

UX, but on Mars: Exploring User Experience in Extreme Environments with Insights from a Mars Analog Mission

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Figure 1: Photograph captured during one of our missions at the Mars Desert Research Station, depicting an environment characterized by extreme constraints, isolation, and confinement, with harsh conditions that can affect physical and psychological well-being. Note the deserted landscape, the strong sunlight, and the bulky equipment. In this setting, closely mimicking a Mars analog environment, we conducted two user experience studies exploring various pragmatic and hedonic dimensions of interacting with computer systems, with a baseline represented by user experience measured in a conventional environment.

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Abstract

Isolated, Confined, and Extreme (ICE) environments, such as those encountered in space missions, deep-sea explorations, and polar expeditions, pose unique physical and psychological challenges that influence user interaction with computer systems and have been significantly less explored compared to conventional environments. In this paper, we report empirical results from two experiments involving two crews of six analog astronauts each and two interactive

systems with graphical and haptic user interfaces, conducted in both a conventional Earth environment and a Mars analog setting at the Mars Desert Research Station. We examine how extreme conditions affect UX and we provide implications for interaction design addressing ICE environments through adaptation, automation, and assistance-resistance mechanisms.

CCS Concepts

• **Human-centered computing** → *Laboratory experiments; Field studies; Interaction paradigms; HCI design and evaluation methods*; • **Applied computing** → *Aerospace*.

Keywords

Extreme user experience, Isolated-confined-extreme environment, Interaction design, Mars Desert Research Station, Space mission, User experience, User interface design

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1 Introduction

In extreme environments [25,66], such as space stations [19], submarines [25], or polar-desert research settings [27], individuals often find themselves isolated [1] or part of a very small team [23,66], working in confined spaces for prolonged periods [24], often with restrictive equipment that limits their sensory perception and movement; see Figure 1 for a photograph captured during our experiments conducted at the Mars Desert Research Station¹ illustrating an extreme environment. These conditions, coupled with limited resources [67], create unique physical and psychological settings that influence the user experience (UX) of interacting with computer technology [58]. We refer to such environments as being Isolated, Confined, or Extreme (ICE) [1,19] given that the contexts of use impose extreme constraints, including psychological [25,58], physical [28,42,67], social [44], cognitive [27], and technological [2,7,16]. In contrast, the common interpretation [8] of a conventional context of use [9] in Human-Computer Interaction (HCI) refers to situations in which users perform tasks with a device or platform in environments characterized by anything but extreme constraints [3].

Despite extensive research on HCI in conventional settings, far from extreme [8], common and ubiquitous [10], or even multi-target contexts of use [3], few works have addressed the challenges faced in ICE environments [10,34], where the extreme physical characteristics of the environment and the remote nature of the habitat [19] can seriously impact the UX of interactive systems [56]. However, such systems [11] remain vital for tasks related to navigation, communication, work, and safety in these environments [16]. Thus, understanding the impact of ICE on UX becomes essential for expanding scientific and design knowledge beyond the conventional and familiar environments typically addressed in HCI research.

In this context, we report empirical results regarding the influence of physical and psychological factors characteristic of ICE environments on a broad range of UX dimensions related to interaction with computer systems, with the following contributions:

- (1) We conduct two experiments involving six analog astronauts each and two interactive systems featuring graphical and haptic interfaces in an ICE environment simulated at the Mars Desert Research Station (Figure 1). We report findings across various UX dimensions, including perceived efficiency, perspicuity, usefulness, adaptability, and trustworthiness, evaluated repeatedly on different days, which we contrast to the baseline condition of UX evaluated in a conventional Earth-like setting. Our results highlight different trends in UX according to the specific dimension being evaluated.
- (2) Based on our findings, we propose a set of practical implications for interaction design addressing ICE environments with exemplification in extraplanetary settings. We highlight *adaptation*, *automation*, and *assistance-resistance* as practical mechanisms to accommodate specific ICE requirements into the design process of interactions with computer systems.

2 Related Work

2.1 Human Factors in ICE Environments

Prior research on ICE environments, conducted outside the field of Computer Science, has highlighted key individual human attributes necessary for successful adaptation, including emotional stability, self-control, and task-oriented coping [1]. Furthermore, environmental design plays a crucial role in this process, with recommendations targeting flexible spaces, personalization options, and areas fostering privacy and socialization [58]. Environmental factors like sensory deprivation [67], sleep disturbances [72], and group dynamics are known to significantly impact the function of ICE sojourners [60]. Additionally, neurobiological systems play a vital role in team dynamics, with factors like nutrition [41], exercise [2], sleep patterns [72], and habitat design [19] known to influence social interactions [44] in ICE settings [23]. However, further multidisciplinary research is needed to fully understand and support teams facing extreme environments [23]. Similarly, training and performance measurement in such environments require novel approaches to equip team members with essential knowledge, skills, and attitudes for effective long-term performance [66].

Following Van Puyvelde et al. [60], an ICE environment shapes the impact of organizational, interpersonal, and individual working and living systems, thus influencing the functioning of people sojourning in these habitats. Inevitable symptoms include sensory and sleep deprivation, fatigue, reduced group dynamics, and displacement of negative emotions. Palinkas and Suedfeld [44] reinforced that these psychosocial factors influence human performance in ICE, while Hauplik et al. [19] emphasized how the unique characteristics of ICE environments impact human factors and habitability considerations. Furthermore, Suedfeld [58] argued that positive psychology can be applied to select personnel for ICE environments, while Weaver and Salas [66] concluded that the characteristics of ICE environments influence team performance and, thus, require novel approaches to training and measurement. Mohanty et al. [37] discussed the importance of integrating habitat design, cognitive

¹<https://mdrs.marssociety.org>. See also a 3D VR navigation of the MDRS facility at <https://storage.net-fs.com/hosting/5682637/18>.

sciences, and psychology to understand human behavior in ICE environments, such as for planetary missions. In this wide body of scientific literature, one of the most relevant studies to our scope is Bartone *et al.*'s [1], who conducted a systematic review of cognitive and behavioral adaptation mechanisms to ICE environments. Based on a corpus of seventy-three studies, they identified several adaptability attributes necessary for operating effectively within ICE environments—intelligence, emotional stability, self-control, openness, achievement facets of conscientiousness, optimism, mastery, introversion, hardiness, task-oriented coping, past experience, low need for social support, and adequate sleep. These attributes impact all activities under ICE constraints, including the experience of interacting with computer systems, as per our scope.

