ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY
Volume 28, Number 3, 2025, 247–259
doi: 10.59277/ROMJIST.2025.3.01

Conducting Human-Computer Interaction Scientific Experiments in Extreme Environments: Insights from Analog Mars Missions

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Abstract. Recent technological and methodological advances at the intersection of space research and human-computer interaction have opened up new opportunities for studying interactions with computer systems in extraterrestrial-like settings. In this context, we address in this paper the challenges of conducting scientific experiments in human-computer interaction within extreme contexts of use by focusing on physical and psychological constraints affecting users, platforms, and environments. We contribute empirical findings from two missions conducted at the Mars Desert Research Station, where we explored the user experience of interacting with computer systems both within the indoor space station habitat and the outdoor Mars analog geological landscape. Drawing from our findings, we highlight the importance of replication, artifact reproducibility in the engineering of interactive computer systems for space research, and the need for more comprehensive conceptual and design frameworks for studying interactions within extreme contexts of use with scientific rigor.

Key-words: Context of use; extreme environments; human-computer interaction; interactive systems; Mars analog missions; scientific experiments; user experience.

1. Introduction

Space exploration—humanity's quest to understand its place in the universe—has become more tangible in recent decades. Notable milestones include the International Space Station [1], continuously inhabited for over twenty years, and the growing low Earth Orbit economy, exemplified by SpaceX's Starship [2], a spacecraft for reusable transportation to the Earth orbit and beyond. In this context, conducting safe space missions and establishing habitats requires robust computer technology featuring user interfaces that remain effective despite the physical and psychological challenges of extraterrestrial travel experiences, including feelings of isolation and confinement [3]. Even with design guidelines for crew user interfaces in place, such as NASA's Human Integration Design Handbook [4], these experiences are yet to be fully understood, even basic activities like playing a musical instrument in microgravity [5] or eating during space travel [6].

The intersection of space research and Human-Computer Interaction (HCI) has been formalized through SpaceCHI [7], a recent initiative centered on the scientific application of established HCI methods and techniques to support space missions. Many contributions followed, such as astronaut-oriented design approaches [8], interaction techniques in microgravity [9], interplanetary virtual spaces [10], and examinations of the extraterrestrial applicability of interaction design frameworks originally developed for Earth-based environments [11]. Recent SpaceCHI topics of interest highlight human-AI interaction for space exploration, wearables for space health, interfaces for human expression in space, and human-robot interaction in deep space missions [12].

Fig. 1. Unlike conventional environments, where interactions between users and computers are typically studied, extreme environments impose unique physical and psychological constraints, introducing new challenges for planning and conducting scientific experiments in human-computer interaction. In this photograph, taken during one of our missions to the Mars Desert Research Station, these constraints are exemplified by high temperatures, intense sunlight, bulky astronaut suits, and heavy gear, which affect mobility, dexterity, and sensory perception.

In this context, we contribute insights from data collected during two missions conducted at the Mars Desert Research Station (MDRS) [13], a space analog facility in the Utah desert surrounded by a geological landscape that closely resembles Mars; see Figure 1 for a representative photograph. Specifically, we examine the three key dimensions of the context of use for interactive systems, according to Calvary *et al.* [14], which in our case correspond to crew members, the computer systems they engage with, and the Mars analog environment. To illustrate these dimensions, we address in Section 2 organizational aspects of conducting HCI experiments in unconventional environments involving crew training, gear requirements, and safety protocols, and present in Section 3 the results of two experiments about the user experience (UX) of interacting with computer systems in such environments. Based on insights from these missions, we reflect in Section 4 on the process of conducting HCI experiments in extreme environments holding the same scientific rigor, ethical considerations, and data privacy principles as in conventional Earth-based research laboratories. Lastly, we show in Section 5 how our findings can foster further HCI research in the context of humanity's ongoing quest for space exploration.

2. Conducting Experiments in Human-Computer Interaction in Unconventional, Extreme Environments

We examine in this section the specific dimensions of the context of use [14] for interactive computer systems—*users, platforms,* and *environments*—and discuss their particularities for planning and conducting HCI experiments in the unfamiliar and unconventional setting of a Mars analog mission. In this context, experimenters and participants constitute the same crew of analog astronauts, subjected to the same physical and psychological stressors. Moreover, the environment presents specific challenges, differentiating it significantly from a controlled laboratory setting. Specific requirements, such as mandatory safety protocols, which interfere with all aspects of daily life in a space habitat, add to the complexity of running scientific experiments.

