Adaptive Performance: A Generative Theory for HCI Design in Extraterrestrial Habitats

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Future habitats in deep space will experience long delays in communication with Earth. These delays will result in unprecedented situations where the crew cannot rely on synchronous support from Mission Control. As a result, the crew will need to act more autonomously and with limited resources when quick decision making is required. Designing displays and others tools that can effectively support the macrocognitive work necessary for these situations is an open challenge. In this position paper, we propose that theories of adaptive performance can play a generative role in designing interactive cognitive tools for extraterrestrial habitats. Drawing on studies of complex sociotechnical systems, we identify several concepts relating to adaptive performance in high-risk, uncertain, dynamic situations. We draw from HCI scholarship on the role of theory in design, suggesting ways that adaptive performance can support the generation of new design ideas. Finally, we describe a study in which contextual knowledge from practitioner interviews is integrated with framing constructs from adaptive performance to support the design of novel displays for extraterrestrial habitats.

CCS Concepts: • **Human-centered computing** → *HCI theory, concepts and models*; • **Applied computing** → *Aerospace*.

Additional Key Words and Phrases: HCI theory, design, macrocognition, adaptation, resilience, displays

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1 INTRODUCTION

Establishing habitats on Mars and beyond will involve several challenges significantly different in kind and scope from those faced in previous space missions. One of the fundamental challenges for such missions is the unavoidable communication delays that will occur between deep space and Earth. Communication between Mars and Earth, for instance, can take anywhere from 4 to 20 minutes for one-way transmission [10]. Such delays make current practices of tight communication and coordination between Mission Control and the crew impracticable. As a result, expertise from Mission Control may not be available when situations requiring urgent attention occur, requiring a small crew to act with more autonomy and less support than in any previous mission [11].

The anticipated nature of communication delays and increased crew autonomy presents both challenges and opportunities for designing interactive artifacts for deep space habitats. For instance, Shakeri and Neustaedter [15] note the challenges of feeling connected to family while on Mars, drawing on the notion of slow technology to propose speculative artifacts for enhancing a family's sense of togetherness while apart. Noting the challenges of unexpected situations in deep space, Boy [2] emphasizes the need to make automation more flexible for effective problem solving. Along similar lines, McTigue et al. [11] discuss challenges for anomaly response, proposing several questions for how technologies can be designed to support increased crew autonomy centered on the notion of 'extreme problem solving'.

In this position paper, we propose that theories of adaptive performance can play a generative role in designing interactive artifacts intended to support anomaly detection, sensemaking, decision making, and other macrocognitive processes that will need to be increasingly carried out by the crew. Drawing on studies of complex sociotechnical systems, we articulate several concepts relating to adaptive performance in high-risk, uncertain, dynamic situations. We then draw on scholarship investigating the generative role of theory in the design of interactive artifacts, suggesting ways that adaptive performance can support the generation of new design ideas. Finally, we describe an ongoing interview study that integrates knowledge elicited from flight controllers and astronauts with adaptive performance constructs to support the design of novel displays in extraterrestrial habitats.

2 ADAPTIVE BEHAVIOR IN COMPLEX SOCIOTECHNICAL SYSTEMS

Studies across a wide range of complex sociotechnical systems—including power plant and air traffic control rooms, hospital operating rooms, and other settings involving high-risk and uncertainty—show that surprises, unexpected events, fluctuations, and disturbances are the norm rather than the exception [6, 14, 16]. To operate effectively in these environments, people adapt continuously to match the demands of the situation with their expertise and the technology affordances available to them [16]. This adaptive performance in the face of complexity and uncertainty is one of the fundamental hallmarks of resilient sociotechnical systems [6].

Due to the dynamic, uncertain nature of work in complex sociotechnical systems, designers cannot imagine and plan for every possible use case of their artifacts, thus adaptations at the 'sharp end' of use are inevitable. The proclivity for users to adapt given technological limitations has been characterized as 'tailoring', 'filling in the gaps', and engaging in 'work-arounds', 'kludges', and 'approximate adjustments' [6, 9, 13, 14]. Despite the fact that adaptive performance is the norm, it is often viewed as an undesirable source of unpredictability and risk rather than as a source of human ingenuity in the face of difficulty [6]. As a result, practitioner engagement in everyday adaptations is often not acknowledged and used to improve the design of artifacts for envisioned future scenarios [14].

The adaptive view of human cognitive work falls under the broader theoretical lens of macrocognition, which refers to the cognitive functions and processes that occur 'in the wild'—particularly those in complex high-risk settings [8]. Important macrocognitive functions include planning and re-planning, problem and anomaly detection, coordination, framing and re-framing, sensemaking and situation assessment, adaptation, managing uncertainty and surprises, managing attention, and mental simulation. The emphasis of the macrocognitive view is on the distributed, collaborative, and situated nature of cognitive work in naturalistic settings, rather than the reductionist, controlled approach often taken in microcognitive research (e.g., in laboratory experiments on attention, memory, and so on).