2.2 HCI Research Involving ICE Environments

Interactive computer systems in ICE environments [11] serve a variety of purposes, including operational efficiency—where they are used for remote control [16] and information work [29]—data collection and communication—such as for medical [32,51] and remote decision support [50,56] and planning [33], to name a few. The demand for such systems is increasing due to the growth of missions to ICE environments, such as those involving space [16] and underwater [27] exploration. More specifically, traditional interaction modalities represented by graphical or haptic interfaces may be less practical in ICE environments [39,40]. For example, zero gravity [13], low gravity [28], or microgravity [12] characteristics are known to interfere with manual dexterity, making physical interaction difficult [68]. Furthermore, microgravity creates a haptic illusion [43], forcing adaptation patterns to come into play [43]—normal gravity creates the illusion that upward forces are larger than downward ones, not present in microgravity but augmented by hypergravity. Next, we relate to prior research in SpaceCHI, an emerging area in HCI addressing a specific type of ICE environment that is closest to the one examined in our experiments.

2.3 HCI Research Involving Space and Extraterrestrial Environments

SpaceCHI [46,47,71] represents a recent initiative of the HCI community to investigate space settings as a representative instance of ICE environments by means of “designing new types of interactive systems and computer interfaces that can support human living and working in space and elsewhere in the solar system” [46, p.1]. In this context, it emphasizes the diversity of topical coverage in space exploration that requires HCI knowledge and expertise ranging from “exoskeletons for supporting humans in low gravity, to virtual and augmented reality systems for interplanetary exploration and even zero gravity musical interfaces for entertainment.”

Prior research contributions to SpaceCHI have addressed a wide palette of topics, including crew collaboration and tools for mission planning [71], human-system resilience and design for maintainability in deep-space missions [35], participatory design for space systems engineering [40], human-robot interaction in extraterrestrial missions [30], food experience design for space travel [41], and examinations of the influence of extraterrestrial conditions, such as microgravity, on human factors and corresponding interaction design [11,12,28]. The UX of space interactions has also been

addressed in the scientific literature. For example, Saint-Guillain *et al.* [50] evaluated twelve UEQ scales [54] during a Mars analog mission, and Nilsson *et al.* [40] reported qualitative findings, from interviews with astronauts and space experts, regarding the capabilities of virtual reality systems to facilitate user-centered approaches in system design for space missions. Vanderdonckt *et al.* [62] proposed extending interaction frameworks designed within an Earth perspective, such as reality-based interaction [22] or sensorimotor realities [63], to extraplanetary environments with a case study involving Mars. Lee *et al.* [26] shared the vision of an interplanetary metaverse to connect users from Earth and Mars.

2.4 Summary

The recent interest of the HCI community in contributing to humanity's quest to understand and inhabit ICE environments, such as those encountered in space exploration [71], sets the context for our work, which focuses on the UX of interacting with computer systems in these settings. However, current interaction design frameworks, originally developed from an Earth-centered perspective [62], may not be directly transferable to extraplanetary or out-of-this-world environments [39]. Furthermore, UX is a multidimensional construct, including usability [17], accessibility [70], and emotional engagement [18], among others. In ICE environments, these dimensions face extreme challenges due to harsh environmental factors and conditions, leading to extreme UX. Next, we describe two experiments designed to evaluate its various facets.

3 Experiments

This section presents methodological aspects common to the two experiments conducted in this work. Specific details about each experiment and the corresponding results follow in Sections 4 and 5.

3.1 Location and Setup

The experiments took place at the [Mars Desert Research Station \(MDRS\)](#), a Mars analog inhabited mission located in Hanksville, UT, USA. The facility provides a Mars-like environment, enabling scientists and astronauts to experience ICE conditions [59]. MDRS is composed of several modules [57], including habitat, extravehicular activity preparation room, and science dome with a science laboratory; see Figures 1 and 3 for a few photographs.

3.2 Participants

Each experiment was carried out with a crew consisting of six analog astronauts,² who spent two weeks at MDRS. The size of the crew was limited by constraints at MDRS, where a maximum of eight crew members can be accommodated simultaneously. Our participants had different backgrounds, including mathematics, astronomy, biology, bioengineering, biomedical sciences, chemistry, computer science, geology, pharmacy, physics, and engineering. The two crews participating in the two experiments were similar in terms of gender (three females and three males per crew)

²An analog astronaut is a trained individual playing the role of an astronaut during a simulated crewed mission by living [60], eating [41], sleeping [72], walking [4], and working [29] in a way that reproduces [59] the expected conditions of a long-duration space mission, in a geographically similar area to those of actual missions.