2.1. Experimenters and participants in scientific experiments

An extreme environment requires significant effort from its inhabitants to adapt to new physical conditions while striving to maintain functional and cognitive performance [15]. This adaptation involves adjusting to new habitats, weather conditions, and social dynamics, where both experimenters and participants in experiments form the same crew. This dual role is unique in the science and practice of HCI, and we identified the following key stages in their establishment:

- *Pre-mission training.* Before arriving in the extreme environment, specialized training is in order for crew members. In our missions to MDRS, this included experiencing Mars-like gravity conditions in an advanced virtual reality simulator (Figure 2a), performing resistance exercises in an aquatic environment at a neutral buoyancy facility (Figure 2b), and engaging with artificial gravity created through a centrifugal accelerator (Figure 2c).
- *During the mission,* the physical conditions of the living environment, the characteristics of social dynamics, and psychological effects can influence task performance. Experimenters and participants must surpass these challenges to ensure the success of the experiment.
- *Post-mission data analysis.* The collected data must be interpreted within the context in which it was collected, accounting for any potential influences of the context of use.

Each of these stages is directly impacted by constraints on sample size, a crucial factor in empirical research where large samples of participants are desirable. For example, detecting an effect size of Cohen's $d=0.4$ in a within-participant study requires at least 50 participants to achieve 80% statistical power [16]. While smaller sample sizes are common in HCI research [17], the reliability of inferential statistical tests depends on the availability of large and diverse samples, not easily attainable in extreme environments. At MDRS, for example, the crew size is limited to a maximum of eight members. This aspect equally imposes constraints on the number of experimenters, especially when the experiment is conducted outside the habitat, for which crew distribution and organization protocols are enforced for safety reasons, *e.g.*, some of the crew members are required to stay inside and supervise the mission. Furthermore, prolonged exposure to confined and isolated environments can lead to several physical symptoms and psychological effects, including depression, which have been documented in psychology research [15, 18].

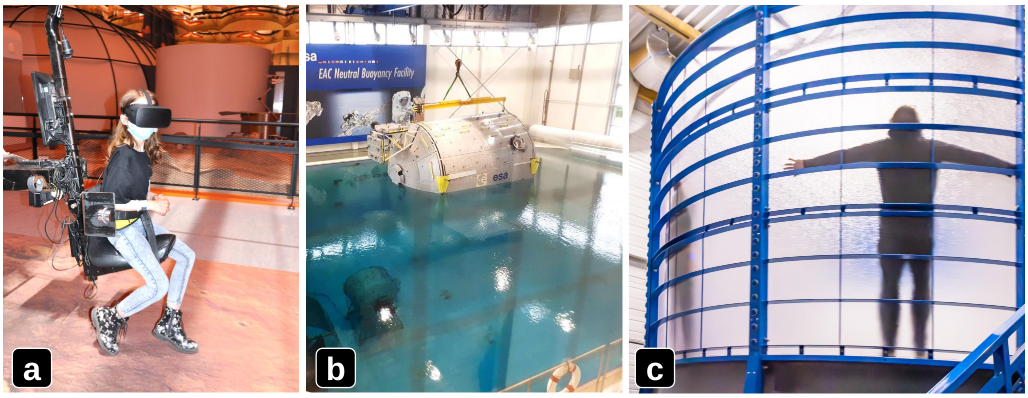

Fig. 2. In a Mars analog mission, experimenters and participants to the experiment form the same crew and undergo specific training. The photographs illustrate: (a) simulating walking on Mars under altered gravity conditions, (b) experiencing pressure changes during underwater submersion, and (c) engaging with artificial gravity through centrifugal acceleration.

