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Acyclic Framework for Mapping Relationships between Behavioral Health and Habitat Design in Austere Environments

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Abstract

As crewed long-duration space exploration missions become increasingly Earth-independent and reliant on on-board technology, risks due to human-system incompatibility become critical to address. Traditionally in the aerospace industry, human factors considerations are focused sets of recommendations for singular applications that are not generalizable across the design space. In a space habitat, establishing objective and meaningful relationships between the individual, crew, environment, and mission outcomes has been challenging due to multidirectional influences between mission and system components. Additional complexities due to feedback loops (e.g., stress affecting sleep, in turn affecting stress) make characterization of influence within the system difficult.

In this work, we have designed a systematic approach to identifying causal relationships between mission parameters, habitat elements, crew composition, operational stressors, and behavioral health and performance outcomes. We leverage a Directed Acyclic Graph (DAG), often utilized in graph theory and systems engineering, which allows us to build a network of factors and connections. The acyclic, or unidirectional, property of a DAG allows us to clearly define causal relationships and provide clarity to the habitat design approach. An extensive literature review informed our design tool that establishes how habitat design parameters serve as powerful mediators between mission stressors and behavioral and physical health outcomes. Herein, we present the tool, available at hecia.space, and explain the benefits and limitations of our approach to capturing complex human systems design.

Keywords: design, space architecture, habitability, behavioral health, ICE environment

Nomenclature

Acronyms/Abbreviations

BHP = Behavioral Health & Performance
CFM = Contributing Factor Map
DAG = Directed Acyclic Graph
DRM = Design Reference Mission
HSRB = Human System Risk Board
ICE = Isolated, Confined, and Extreme
NASA = National Aeronautics and Space Administration
SME = Subject Matter Expert

1. Introduction

As of 2020, the NASA Human System Risk Board tracks and manages approximately 30 risks associated with human spaceflight to prepare for long-duration spacflight missions to the Moon, Mars, and beyond [1]. NASA's Human System Risk Board (HSRB) is currently tracking 19 active risks that require mitigation for Lunar and Martian Design Reference Missions (DRMs) available via the NASA Human Research Roadmap website.

To manage human spaceflight risks, several tools have been developed and implemented over the years. For instance, NASA developed standards defining acceptable mission and lifetime health risk, as well as a risk mitigation analysis tool to evaluate the effectiveness of mitigation strategies [8]. A visual tool was developed by Mindock and Klaus [9], named the Contributing Factor Map, a simplified version of which is shown in Figure 1. The CFM maps performance-influence factors in a vertical hierarchy from the most general levels at the top (i.e., Operations, Vehicle Design, and Human) to factors that directly influence performance. Most recently, NASA has developed a visual representation of the compounding and synergistic risks through a Directed Acyclic Graph structure, which connects mission hazards, contributing factors, countermeasure capabilities, human system risks, and mission outcomes [10].

The work presented herein is focused on addressing one of these risks, namely the 'Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders'. Evidence from spaceflight and analog studies have shown that long-term isolation and confinement in an extreme environment have negative impacts on psychological and behavioral health [12][13][14][15]. With future missions' increased duration in isolation and confinement in spacecraft habitats and high consequence of evacuation, the built environment becomes an even more salient mediating factor in crew health [16]. Indeed, past evidence suggests that habitat design has a close relationship to behavioral health and performance. For instance, the interior décor of spacecrafts can affect wellbeing [17]; colors can be used as navigational aids in the microgravity environment [20]; and lighting systems need to provide both adequate task lighting and circadian entrainment [16].