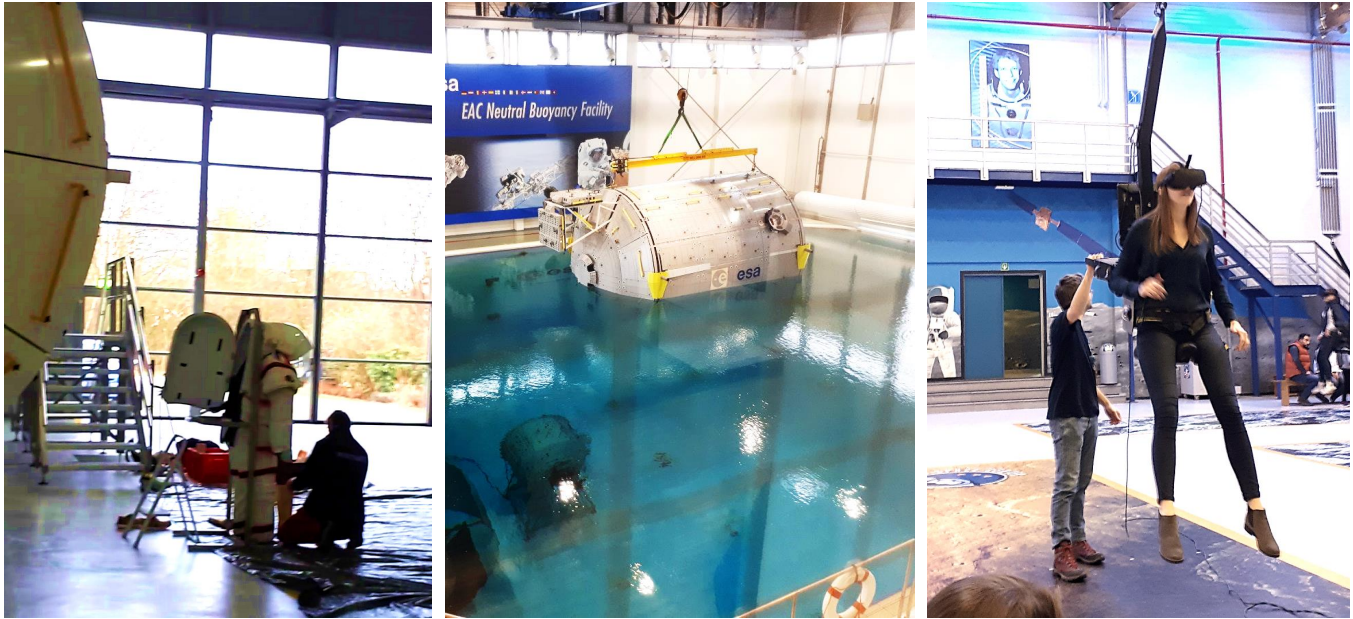


Figure 2: Facilities used for astronaut training involving microgravity resistance in an aquatic environment (left and middle photographs) and engaging in simulated VR-based Mars walking experiences (right photograph).

and age demographics (between 26 and 31 years, $M=26.6$ and between 22 and 30 years, $M=25.6$, respectively). Before arriving at MDRS, all crew members underwent special physical training procedures involving microgravity resistance exercises in an aquatic environment or experiencing different gravity conditions through simulated Mars walks enabled by a virtual reality installation; see Figure 2. For practical reasons related to the geographical proximity to the teams' institutions of origin, we conducted the training at nearby locations, such as the Euro Space Center³ or the European Space Agency's Neutral Buoyancy Facility.⁴

3.3 Evaluation Method

To evaluate the UX of various interactive computer systems, we adopted the **UEQ+** method, a modular extension of the **User Experience Questionnaire (UEQ)** [54], designed to measure various UX dimensions quickly and simply [55]. UEQ+ covers both pragmatic and hedonic UX dimensions and is supported by analysis instruments and published norms [36] to interpret the results [20]. We chose to measure UX across the following 14 dimensions:

- D₁. *Attractiveness*: What is the overall impression of the system?
Do users like or dislike it?
- D₂. *Efficiency*: Can users solve their tasks without unnecessary effort? Does the system react fast?
- D₃. *Perspicuity*: How easy is it to learn how to use the system?
- D₄. *Dependability*: What impression does the system provide of being in control of the interaction?
- D₅. *Stimulation*: Is it exciting and motivating to use the system?
Is it fun?

- D₆. *Novelty*: Is the system design creative? Does it catch the interest of users?
- D₇. *Trust*: What do users think about their data being safe and not misused to potentially harm them?
- D₈. *Adaptability*: What impression does the system give regarding its ability to adapt to personal preferences?
- D₉. *Usefulness*: Does the use of the system offer any advantages?
- D₁₀. *Value*: Does the system's design convey a professional and high-quality appearance?
- D₁₁. *Visual Aesthetics*: Does the system look appealing?
- D₁₂. *Intuitive Use*: Can the system be used immediately without the need for training or assistance?
- D₁₃. *Haptics*: What is the feeling that results from touching and physically manipulating the system?
- D₁₄. *Trustworthiness of content*: What impression does the system give regarding the quality and reliability of the information it provides?

According to UEQ+, each dimension D_i , $\forall i=1..14$, is decomposed into multiple subdimensions $D_{i,j}$ involving pairs of contrasting attributes, e.g., the *Attractiveness* dimension (D_1) encompasses evaluations across *annoying vs. enjoyable* ($D_{1,1}$) *bad vs. good* ($D_{1,2}$), *unpleasant vs. pleasant* ($D_{1,3}$), and *unfriendly vs. friendly* ($D_{1,4}$), respectively. This approach enables a multi-faceted perspective on UX evaluation, in which the same construct, such as perceived *Attractiveness* or *Perspicuity*, is interpreted through various connotations using ratings $\lambda(D_{i,j})$ ranging from 1 (strongly disagree) to 7 (strongly agree), e.g., $\lambda(\text{annoying vs. enjoyable})=5$. At the same time, we obtain ratings of the perceived importance or weight of each subdimension, $\omega(D_{i,j})$, from 1 (least important) to 7 (most important), e.g., $\omega(\text{unpleasant vs. pleasant})=2$. Based on individual λ and ω ratings, we define the following aggregated UX scores:

³<https://www.eurospacecenter.be/en>

⁴https://www.esa.int/About_Us/EAC/Refreshing_the_Neutral_Buoyancy_Facility

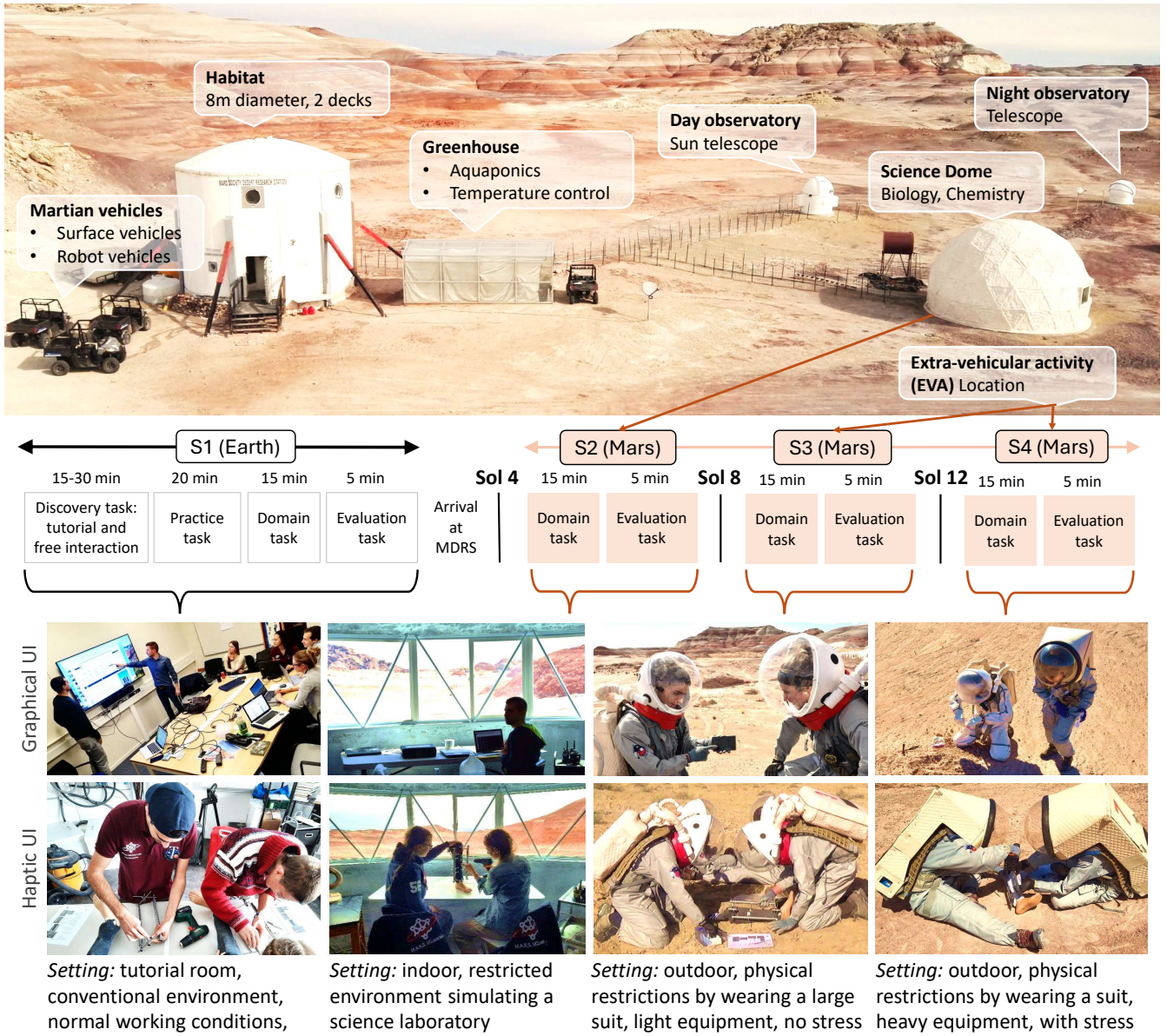


Figure 3: Top: The Mars Desert Research Station, where sessions S2 to S4 of our experiments were conducted. Bottom: the timeline of the various stages of the experimental procedure: discovery, practice, and a four-times repetition of a domain task followed by its evaluation in sessions S1 to S4; see Figures 1 and 7 for additional photographs taken during the experiments.

- The mean score $\bar{\lambda}$ for a specific dimension D_i , computed as the average, across all participants, of all individual ratings associated to the corresponding connotations $D_{i,j}$ is:

$$\bar{\lambda}(D_i) = \frac{1}{n} \sum_{j=1}^m \lambda(D_{i,j}) - 4 \quad (1)$$

where n is the number of participants engaged in the evaluation. By subtracting 4, the median point of the original Likert scale, $\bar{\lambda}$ reports an aggregated value admitting intuitive interpretations from negative (−3) to positive (+3).

- The mean weight of importance $\bar{\omega}$ for each dimension D_i :

$$\bar{\omega}(D_i) = \frac{1}{n} \sum_{j=1}^m \omega(D_{i,j}) - 4 \quad (2)$$

We interpret the UEQ+ results following the guidelines in Schrepp and Thomaschewski [55], according to which values above 2 or below −2 are extremely unlikely, values between −0.8 and 0.8 indicate a neutral evaluation, values above 0.8 reflect a positive evaluation, and values below −0.8 signify a negative evaluation, respectively. All fourteen dimensions reflect a higher user experience when the

Table 1: Characteristics of the two experiments conducted in this work with results reported in Sections 4 and 5.

Characteristic	Experiment #1	Experiment #2
UI type	Graphical UI	Haptic UI
Interaction style	WIMP	Tangible
Platform	Laptop computer	Haptic device
Operation mode	Single user	Collaborative work
Environment	Indoor	Outdoor
Task requirements	Visual attention	Manual dexterity
Physical constraints	Fatigue, indoor lighting	Heavy gear and equipment, gloves, high temperature and humidity
Psychological constraints	Perception of a confined space, feelings of isolation, claustrophobia	Perception of vast uninhabited territory, kenophobia

corresponding scores are positive and higher. In the following analysis, we report the mean (M) and standard deviation (SD) for $\bar{\lambda}$ and $\bar{\omega}$ to describe the central tendency and variability for each dimension, based on the ratings of all participants. We also monitor the evolution of these measures across different measurement points, called sessions in the following, and characterize trends such as increasing, decreasing, V-shaped, or plateau-like patterns of user experience. For example, increasing user experience in terms of *Dependability* may suggest that the crew is becoming more confident in using the system, as well as in the system's ability to support control over the interaction. A V-shaped pattern in *Usefulness* may indicate similar levels of user experience at the beginning and end of the evaluation, with noticeable differences at intermediate time points as the Mars analog mission progressed.

3.4 Procedure

Both experiments involved four stages each, as follows (Fig. 3):

- During the *discovery* stage, meant for accommodation, the participants received a tutorial on the interactive system, which lasted between 5 and 15 minutes, and then interacted freely with the system for another period of 10 to 15 minutes.
- The *practice* stage followed, during which the participants performed a representative task with the system to become familiarized with it. This stage lasted about 20 minutes.
- During the *domain task* stage, the participants received instructions to perform a series of domain-specific tasks using the interactive computer system. The experimenter proposed, but did not enforce, a time limit of 10 minutes.
- Finally, during the *evaluation* stage, the participants filled in the UEQ+ questionnaire encompassing the various UX measures described in the previous subsection.

The discovery and practice stages were conducted before the mission in a dedicated tutorial room (Figure 1, left), representing our control condition for each experiment. The domain tasks and evaluation stages were performed four times during four subsequent sessions, denoted S1 to S4, as follows (Figure 3):

- S1. The first session was conducted one week before the mission in the tutorial room.