3 THEORY AND INTERMEDIATE-LEVEL DESIGN KNOWLEDGE

While theories can explain or describe human behavior, there is often a challenge in bridging the abstractness of theory with the design of particular artifacts. Theories are often appreciated as *applicable* to design, but making them *actionable* for design is often underspecified. Beaudouin-Lafon and colleagues [1] have proposed 'generative theories of interaction', referring to empirically derived theories of human behavior that have actionable principles for design. Such theories have 3 necessary characteristics—they are: grounded in empirical studies of human activity and behavior with technology; amenable to analytical, critical, and constructive interpretation; and actionable through the concepts and principles contained in the theory. HCI scholars have elaborated the notion of 'intermediate-level' design knowledge, referring to a middle space between highly abstract theory and particular design instances [3, 7, 12]. Several constructs have been proposed to aid in the transfer of knowledge up and down this continuum of abstraction, including bridging concepts [3], strong concepts [7], and framing constructs [17]. We see framing constructs as a particularly useful descriptor of the generative work that concepts within a 'generative theory of interaction' perform. Framing constructs

[17] act as lenses for designers to frame both the problem and solution in relation to higher level theory. The framing of problem and solution can offer rich intermediate-level points of connection between theory and particular designs.

4 ADAPTIVE PERFORMANCE AS A GENERATIVE THEORY FOR DESIGN

Typical approaches to designing displays and other tools for space missions rely on guidelines and principles relating to human capabilities and limitations (e.g., principles of attention, memory, or workload). For instance, consider NASA's Human Integration Design Handbook (HIDH) [10], which is intended to assist the design of human interfaces. The handbook contains substantial detail on physical and cognitive workload, auditory and visual perception, anthropometry, and other human performance limitations. This kind of information is important for developing requirements and testing standards, but is often not actionable for generating novel design ideas. Knowledge of human memory limits, for example, may suggest what to avoid with a design, but it does not suggest how to come up with a new design idea. We propose that new *generative theories* for design be considered, in addition to the more traditional approaches for generating requirements and standards, to support fruitful ideation for future deep space missions.

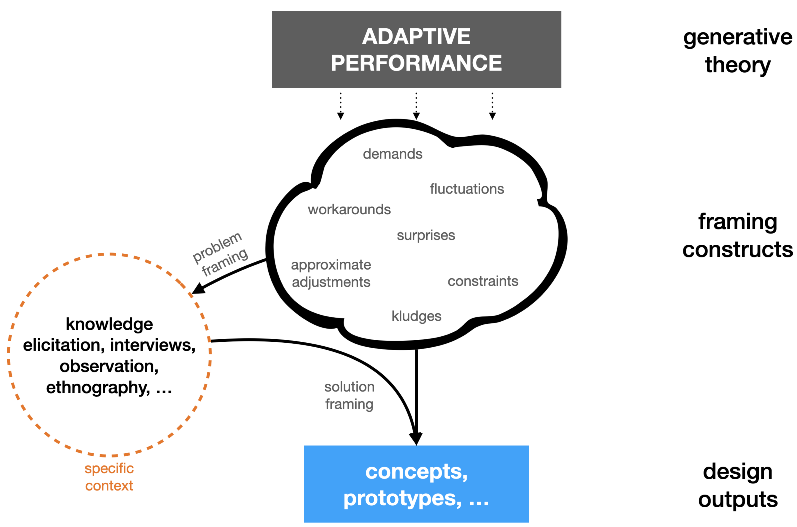

Fig. 1. Adaptive performance as a generative theory. Several constructs can play an actionable role when combined with insights from a specific context for creating design ideas.

We suggest that adaptive performance is a 'generative theory of interaction' [1], as it has been studied empirically in several domains, is open to various forms of interpretation, and contains several principles and concepts that can be made actionable. We also propose that it can be viewed as having several intermediate-level framing constructs that can help with problem and solution framing for design. Figure 1 depicts the relationships among adaptive performance as a generative theory, several framing constructs from studies of human behavior in complex sociotechnical systems [9, 14, 16], and the injection of data derived from specific contexts of real-world practice (e.g., via ethnographic or observational work, interviews, and so on). The input of data from an area of practice is important, as it can help make the constructs more actionable and context specific. We mention an ongoing study in which we are engaged as an example. Our work is in the context of a NASA-funded space technology research institute that aims to generate knowledge for designing resilient extraterrestrial smart habitats [4]. One thread of the ongoing work involves an interview study focused on understanding adaptive performance of Mission Control operators and astronauts with ISS experience. In this study, we are using knowledge elicitation techniques [5] to uncover how practitioners currently adapt in response to situational demands using the computational artifacts available to them. We are using concepts of adaptive performance to frame the interview questions, focusing on adjustments, surprises, workarounds, constraints, and so on. We are doing this with a focus on data, displays, and situation awareness—e.g., how do flight controllers assess the current state of the station, what data do they look for to see when something might be off-nominal, what do they see and interact with on their displays when doing so, and how do the tacit aspects of their expertise support adaptation under uncertainty. Because adaptation is the norm in real-world practice, surfacing current adaptive strategies of experts can be useful for envisioning future design possibilities. Insights yielded from the interview data can combined with the framing constructs to generate new design ideas (e.g., visual interface mockups that support anomaly response and planning on Mars without input from Mission Control). Following this approach, design ideas can be grounded in both established generative theory and contextually-relevant data from real-world practice.

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