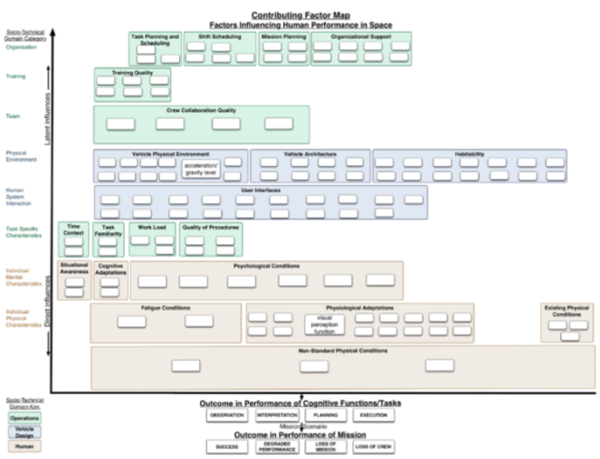


Figure 1: A simplified overview of the Contributing Factor Map, published by Mindock and Klaus.

2. Methods

2.1 Directed Acyclic Graphs

Graphs are defined through a set of finite nodes and a set of edges that connect two nodes [2]. An example of a graph is shown in Figure 2a. An edge can also be assigned with a direction from one node to another, which creates a directed graph (example shown in Figure 2b) [2]. Finally, a cycle in a graph is a closed loop, beginning and ending at the same vertex while repeating no edges [2]. Examples of directed cyclic and acyclic graphs can be found in Figures 2c and 2d.

Directed Acyclic Graphs (DAGs) are flexible tools that have been utilized in varied scientific applications to establish linkages between upstream events and downstream consequences [3][4][5][6].

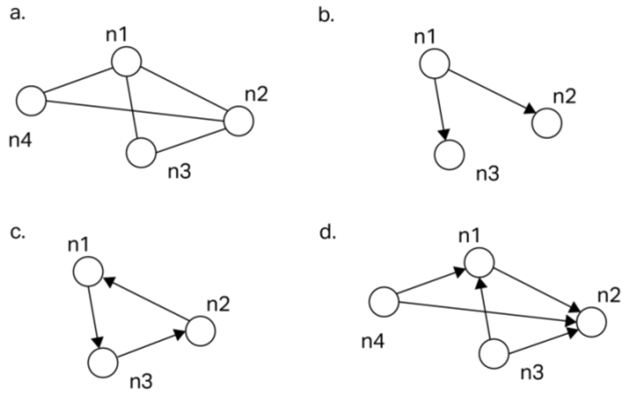


Figure 2: Examples of graphs. a) Graph with four nodes (n1-4) and five edges. b) Directed graph with three nodes (n1-3) and two edges, from n1 to n2 and n3. c) Directed cyclic graph, with three nodes whose connected edges form a loop. d) Directed acyclic graph, with four nodes whose connected edges never form a loop.

2.2 NASA Directed Acyclic Graphs

The NASA HSRB has created a DAG for each of the 30 human spaceflight risks. These DAGs have been harmonized, meaning that the same variables (represented as nodes) are used across the 30 DAGs. One example of the DAGs available on the HSRB website (https://www.nasa.gov/directorates/esdmd/hhp/human-system-risk-board/) is included here in Figure 3 [7]. The HSRB has also created the first draft of incorporating DAGs across the 30 risks, which is shown in Figure 4 [10].

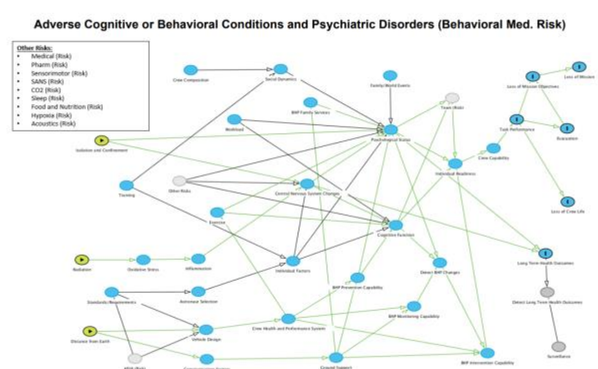


Figure 3: The Directed Acyclic Graph for the Behavioral Medicine Risk, published by the NASA Human Systems Risk Board.