- S2. The second session was conducted after four Mars days,⁵ at sol 4, in the science laboratory of MDRS.
- S3. The third session was conducted after eight Mars days, at sol 8, outside the station with light equipment.
- S4. The fourth session took place after twelve Mars days, at sol 12, outside the station, and involved heavy equipment and additional stress constraints.

Figure 3, bottom presents representative photographs of each session, S1 to S4, collected during each experiment. This planning facilitated the evaluation of our participants' evolving UX perceptions of the interactive computer systems they engaged with with a baseline on an Earth-like environment and the following sessions introducing progressively more challenging constraints. In addition to environmental constraints, extreme temporal effects also due to the unconventional nature of the environment and habitat. For example, Table 2 reports the average unproductive time of our crew members, amounting to seventeen hours per day, leaving only seven hours for actual work—data consistent with previous findings from the literature [6]. Furthermore, time sharing in the science lab between geologists, biologists, and engineers required negotiation and compromises between all parties involved.

4 Experiment #1: The UX of a Graphical User Interface in a Mars Analog Environment

4.1 Experiment Specifics

The first crew engaged with self-scheduling and planning tasks, such as maintaining a to-do list, planning a Martian workday, and editing scheduled tasks with the graphical user interface of the ROMÉ [50] system, an operations management application designed for advanced modeling and scheduling of astronaut tasks during missions; see Figure 4 for a screenshot. The application features a standard graphical user interface and WIMP interaction style, accessed via a conventional laptop computer. While there are no particular physical constraints inherent to the application itself, the external environment in which it is used—an isolated and confined setting—introduces unique conditions for UX evaluation. Thus, this first experiment emphasizes how a conventional computer, software application, and graphical user interface are experienced in an unconventional context; see Table 1 for the characteristics of this experiment and a comparison with the second. The procedure and UX evaluation were carried out as described in Section 3.

4.2 Results

Figure 5 presents the mean scores $\bar{\lambda}$ and importance $\bar{\omega}$ for the fourteen UX dimensions, with session S1 serving as the baseline and S4 implementing the most challenging condition. Two of the scales start with a slight negative tendency in S1, *Perspicuity* ($M=-0.22$, $SD=1.36$) and *Visual Aesthetics* ($M=-0.34$, $SD=1.63$), yet both in the neutral zone of UEQ+ interpretability of $[-0.8, 0.8]$. The rest of the scales start with positive scores, of which eight have scores larger than the 0.8 threshold. After a drop in S2 caused by the first encounter with ICE conditions in MDRS, all scales except for *Visual*

⁵ A Mars-day, or a *sol*, constitutes a solar day on Mars, i.e., the apparent interval between two successive returns of the Sun to the same meridian as seen by an observer on Mars, which is approximately 24 hours, 39 minutes, and 35 seconds on Earth.

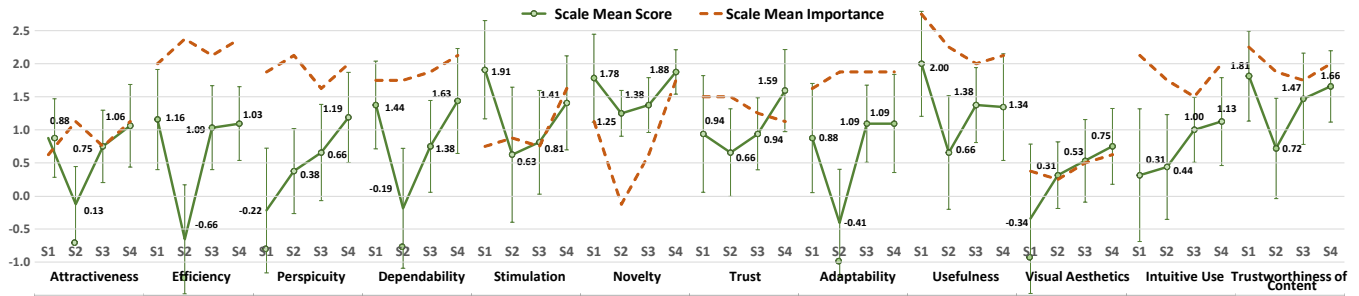


Figure 5: Panel chart of the twelve UX dimensions evaluated for the graphical interaction in the first experiment, showing mean scores (solid lines) and scale importance (dotted lines) for sessions S1 to S4. The error bars show 95% confidence intervals.

