the cutting room floor' during the iteration process for being too specific, too particular to one astronaut's experience, or running the risk of confidentiality concerns. The evaluative interview sessions not only allowed us to improve our final design principles, but also spurred conversations that provided additional insights into human life in space. We recognize that there is tremendous value in these descriptive, anecdotal insights, and the desire to find ways to share them alongside our synthesized design principles serves as motivation for future work.

V. Discussion

We explore the various contexts in which astronauts are "in-the-loop" during mission planning and environmental design, synthesize qualitative data from nine spacefaring individuals into a series of categories and insights, and use an iterative design research framework with five spacefaring participants to evaluate and convert these insights into a consolidated set of design principles. We now review how our approach and findings align with and contribute to the contemporary body of space design research, with respect to both methods and outcomes.

With respect to outcome, Häuplik-Meusburger's *Architecture for Astronauts: An Activities-Based Approach*[24] serves as a thorough and valuable design resource and precedent. Significant archival research into both agency standards and existing qualitative data sources inform an overview of space vehicles and habitats from Apollo to the ISS, as well as a comparison of the performance of these space environments through five "human activities"—*sleep, hygiene, food, work,* and *leisure*—which have some overlap with our own recommendations.[24] In addition to archival research, nine astronauts spanning the Apollo to ISS era were interviewed by the author in order to solicit their input. Each "human activity" section culminates with a series of design directions, ranging from near-term considerations similar to our own example recommendations, to more speculative suggestions on topics ranging from personal greenhouses to human intimacy in space.[24] The overlap in recommendations suggests that archival and interview-based methods are both valid approaches to develop a human-centered understanding of life in space.

In comparison to this resource, our design principles are organized around human senses and needs rather than activities. While human activities map well to operational and spatial needs, we hope to instead emphasize the human-centered nature of the principles, both individual and communal. Another important difference to note between this resource and our own is the depth and detail of information provided in the former. While the richness found in *Architecture for Astronauts* is incredibly valuable, we opted to develop a more compact design resource that could be examined cumulatively at-a-glance and evaluated during hour-long sessions with astronauts.

Jack Stuster's analyses[3,20] of human resilience and performance in extreme environments serve as methodological precedent for our work. The categories developed in his research highlight key similarities and differences between space exploration and other forms of survival in extreme environments. While primary data sources used in these studies include diaries, logs, and journals rather than retrospective interviews, similar coding and categorization methodologies are employed to provide structure to qualitative data. In particular, the 2010 Journals Study[3] used existing codes from prior research with French explorers[20] to seed a qualitative journal study with ISS astronauts, which were then modified and re-prioritized based on astronaut feedback. There is considerable overlap between the Journal Studies categories and our own, though greater emphasis is placed on operational and emergency considerations in the Journals work with the inclusion of separate categories for *work, procedures/rituals, safety,* and *medical.* While behavioral insights are coded and quantified, the study also presents humanizing examples and anecdotes to bolster conclusions.[3] The qualitative research methods used by Stuster are similar to our own, particularly those used in the creation of our initial generative dataset. However, the primary work of this study builds off of that existing generative research, using evaluation and iteration methods borrowed from design research and HCI. There are similarities between the recommendations provided by the Journals study and our principles, though Stuster's work focuses more on ways to improve behavioral outcomes for missions, "through selection, training, support, scheduling, and the design of equipment and procedures."[3] As part of overall recommendations, the Journals study encourages a mindset shift from designing for exploration to designing for *routine operations* with respect to human comfort and resilience in space, as the route to LEO in 2010 had become a "well-traveled highway."[3] In 2021, an increase in the number of new space enterprises, astronauts, and missions raises the question of whether there are other behavioral paradigms beyond *routine operations* that we should consider when designing for space, and how to anticipate the needs associated with new spacefarers and their goals.

While insights from astronauts are invaluable to developing a current understanding of life in space, there are limitations to the applicability of their feedback to future space environments. The majority of today's spacefaring individuals are highly trained and adaptable people, which may limit what they notice and recommend with respect to improving environmental conditions. We were also only able to include a limited number of perspectives, given the relatively small sample size of our generative and evaluative datasets. Additional astronaut voices from interviews and other first-person accounts of space would bolster the reliability of our findings, and specifically including insights from space tourists may help to incorporate more diverse perspectives into this research. As next steps, we plan to continue to iterate on the design principles, incorporating feedback from potential users and experts within and outside of space agencies. We aim to present these principles in an accessible, web format to a broad audience – including designers, engineers, students, and new actors in space exploration industry – in the hopes that the principles contribute to and inspire conversations about the future of space design. Overall, we hope that this research effort contributes to a broader democratization of direct, experiential knowledge of the challenges of human spaceflight.

VI. Conclusion

In this work, we present a consolidated set of design principles for designing space environments, informed by and iteratively developed through "astronaut-in-the-loop" feedback. We first define "astronaut-in-the-loop" and the ways spacefaring individuals are incorporated into space design, testing, and in-situ use of space technologies. We then utilize qualitative coding methods, participatory design, and modified heuristic evaluation to iteratively develop a set of human-centered design principles for space environments. Our aim with this work has been to develop a human-centered, human-informed resource about life in space, as well as to demonstrate the use of an iterative design research framework in a space research context. As our relationship to LEO—and human space exploration as a whole—changes, we see significant value in continuing to learn from individuals with lived experience in space, and in continuing to develop human-centered design principles for future space environments and missions.

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