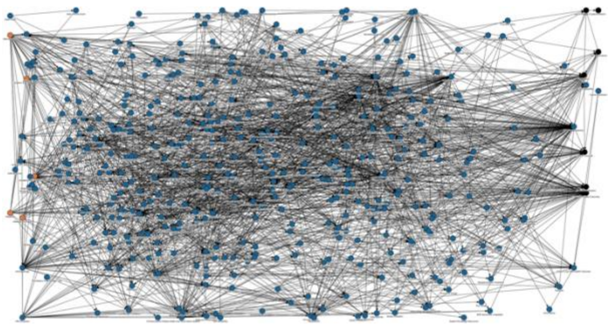


Figure 4: NASA Human Systems Risk Board's draft risk network combining 30 individual directed acyclic graphs, published by Antonsen et al. 2024 under copyright https://creativecommons.org/licenses/by/4.0/

2.3 Challenges in the existing frameworks

This project developed a framework that addressed some key opportunities posed by the habitat-design specific knowledge, comprehensibility, and legibility gaps presented by existing methods, namely the standards [8], factor mapping [9], and NASA DAGs [7].

2.3.1 Limitation in fidelity

Within the documents publicly available on the HSRB website, DAGs for each risk are shown, with a combined table of nodes/factors at the end. Each of the nodes has a definition of 1-2 sentences created by internal NASA Risk Subject Matter Experts. While this format may be adequate for some nodes (e.g., 'Resupply – the ability to restock consumables'), some lack detail that could be easily included to improve understanding (e.g., the inclusion of specific chemicals and rationale for concern in 'Payload Chemicals – chemicals that are used in experimental payloads') [7]. There exists an internal-only 'DAG-tionary' with more detailed definitions, but still lacks citations from literature. Considering that stakeholders for the communication and management of risks would be the subject matter experts at NASA, it is reasonable to assume that an expert in one risk may have little insight into the specifics of another risk. Therefore, there exists an opportunity for the inclusion of more detailed information to ensure that the risks are communicated adequately through the DAGs.

2.3.2 Limitation of focus on 'task performance'

At an agency level, NASA's risk posture is concerned with mission level outcomes and individual level outcomes. Currently, the NASA DAGs acknowledge the following nodes as outcomes: Loss of Mission, Loss of Crew Life, Evacuation, Flight Recertification, Long Term Health Outcomes, and Task Performance [10]. The current framework does not explicitly account for behavioral health and team functioning in-mission as part of this set of Outcome nodes. The NASA DAGs account for BHP factors under 'Individual Readiness', defined as 'the level to which a crewmember is prepared mentally and physically to perform necessary tasks', and 'Team Functionality', defined as 'the degree of coordination, cooperation, communication, and psychosocial adaptation that enables a team to successfully complete tasks and live and work as a team' [7]. However, one of the open gaps of the Behavior and Cognition Risk (BMed) is the identification and characterization of relevant cognitive, behavioral, psychological, and neurological outcome measures [11]. With the current lack of detail and vocabulary within the NASA DAGs representing behavioral health outcomes of concern, there is an opportunity to introduce BHP outcome measures that are of interest to the spaceflight community on the same level as task performance has been historically considered.

2.3.3 Usability

Spaceflight is a complex system; this is represented well through the merging of all 30 risks of concern to human spaceflight, as shown in Figure 4. As system complexity increases, the amount of information can become unmanageable, and great care should be taken to ensure information is stored and delivered in a manner that remains legible, understandable, and usable. Standards and documents can be difficult to work with due to the large volume of text, which can be a challenge to interpret and comprehend. Moreover, documentation may not be accessible to all stakeholders, or revisions become so numerous that the text is dominated by bureaucratic information as opposed to actual content. In comparison, DAGs are valuable communication pathways for those working across risk fields, or for management to understand causal relationships without the need to gain expertise.