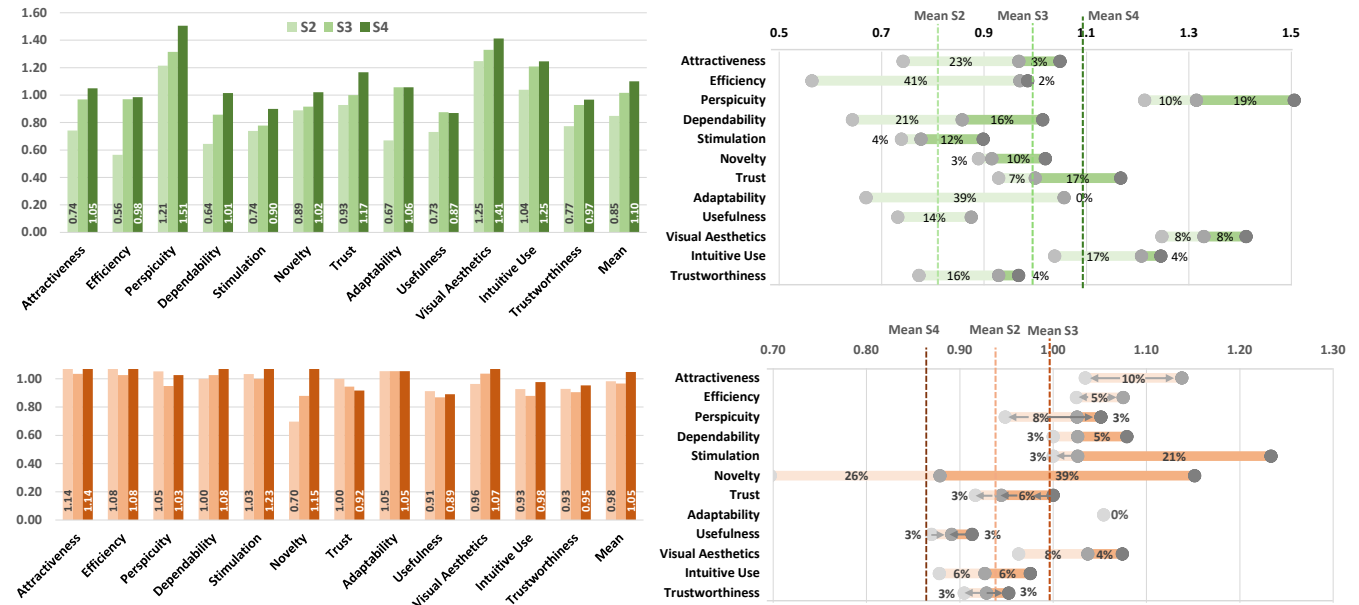


Figure 6: Bar graph (left) and Dumbbell plot (right) of the UX evolution ratings (top) and importance (bottom) across S2 to S4.

affected dimensions related to performance and efficiency, as the increasingly stringent conditions from session S2 to S4 were not mitigated even by learning effects. The following trends can be identified:

- *V-shaped curves* for *Novelty*, *Visual Aesthetics*, *Intuitive Use*, and *Trustworthiness of content*. This trend represents the most frequently occurring one, starting from a high score in S1, followed by both a decrease and increase in sequence.
- *U-shaped curve* observed for the *Usefulness* dimension only.
- *Zig-zag curves*, presenting increasing and decreasing behaviors in the corresponding scores; see *Attractiveness*, *Efficiency*, and *Perspicuity*. These UX dimensions were appreciated differently during the various sessions, not only because of the changing ICE conditions but also because of the diversity of the participants' profiles (see Subsection 3.2).
- *Descending curve* observed for *Trust* only; see Figure 6.
- *Ascending curves* for *Dependability*, *Stimulation*, and *Adaptability*. The scores of these UX dimensions and their importance increased with the number of sessions evaluated.

5 Experiment #2: The UX of Haptic Interaction in a Mars Analog Environment

5.1 Experiment Specifics

The second crew conducted a fixation task involving EASYFIX [31], a haptic device designed for stabilizing tibial shaft fractures, one of the most common types of long bone fractures in space; see Figure 7. This device fixes all types of tibial shaft fractures, including complex or comminuted ones with significant soft tissue lesions. The crew received a theoretical training session and a practical demonstration, during which they were taught anatomical landmarks and how to use the haptic device. This second experiment emphasizes how a conventional haptic interface requiring manual dexterity is experienced in an unconventional context and under physical constraints imposed by wearing heavy equipment, all conditions affecting sensory perception, manual dexterity, and body movement. Unlike the first experiment, centered on an indoor environment with ICE characteristics, the second experiment highlights the influence of the external environment; see Table 1 for the characteristics



Figure 7: Outdoor activity involving EASYFix, a haptic device designed for stabilizing tibial shaft fractures [31].

of this experiment and a comparison with the first. The procedure and UX evaluation were carried out as described in Section 3.

5.2 Results

Figure 8 presents the mean ratings $\bar{\lambda}$ of the various UX dimensions and their importance $\bar{\omega}$ across the four sessions. Three UX dimensions started in the neutral zone of $[-0.8, 0.8]$: *Efficiency* ($M=0.75$, $SD=0.48$), *Adaptability* ($M=0.67$, $SD=0.48$), and *Haptics* ($M=0.79$, $SD=0.48$). All the dimensions dropped down in S2 because of participants' first confrontation with the ICE environment, except for *Adaptability* ($M=0.79$, $SD=0.48$), which slightly increased. Also, all dimensions ended up in S4 with a positive evaluation, above 1, except for *Haptics*, which nevertheless scored above the neutral zone ($M=0.88$, $SD=0.48$). Lastly, four of the UX dimensions reached very similar scores in S4: *Efficiency* ($M=1.78$, $SD=0.48$), *Perspicuity* ($M=1.79$, $SD=0.77$), *Trust* ($M=1.79$, $SD=0.10$), and *Usefulness* ($M=1.79$, $SD=1.04$). Overall, three patterns can be distinguished:

- *V-shaped curves* for *Attractiveness*, *Perspicuity*, *Usefulness*, and *Intuitive Use*. These dimensions increase in mean rating in session S3 or after. For example, *Attractiveness* started at $M=1.00$ ($SD=1.15$) in S1, dropped to $M=0.63$ ($SD=1.35$) in S2, and reached its maximum score of $M=1.50$ ($SD=0.02$) in S4. Similarly, *PERSPICUITY* starts in S1 at $M=1.38$ ($SD=1.09$) to reach a lower score in S2 ($M=1.13$, $SD=0.80$) and ends with its highest value in S4 ($M=1.79$, $SD=0.86$).

- *Overall upward trends* progressively increase from S1 to S4; see the case of *Efficiency*, *Trust*, and *Adaptability*. For example, *ADAPTABILITY* starts with a low value ($M_{S1}=0.67$, $SD_{S1}=0.86$), increases in S3 ($M_{S3}=0.25$), and maintains this score until the end.
- *Zig-zag curve* for the *Haptics* dimension, which started with a moderate score of $M=0.79$ ($SD=0.43$) that decreased during session S2 to $M=0.33$ ($SD=0.48$), reached a plateau in S3 ($M=1.38$, $SD=0.37$), and decreased again in the most challenging session, S4, to $M=0.88$ ($SD=0.22$).

Figure 9 complements these results with the importance ratios $\bar{\omega}$ for the UX dimensions evaluated in this experiment, for which the following trends can be distinguished:

- *V-shaped curves* for *Efficiency*, *Trust*, *Intuitive Use*, and *Usefulness*, representing the pattern observed the most frequently. It starts with a high score, above 1, in session S1 and, after variations, ends with a similar score in session S4.
- *Ascending curves* for *Attractiveness* and *Haptics*, two UX dimensions that revealed neutral scores in the control session S1, but which significantly increased in S4.
- *Descending curve* observed for *Perspicuity*; see Figure 9.
- *Zig-zag curve* for *Adaptability*. This UX dimension varied slightly up and down, but stayed mostly within a small range, since the evaluated device did not present an explicit capacity to adapt to the various conditions from S1 to S4.