2.2. Environments

Both external and internal environmental conditions can influence individual participation and performance in HCI scientific experiments conducted in extreme environments, potentially affecting the integrity, validity, and replicability of the collected data. For example, the MDRS facility [13] was specifically designed to support research aimed at advancing the technology and science for human space exploration. To this end, it provides realistic environmental constraints for a simulated Mars mission, given its location in the Bentonite Hills: a Jurassic-Cretaceous geologic landscape characterized by multi-colored bands of red, brown, purple, and gray hues. However, this environment can pose significant physical and psychological challenges for the human body because of extreme temperature and humidity conditions; see Figure 3 for daytime and nighttime photographs taken during our missions at MDRS. Daytime temperatures in Capitol Reef Country, where MDRS is located, can reach 40°C (104°F) in June, and the dessert loses heat quickly after sunset because of low humidity, leading to cold nights with recorded lows of 1°C (34°F) during the same month. These fluctuations can severely impact human physiological adaptation and cognitive performance and, thus, introduce additional variables to be accounted for in the experimental design, compared to a lab-controlled setting on Earth. In the shelter of the indoor environment, new challenges arise due to operating within confined spaces and navigating narrow passageways (Figure 4a), specifically designed to optimize storage and resource efficiency for the maximum allowable crew. These challenges may be balanced by the psychological benefits of engaging in activities involving Earth-like vegetation (Figure 4b). However, the architectural elements of a space station, such as porthole-style windows (Figure 4c), may amplify feelings of isolation, where crew members cannot leave the mission at will.

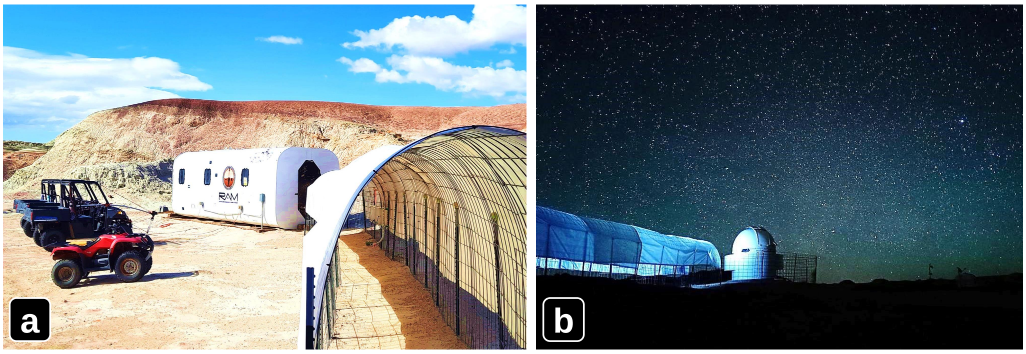

Fig. 3. The outside environment at MDRS, showcasing a typical day and night in the Utah desert. Low humidity makes heat dissipate rapidly, resulting in cold nights even after very hot days.

Fig. 4. The habitat environment with a minimalist architectural design centered on high efficiency, featuring constrained spaces and narrow passageways (a), dedicated areas that evoke Earth-like vegetation (b), and porthole-like windows offering views of the outside world (c).

2.3. Platforms, tasks, and protocols

The platforms and tasks used in HCI scientific experiments depend on the specific investigation addressing one or more dimensions of the context of use [14]. In traditional HCI research, these typically involve evaluating user performance and/or experience with interactive devices, computer systems, interaction techniques, and user interfaces across desktop, mobile,