Each node in the NASA DAGs falls into one of the following categories: Spaceflight Hazard, Contributing Factor, Countermeasure, Associated Human System Risk, and Mission Level Outcome [10]. However, this categorization scheme has not been integrated into the publicly available DAGs [7]. Furthermore, the distribution of nodes does not take advantage of the spatial aspect of a graph; the categories of the nodes do not influence the position or visual importance of the node beyond its coloring. Therefore, there is an opportunity to introduce additional visual organization to increase the legibility and comprehensibility of the network in order to strength its value as a communication tool.

2.3.4 Inclusion of habitat design factors

Habitat design factors are included in the NASA DAGs under 'Vehicle Design'. While some aspects of habitat design (e.g., privacy, noise) are included, some are not (e.g., lighting, layout), despite the known impact on crew performance [11][18][19]. While habitat design is acknowledged as both a risk factor and countermeasure in several DAGs, the NASA DAGs remain high-level in describing these relationships due to the need to communicate information across disparate subject areas. For habitat designers, more information is needed to understand the nuanced relationship to BHP outcomes. Therefore, there is an opportunity to integrate habitat design factors into the risk networks to complement the existing framework.

3. Framework development

To address the opportunities presented through the existing DAG framework, we created *HECIA*: Human-Environment Connection & Interaction Atlas. Through this tool, we implemented the following capabilities:

1. Limitation in fidelity → utilizing categories as visual organizers, incorporating literature into the expanded definitions of each node and edge to facilitate further learning
2. Limitation to 'task performance' → including specific behavioral health & performance outcomes
3. Usability → improving readability, introducing spatial hierarchy, interactive user interface
4. Inclusion of habitat design factors → including specific habitat design factors as nodes in the network

HECIA is a three-layered framework that is hierarchically organized based on fidelity. To facilitate ease of comprehension, these factors are arranged temporally according to the design process. 'Mission Parameters' encompasses decisions that are made at a program level, including selection criteria, mission duration, distance, mission goals (e.g., surface exploration), and the extent of isolation, confinement, and extremeness. 'Mediator Variables' represent designed factors that mediate the influence of mission parameter stressors. For instance, individual traits, supplies, medical capability, and habitat design are part of mediator variables. 'Processes' are team and individual activities that are pertinent in spaceflight, such as team cohesion, stress regulation, and sleep. 'Outcomes' are BHP criteria that have spaceflight relevance due to their prevalence in existing BHP measures, or in isolation analog psychology. The four categories make up the first layer of the network, as shown in Figure 5. Each factor

Layer 2 of the framework, shown in Figure 6, is a finer grouping of the Layer 1 categories. Finally, Layer 3 is the finest level of the framework, and comprises all factors, shown in Figure 7. Each layer is introduced incrementally, which aids comprehension.

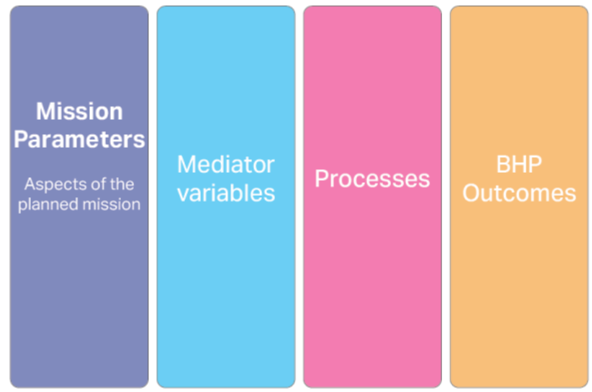


Figure 5: Layer 1 of the HECIA user interface. Categories 'Mission Parameters', 'Mediator Variables', 'Processes', and 'BHP Outcomes' are shown in colored boxes. Hovering over 'Mission Parameters' reveals the description 'aspects of the planned mission'.