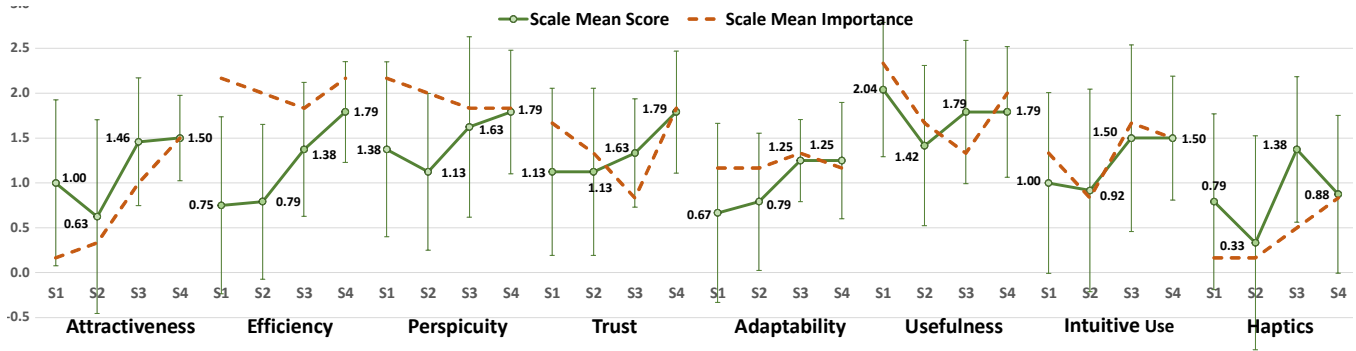


Figure 8: Panel charts of the eight UX dimensions evaluated for haptic interaction: mean scores (solid lines) and scale importance (dotted lines) are shown across sessions S1 to S4. The error bars show 95% confidence intervals.

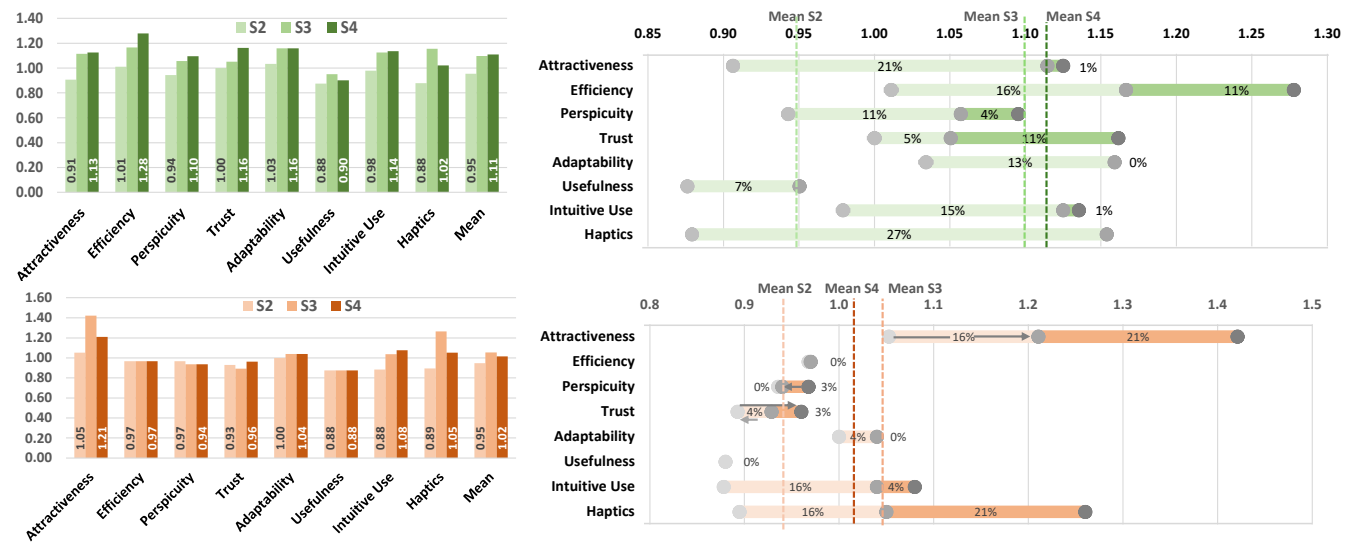


Figure 9: Bar graph (left) and Dumbbell plot (right) of the UX evolution ratings (top) and importance (bottom) across S2 to S4.

6 Discussion

In this section, we use our findings to extract implications for interaction design involving ICE conditions and propose directions for future work in HCI intersecting ICE environments. We also analyze potential limitations in our findings from the perspective of validity threats in experimental designs to be addressed in the future.

6.1 Implications for Interaction Design in ICE Environments

The various UX dimensions examined in our experiments revealed different patterns across increasingly challenging conditions, which were reflected in ascending or descending levels of the reported experience, undecided patterns featuring an alternate of high and low points, or V-shaped patterns equalizing the experience reported in the simplest and most challenging environmental conditions, respectively. These findings indicate a complex process of how ICE conditions influence the perceived UX of interacting with computer

systems featuring graphical and haptic UIs. For example, *Attractiveness* received increased appreciation over the various sessions, *Efficiency* was severely impacted, *Perspicuity* and *Dependability* left room for improvement, *Novelty* revealed growing importance when interacting under ICE conditions, *Trust* and *Trustworthiness of content* deteriorated across more challenging sessions, the perception of *Usefulness* diminished across sessions, whereas *Adaptability* was perceived equally in all conditions. Based on these findings, we draw several implications for informing interaction design addressing ICE environments, denoted in the following with symbols ❶ to ❹, which we exemplify in relation to emerging areas of HCI, represented by SpaceCHI [46,47] technology involving interactions with computers in extraplanetary environments. The degradation of the UX that we observed in some of the dimensions included in our evaluation could significantly impact interaction effectiveness in such environments. Thus, dedicated countermeasures, such as based on compensatory or coping techniques [10,67], could be explored to address the negative impacts of ICE conditions towards