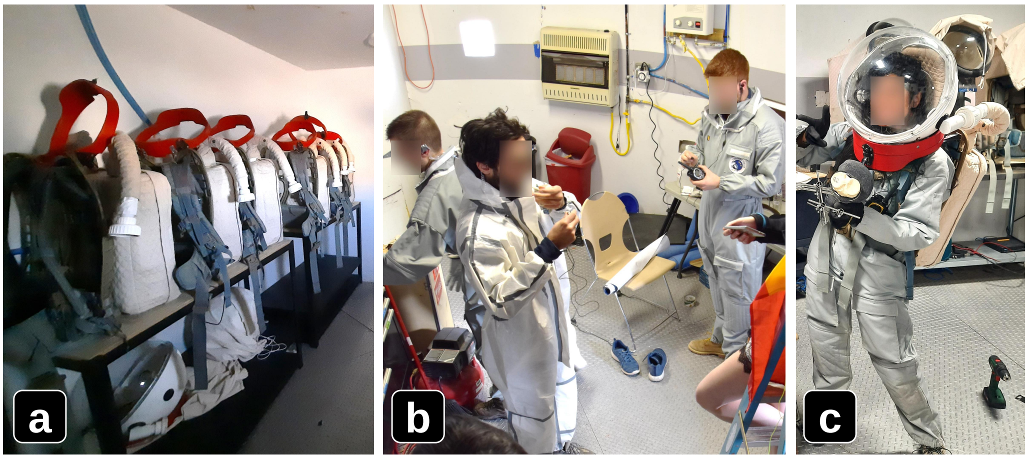

Fig. 5. Specific procedures, such as implementing safety protocols, are mandatory for living and surviving in extreme environments. These photographs illustrate leaving the habitat protocol, where suits and gear (a) are used during the process (b) to achieve the final result (c).

and wearable computing paradigms. Rigorous planning requires positioning experiments within established HCI theories, conceptual spaces, and design frameworks, such as reality-based interaction [19]. Our theoretical analysis of these frameworks, originally developed from an Earth-centric perspective, revealed their potential adaptability to extreme environments, including extraterrestrial settings [11]. However, such explorations are still in their early stages, making it difficult for HCI scientists to properly ground their experiment designs in unconventional contexts of use.

One option for studying interactions in extreme settings is to mirror terrestrial paradigms, such as the desktop computing model. In other cases, these paradigms are disrupted by the distinctive characteristics of the new environment and the requirements for safety and protective gear (Figure 5). These aspects may necessitate reinterpretation of mobile computing and interaction design [20], as illustrated in Figure 1, where an exploratory walk takes on new meaning in a Mars analog environment. Furthermore, engaging with mandatory gear for outdoor missions, such as roving vehicles, enables taking the study of inside-the-vehicle interactions to a new level by involving extreme conditions. Other modern interaction paradigms, such as ubiquitous computing [21] or augmented reality media [22], heavily based on integrating technology into the environment, are still out of reach in such settings.

Conventional HCI research involving human participants requires adherence to ethical standards and procedures that emphasize openness and transparency [23], obtaining ethical committee approvals, securing informed consent from participants, and ensuring proper data management during and after the experiment. The latter is typically guided by the FAIR principles for digital research artifacts that are findable, accessible, interoperable, and reusable. Besides these standard procedures in HCI experimental research, unconventional environments necessitate supplemental procedures, such as those involving safety protocols. For example, the following protocol was implemented for all activities taking place outside the MDRS habitat:

- *Crew distribution.* A maximum of four crew members were permitted to participate simultaneously in outdoor activities with at least one crew member required to remain inside to assist with exit and reentry procedures, monitor the external crew, and collect data.

- *Equipment.* Space suits were mandatory when operating outside the main habitat. Standard gear included a GPS unit, battery pack, ventilation system, and a radio configured with two distinct frequencies for both long-range and short-range communications; see Figure 5 for photographs captured at MDRS, illustrating the exit procedure.
- *Leaving the habitat* involved suiting up, performing a radio check, unplugging chargers, verifying battery levels, donning and adjusting gear, and activating ventilation. This was followed by a five-minute depressurization process.
- While *outside the habitat,* the protocol required periodic check-ins with the habitat every fifteen minutes to report current status, GPS coordinates, and a brief description of the ongoing task. During these intervals, the scientific experiment was conducted.

Unlike controlled laboratory settings, conducting scientific experiments in extreme environments presents unique challenges. To understand their implications, we planned several HCI experiments involving various devices and interactive tasks; details follow in the next section.

3. HCI Experiments in Mars-Analog Conditions

To illustrate the context of use in extreme environments, we present in this section empirical results from two experiments conducted during two missions organized at MDRS [13]. In the first experiment, taking place indoors, we asked participants to engage with a conventional graphical user interface, designed for astronaut self-scheduling tasks [24], running on a laptop PC. In the second experiment, conducted outside the habitat, we involved a handheld controller for operating a Parrot ANAFI USA drone via the FreeFlight 6 mobile application, while wearing astronaut protective equipment. Whereas the indoor environment evokes feelings of isolation and confinement because of the architectural style and organization of the space habitat (Figure 4), the outdoor environment is characterized by physical constraints related to both weather conditions and the need for wearing protective equipment (Figure 3). The protocols presented in the previous section were in place. We measured the following dimensions [25] of perceived UX, which we assessed longitudinally [26] over the twelve days of each mission, as follows:

- *Efficiency*, representing the subjective perception of completing tasks fast and without unnecessary effort with the computer system. Perceived efficiency was evaluated across four scales involving opposite adjective descriptors: slow *vs.* fast, inefficient *vs.* efficient, impractical *vs.* practical, and cluttered *vs.* organized.
- *Dependability*, encompassing the subjective impression of being in control of the interaction involving the computer system. Perceived dependability was evaluated across the following four adjective scales: unpredictable *vs.* predictable, obstructive *vs.* supportive, not secure *vs.* secure, and does not meet expectations *vs.* meets expectations.
- *Trustworthiness*, representing the subjective perception about the quality and reliability of the information and feedback delivered by the computer system. Perceived trustworthiness was evaluated across the following four adjective scales: useless *vs.* useful, implausible *vs.* plausible, untrustworthy *vs.* trustworthy, and inaccurate *vs.* accurate.

Together, these three dimensions enable a multi-faceted evaluation, primarily focusing on subjective perceptions related to one's ability to perform tasks using a computer system (efficiency), the system's reliability in the relationship with the user (dependability), and the confidence inspired by this relationship (trustworthiness). For each experiment, the sample size was limited to eight participants due to housing constraints at MDRS [13]. The two crews involved in the two experiments were comparable in terms of gender distribution and age demographics, between 21 and 34 years old. Each UX dimension was evaluated using a 7-point Likert scale with items ranging from -3 (low) to 3 (high) corresponding to several specific adjective scales, following the scoring procedure of the User Experience Questionnaire (UEQ) [25]. For example, perceived dependability was evaluated in relation to four pairs of contrasting attributes ("unpredictable" *vs.* "predictable," "obstructive" *vs.* "supportive," "not secure" *vs.* "secure," and "does not meet expectations" *vs.* "meets expectations"), which were individually rated according to the instructions: *"The circles between the attributes represent gradations between opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression."* and *"Please decide spontaneously. Don't think too long about your decision to make sure that you convey your original impression"*; see Schrepp and Thomaschewski [25] for details. We report average ratings computed for each pair of attributes in Table 1, *e.g.*, -0.63 for the "obstructive" *vs.* "supportive" pair, as well as the average rating computed across all four UX dimensions in Figure 6, *e.g.*, -0.19 for perceived dependability representing the average of -0.25, -0.63, 0.38, -0.25 at sol-4. Evaluations were performed repeatedly at three time periods, denoted by sol-4, sol-8, and sol-12, where "sol", a Martian day, represents the apparent time interval between two successive returns of the Sun to the same meridian, as seen by an observer on Mars. One sol is equivalent to 1.0275 Earth days. The missions lasted twelve days each.

For the indoor experiment, the lowest ratings were observed at sol-4, indicating a negative impact of the unfamiliar environment on our participants' perceptions of the interactive computer technology they were engaging with, despite the conventional setup involving a standard PC and graphical user interface (GUI). Perceived efficiency and dependability even fell below the midpoint of the $[-3, 3]$ scale, scoring -0.66 and -0.19, respectively. However, UX improved over the remainder of the mission across all dimensions, indicating adaptation to the physical and psychological conditions of the isolated and confined indoor environment. By sol-12, participants felt more efficient (1.09), more in control (1.44), and more trusting (1.66) of the computer system they were engaging with; see Figure 6, left for UX trends and Table 1 for numerical results across all corresponding adjective scales. For example, the 0.75 average in perceived dependability observed at sol-8 (Figure 6, left) reflects interactions that felt more predictable than not (0.38), more supportive rather than obstructive (0.63), more secure (1.38), and more aligned with participants' expectations (0.63); see rows 6 to 9 in Table 1. Friedman's ANOVA tests revealed a statistically significant effect of time on perceived efficiency ($\chi^2_{(8)}$=12.800, p=.001), dependability ($\chi^2_{(8)}$=12.250, p=.001), and trustworthiness ($\chi^2_{(8)}$=6.250, p=.047).