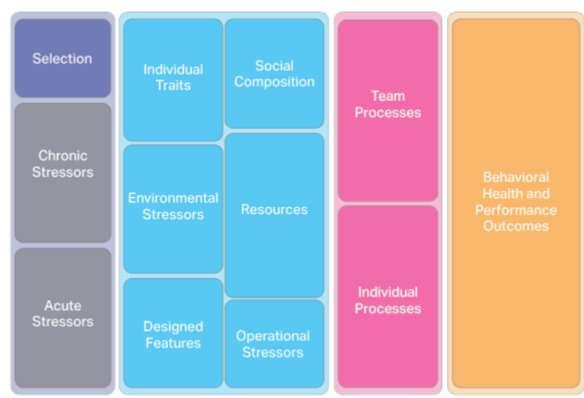


Figure 6: Layer 2 of the HECIA user interface. Categories from Layer 1 are broken into finer groupings.

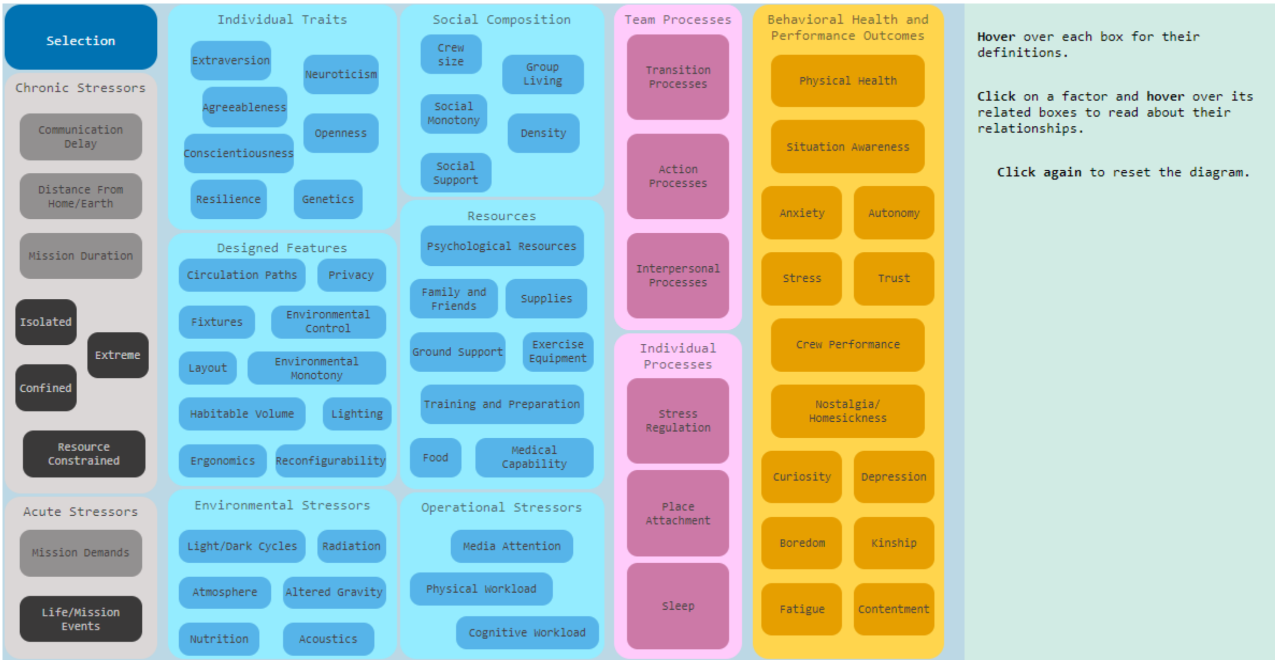


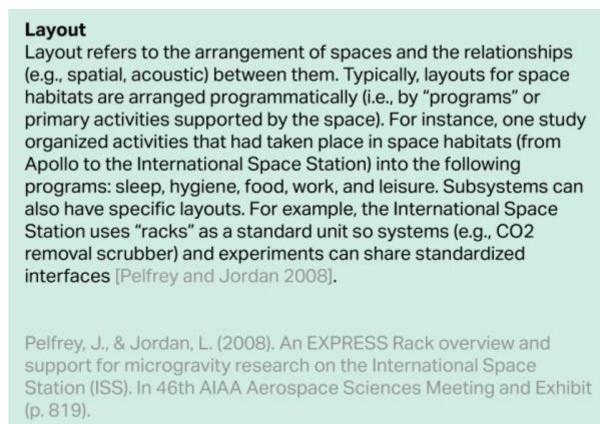
Figure 7: Layer 3 of the HECIA user interface. Factors are represented in dark colored boxes, and the lighter colored boxes represent their groupings that have been inherited from Layer 2. The right-most box shows definitions when hovering over each factor.

4. Example design use case

4.1 Forward case – design variable impact on BHP outcome

We present a forward path case study, which centers a design variable of interest to see how it propagates forward to the BHP outcomes. Understanding the potential impacts of a design decision can allow for more informed choices and encourage conversations around the tradeoff between benefits and risks. In this instance, we are interested in understanding how 'Layout' impacts other design variables and BHP outcomes, in this case: 'Circulation Paths', 'Privacy', 'Reconfigurability', and 'Interpersonal Processes'. By hovering on 'Layout', we can read the definition with literature citations on the right-hand side. The definition is shown in Figure 8. By clicking on 'Layout', we can highlight the first-level relations and hover over each factor to explore the causal relationship between 'Layout' and each factor. This is shown in Figure 9.