The findings of the outdoor experiment, illustrated in Figure 6, right, follow a similar pattern, with the lowest ratings observed on sol-4 and increasing over the remainder of the mission. In this second experiment, adaptation involved both the weather conditions, represented by temperature and humidity, and the requirement to wear a protective suit and gear, affecting mobility and dexterity during the drone controlling task. However, Friedman's ANOVA tests revealed no statistically significant differences across the various measurement points for perceived efficiency ($\chi^2_{(8)}$=0.621, p=.754, $n.s.$), dependability ($\chi^2_{(8)}$=1.724, p=.459, $n.s.$), or trustworthiness ($\chi^2_{(8)}$=1.407, p=.579, $n.s.$), with evaluations remaining consistent across the mission and that even started from positive scores; see Table 1 for results across all adjective scales. For example, the 1.63 average in perceived trustworthiness observed at sol-12 (Figure 6, right) reflects interactions that felt useful rather than useless (1.50), plausible rather than implausible (1.88), trustworthy rather than untrustworthy (1.50), and accurate rather than inaccurate (1.63); see rows 11 to 14 in Table 1. We explore implications of these results in the next section.

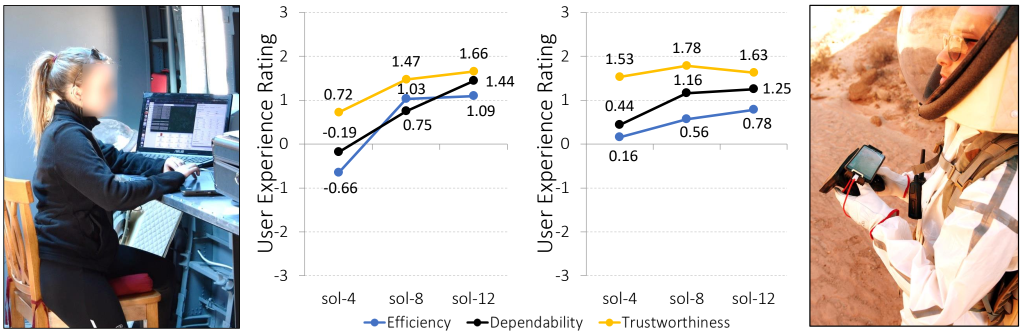

Fig. 6. Results from our two experiments on the user experience of interacting with computer systems in extreme environments, represented by the indoor (left) and outdoor (right) settings of the Mars Desert Research Station; see Table 1 for the adjective scales used in each dimension.

Table 1. User experience results across specific dimensions, self-reported across twelve days.

	Adjective scale, from negative (-3) to positive (+3) experience	Indoor environment sol-4	Indoor environment sol-8	Indoor environment sol-12	Outdoor environment sol-4	Outdoor environment sol-8	Outdoor environment sol-12
E_1	slow *vs.* fast	−1.50	0.88	1.13	−0.25	0.13	0.38
E_2	inefficient *vs.* efficient	−0.75	1.25	1.25	0.38	0.63	0.88
E_3	impractical *vs.* practical	−1.00	1.00	1.00	−0.50	0.63	0.88
E_4	cluttered *vs.* organized	0.63	1.00	1.00	1.00	0.88	1.00
Efficiency ($=0.25\cdot(E_1+E_2+E_3+E_4)$)		**−0.66**	**1.03**	**1.09**	**0.16**	**0.56**	**0.78**
D_1	unpredictable *vs.* predictable	−0.25	0.38	0.88	0.88	1.13	1.38
D_2	obstructive *vs.* supportive	−0.63	0.63	1.38	0.38	1.38	1.13
D_3	not secure *vs.* secure	0.38	1.38	2.00	0.50	1.00	1.38
D_4	does not *vs.* meets expectations	−0.25	0.63	1.50	0.00	1.13	1.13
Dependability ($=0.25\cdot(D_1+D_2+D_3+D_4)$)		**−0.19**	**0.75**	**1.44**	**0.44**	**1.16**	**1.25**
T_1	useless *vs.* useful	1.50	1.88	2.00	1.50	1.38	1.50
T_2	implausible *vs.* plausible	0.88	1.63	1.88	1.50	1.88	1.88
T_3	untrustworthy *vs.* trustworthy	0.50	1.38	1.50	1.38	1.75	1.50
T_4	inaccurate *vs.* accurate	0.00	1.00	1.25	1.75	2.13	1.63
Trustworthiness ($=0.25\cdot(T_1+T_2+T_3+T_4)$)		**0.72**	**1.47**	**1.66**	**1.53**	**1.78**	**1.63**

4. Discussion

Our empirical results highlight how unfamiliar and unconventional environments can influence the relationship with and perception of interactive computer technology, while determining adaptation processes to the context of use. They also show how user perceptions of the corresponding interactions are determined by the nature of the computer systems and the environments in which they occur. The implications are important for designing interactive computer technology for extreme contexts of use as well as for planning and conducting HCI scientific experiments in such settings. In this section, we capitalize on our findings to reflect on HCI experimental research involving extreme contexts of use, such as extraterrestrial habitats. To this end, we connect to key challenges in traditional HCI research, including aspects of replication [27], reproducibility of artifacts in engineering interactive computing systems [28], and advancing the field by challenging existing theories and frameworks [29].

Conducting HCI experiments in extreme contexts of use. Unlike traditional, lab-controlled settings, an extreme context of use introduces distinctive challenges that manifest both physically and psychologically, affecting the relationship between users with the platforms they engage and the environments in which interactions occur. Therefore, empirical findings must be interpreted within the perspective outlined by living and working in contexts of isolation, confinement, and extremes [3, 18]. Rigorous experiment planning in such settings requires isolating variability induced by factors internal and external to the participants, ensuring ethical considerations about safety and well-being, and understanding validity and integrity threads on collected data. We addressed this aspect through multiple measurement points at three moments during the simulated mission (Figure 6 and Table 1), enabling a more comprehensive perspective on UX evolution.

Replication of empirical findings. The fact that sample size is limited (for example, eight participants in our experiments due to housing constraints at MDRS [13]) and the effort for training crew members is significant (Figure 2) makes replications more challenging, not to mention more resource intensive, compared to conventional HCI studies. Unfortunately, replications have historically been scarce in HCI, with estimates around 3% [27]. These factors impact negatively the ability to easily confirm empirical findings with more users and diverse user groups as well as under variations of the original context of use, which is essential for a rigorous understanding of user performance and experience in extreme settings. Logistical difficulties, represented by the small number of crew members, their training requirements, and resource restrictions, further impact the validation and consolidation of scientific knowledge in this area. Moreover, findings from experiments conducted on Earth, even under realistic simulations involving complex research facilities with advanced space technology, may not be directly transferable to actual extraterrestrial settings. In this context, replication and generalization of findings are concerning.

Reproducibility of artifacts. Artifacts in engineering interactive computer systems (EICS) include hardware prototypes, software applications, and toolkits contributing to the development of scientific and practical knowledge within a specialized HCI subcommunity [28]. However, interactive artifacts designed for space missions are challenging to evaluate in similar conditions by other researchers because of the need to access specialized facilities, such as centrifugal accelerators or neutral buoyancy tanks, as shown in Figure 2. This limitation restricts research to a small community of experts, although SpaceCHI [12] has been steadily expanding.

Relying on existing interaction frameworks and the need for new ones. Rigorous planning of scientific experiments for extreme contexts of use requires a solid foundation in conceptual and design frameworks which, unfortunately, is missing. Existing frameworks, such as reality-based interaction [19] or sensorimotor realities [30], may provide a starting point, but further work is needed to account for the unique conditions of extreme environments. Specifically, the boundaries of what constitutes reality must expand to encompass physical conditions different from those on Earth, and sensorimotor capabilities should account for both sensory limitations and augmentations when being exposed to those conditions.

5. Conclusions

We addressed in this work challenges of conducting scientific experiments in human-computer interaction within extreme contexts of use by focusing on users, platforms, and environments. Drawing from insights gained during our missions at the Mars Desert Research Station, we were able to pinpoint specific challenges and propose directions for addressing them in the future, such as replication, artifact reproducibility in engineering interactive systems, and the need for more encompassing conceptual and design frameworks in this area. These contributions mark the start of a deeper understanding of designing interactions with computer systems in space exploration and, particularly, in unfamiliar, unconventional, and extreme environments.

Acknowledgement. This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CCCDI-UEFISCDI, PN-IV-P8-8.3-PM-RO-BE-2024-0003, within PNCDI IV.

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