By hovering over each factor that 'Layout' is connected to, the definition box on the right-hand side changes accordingly. Hovering over 'Privacy' brings up the linkage between 'Layout' and 'Privacy', as shown in Figure 10.



Layout
Layout refers to the arrangement of spaces and the relationships (e.g., spatial, acoustic) between them. Typically, layouts for space habitats are arranged programmatically (i.e., by "programs" or primary activities supported by the space). For instance, one study organized activities that had taken place in space habitats (from Apollo to the International Space Station) into the following programs: sleep, hygiene, food, work, and leisure. Subsystems can also have specific layouts. For example, the International Space Station uses "racks" as a standard unit so systems (e.g., CO_2 removal scrubber) and experiments can share standardized interfaces [Pelfrey and Jordan 2008].

Pelfrey, J., & Jordan, L. (2008). An EXPRESS Rack overview and support for microgravity research on the International Space Station (ISS). In 46th AIAA Aerospace Sciences Meeting and Exhibit (p. 819).

Figure 8: Definition of 'Layout' as captured from HECIA.

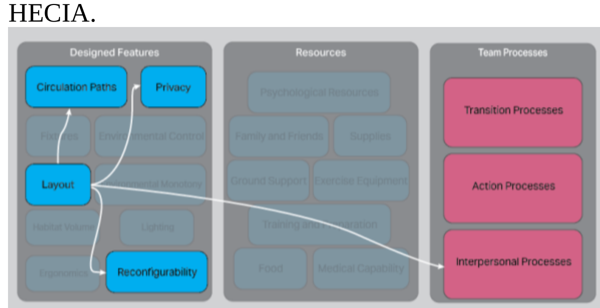


Figure 9: Highlighting 'Layout' in HECIA.

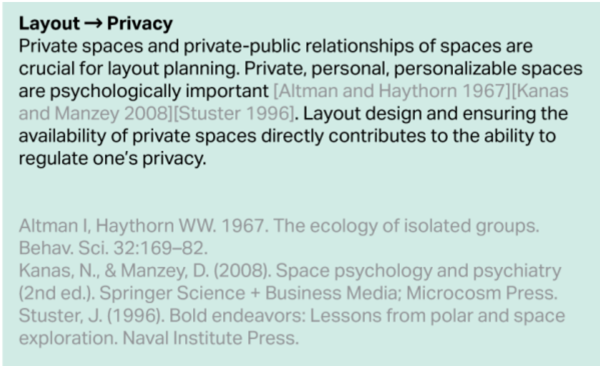


Figure 10: Causal relationship between Layout and Privacy and supporting literature as captured from HECIA.

In this way, one can understand the downstream impacts that ould be considered when designing a habitat layout.

4.2 Backward case – contributing factors toward BHP outcome

We also present a backward case study, which centers a BHP outcome of interest to see how mission and design factors might affect it. In Figure 11, we choose 'Stress' and see that it is influenced by 'Communication Delay', 'Isolated', 'Life/Mission Events', 'Neuroticism', 'Group Living', 'Cognitive Workload', and 'Stress Regulation'.

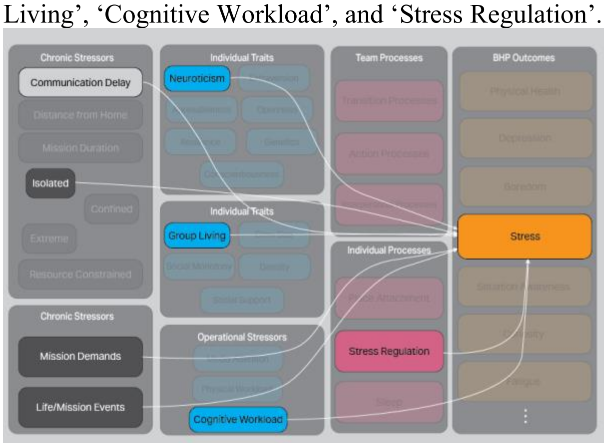


Figure 11: Highlighting 'Stress' in HECIA. Categories 'Designed Features', 'Environmental Stressors', and 'Resources' excluded for readability.

Similarly, one can click on 'Stress' and hover over any of the highlighted boxes to read about their relationship, as shown in Figure 12.

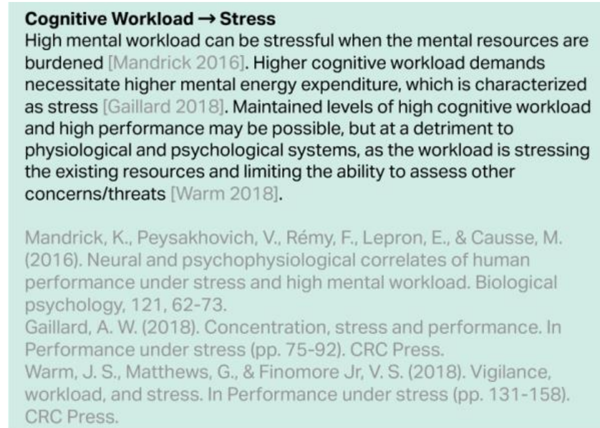


Figure 12: Causal relationship between Stress and Cognitive Workload and supporting literature as captured from HECIA.

This use case can help users explore contributing factors to elements of BHP. *HECIA* also helps distinguish components comprising 'behavioral health and performance', traditionally an umbrella term for individual and crew wellbeing, and illustrate how different design factors impact different BHP constructs. Coupled with the forward case studies, these explorations address the nuance and complexity of design in a systematic manner.

5. Discussion

5.1 Contributions

We have developed a framework and interactive user interface detailing causal relationships between mission parameters, environmental factors, habitat design, and behavioral health and performance outcomes. This development addressed gaps and opportunities within the existing risk mitigation strategies for human spaceflight. Firstly, this tool is a complementary addition to the NASA DAGs, utilizing the same acyclic nodes-and-edges structure that NASA risk custodians are familiar with. The focus on habitat design parameters and detailed BHP outcomes are both gaps that were addressed through our approach. We provided literature-based definitions and causal relationships between nodes to increase the fidelity and detail of the framework, allowing novices and experts alike to understand the context of the presented information. Visual and graphical organization allowed complex information to be categorized and presented in a more intuitive and user-friendly manner, facilitating communication across stakeholders who may be unfamiliar with these topics. Finally, the interactive nature of the tool allows for designers, scientists, engineers, and researchers to extract relevant information and to explore impacts of design decisions in a clear and detailed manner.

A conscious design decision was made for *HECIA* to not use the exact same vocabulary for the nodes as the NASA DAGs. While harmonization may allow for this tool to be fully integrated into the existing NASA system, many of the nodes in *HECIA* do not exist in their current form in the NASA framework. By considering NASA vocabulary where available and providing literature-based definitions for each node, this tool can be a complementary source of knowledge for stakeholders working in this specific risk area of human-habitat integration.

Furthermore, the framework of *HECIA* is intended to be context agnostic. While the existing tool addresses the impacts of spaceflight specifically through the inclusion of factors such as astronaut selection, communication delay, and ground/mission support, the definitions for many nodes also incorporate Earth-based perspectives where applicable. The inclusion of literature reference from psychology, anthropology, architecture, and existing work on voluntary and involuntary migration grounds the framework in the larger context beyond spaceflight. By drawing on a deeper understanding of the human experience, this framework can be used to address challenges in similar ICE environments on Earth, and those in spaceflight with a context of humanity and multidisciplinary expertise.

5.2 Limitations

In any representational tool or model, the fidelity and depth of the knowledge is limited due to a trade-off with usability and readability. Similarly, the content of each factor is limited to the depth required for comprehension by a wide range of users with variable expertise, the time and effort required to develop this extensive literature review, and the familiarity of the topic to the intended audience. The number of factors were also constrained to fit on a full-screen browser-sized page when viewed from a laptop, to address some of the aforementioned concerns with usability.

The selection of items and relationships between items were based on literature review and preliminary review from project SMEs. Not all possible factors of ICE environments were able to be included in the framework due to the scope of these factors. For instance, ‘environmental control’ was included as a factor instead of the specific mechanisms used in this process (e.g., CO2 removal, Sabatier reactions, etc.) We sought to maximize specificity of the included items, as action and design decisions are more easily made when the framework is more specific, while maintaining usability of the interface. Not all relationships are captured, as the nature of complex systems means that most factors are somehow related to each other; instead, we have selected the most salient relationships to highlight. These selections will be further refined with additional SME input.

5.3 Future work

Future directions include the refinement of the knowledge contained within the network. This is planned to be completed through interviews with Subject Matter Experts (SMEs) and prospective end-users. SMEs across NASA, industry, and academia with expertise across mission management, space medicine, behavioral health & performance, architecture, habitat design, and bioastronautics will be invited to participate in a semi-structured interview. Feedback on the completeness, representativeness, and usefulness of the tool will be integrated into the iterative tool development process. Furthermore, prospective end-users and participants who are representative of the tool’s intended audience (e.g., students, design/architecture/aerospace experts who may be novices to one of the other areas but are specifically interested in habitat design) will be interviewed and their feedback incorporated.

After the comments from the interviews are incorporated, the tool will be ready for public dissemination and feedback. The reactions and suggestions from the wider community are important processes for iterative design. The opportunity for impact relies on the engagement with the tool, as no one tool can serve as the “ground truth”, but rather a baseline to inform and inspire design decisions.

6. Conclusions

The framework we have presented herein is a point of departure for the integrated and equitable consideration of architectural design, mission capabilities, and behavioral health and performance outcomes. Utilizing the existing structure of Directed Acyclic Graphs used by NASA, we were able to include habitat design factors into the consideration of risk, as well as create an interactive user interface that serves as an exploration and educational tool. We expand on the depth of existing ‘outcome’ nodes, defining 13 distinct behavioral health and performance outcomes that were previously grouped under abstract mission-level outcomes. The result is a cohesive and systematic framework that encompasses factors across spaceflight hazards, various mediating factors (Social Composition, Environmental Stressors, Designed Features, etc.), and behavioral health outcomes.

As emphasized previously, *HECIA* is as much about the content itself as it is about the reactions, debate, and commentary that follow.

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