Scale	$\bar{\lambda}(D_i)$		$\bar{\omega}(D_i)$	
	Graphical	Haptic	Graphical	Haptic
<i>Attractiveness</i>	$\approx$	$>$	$>$	$\gg$
<i>Efficiency</i>	$<$	$\gg$	$>$	$<$
<i>Perspicuity</i>	$\gg$	$>$	$>$	$<$
<i>Dependability</i>	$\approx$		$>$	
<i>Stimulation</i>	$\ll$		$\gg$	
<i>Novelty</i>	$\approx$		$\gg$	
<i>Trust</i>	$>$	$\gg$	$<$	$\approx$
<i>Adaptability</i>	$\approx$	$\gg$	$\approx$	$\approx$
<i>Usefulness</i>	$\ll$	$\ll$	$\ll$	$\ll$
<i>Visual Aesthetics</i>	$\gg$		$>$	
<i>Intuitive Use</i>	$\gg$	$\gg$	$<$	$>$
<i>Trustworthiness</i>	$\ll$		$<$	
<i>Haptics</i>		$\gg$		$\gg$

Table 3: Evolution of the UX dimensions from Earth to S4: $\approx$ = ratio similar to Earth, $<$ = ratio inferior to Earth, $>$ = ratio superior to Earth, $\ll$ = ratio largely inferior to Earth, and $\gg$ = ratio largely superior to Earth. $\bar{\lambda}(D_i)$ = scale mean score, $\bar{\omega}(D_i)$ = scale mean importance.

delivering interactions with a UX comparable to that experienced in conventional, Earth-like environments (Table 3).

6.1.1 Interactive systems featuring assistance and resistance aligned to ICE environmental conditions. Drawing from UI plasticity [3,61], *assistance* refers to the UI's capability to progressively enhance [38] the underlying interaction modalities to support or facilitate the user's goals, actions, and decision-making. This aspect is particularly relevant for ICE conditions to preserve experiential qualities across various UX dimensions. For example, by providing increased assistance from one interaction session to the next, specific UX dimensions, such as *Dependability* or *Stimulation*, could benefit from increasing trends, unlike the situation observed in our experiment (Figure 5) where assistance measures were not available. Alternatively, *resistance* refers to the UI's capability to deliberately reduce, restrict, or gracefully degrade [14] the underlying interaction modalities to preserve certain user actions or behaviors, prevent errors, or guide users in achieving their goals. For example, *Efficiency* and *Usefulness* are UX dimensions in which enabling users to replicate successful behaviors and actions can help sustain a high level of experience. This contrasts with the situation observed in our second experiment (Figure 8), where UI resistance was not available and, consequently, despite increasing efficiency, perceived usefulness followed a different trend. Furthermore, assistance and resistance interventions could contribute to increasing UX across the *Trust* and *Trustworthiness of content* dimensions, which we found in our experiments to be significantly impacted by ICE conditions. These observations can be distilled into two actionable implications for UI design: ❶ incorporate assistance mechanisms within the interface to support user actions where needed in order to account and compensate for the negative effects of physical and psychological factors on user input, and ❷ implement forms of interface resistance to help preserve user behavior when successful.

6.1.2 Assistance and resistance contribute to adaptive UIs for dealing with ICE constraints. We found that the *Adaptation* dimension was equally perceived across the various sessions, which leaves room for improvement in situations of challenging conditions. Adaptive UIs that self-adjust based on feedback from users, sensed cognitive load, or inferred emotional states should provide a higher level of UX. One example is microgravity-friendly UIs, where displays, controls, and widgets adapt in terms of their physical characteristics, e.g., the size of soft buttons, to enable more effective interactions despite the more challenging physical conditions. Adaptability could also be implemented through user profiles and customization of UI settings, such as switching to a particular color scheme for interactions taking place during extravehicular activities [53] or to one specific UI layout when interactions are intended for the less demanding in-habitat environment [52]. These observations can be distilled into the following implication: ❸ enable adaptive behavior in the user interface to align with changing environmental factors and user behavior. In unconventional settings, where users experience stressful physical and psychological conditions, adaptation to context becomes even more crucial for effective interactions.

6.1.3 Automating interactions in ICE environments. To complement aspects of system adaptivity design, automation integrated into interaction techniques could enable new UIs that assist users engaging in routine or complex tasks in ICE environments. One example is predictive UX [5], where machine learning techniques capture user behavior to anticipate needs, suggesting possible actions and flagging out potential issues [49]. This may have a direct, positive effect on specific UX dimensions, such as *Usefulness* and *Intuitive Use*, both of which could be further improved, given the empirical findings from our experiments (Figures 5 and 8). At this level, we recommend: ❹ enhancing user experience by shifting the burden of physically repetitive tasks to the computer, thereby reducing the impact of environmental physical stressors. This recommendation complements *assistance*, *resistance*, and *adaptivity* with *automation*, each representing a distinct strategy for mitigating the physical and psychological burden on users. Next, we focus on pragmatic and hedonic UX dimensions for interacting with computer systems.

6.1.4 Pragmatic UX dimensions require targeted support in ICE environments. Dimensions such as *Efficiency*, *Perspicuity*, and *Dependability* were among the most affected ones in our experiments when involving progressively more challenging ICE conditions. This result suggests that future designs of interaction modalities and techniques should compensate for losses across these dimensions caused by environmental factors, such as through consistent design that ensures UI consistency across multiple interactive applications and systems to reduce learning curves and enhance familiarity and efficiency. In the case of graphical user interfaces, design considerations may consist in leveraging the visual presentation of information in terms of shape, color, and size to compensate for the negative effects of environmental factors, such as impaired depth perception caused by astronaut equipment or altered color perception due to lighting conditions. Moreover, use of alternative output modalities may achieve a similar positive effect on UX. For haptic interfaces, design considerations may include dynamic adjustment of force feedback to account for reduced manual dexterity caused by wearing gloves and limited ranges of movement due to astronaut

suits. In relation to *assistance* and *resistance*, haptic enhancement can compensate for performance decrements in aiming and tracking tasks under microgravity through low/medium spring stiffness and virtual mass of a force feedback joystick. Besides haptics alone, multisensory feedback could enable more intuitive control modes, as demonstrated during spaceflight [67]. These observations can be summarized into the following actionable implication: ⑤ enhance the pragmatic dimensions of UX through designs specifically aimed at compensating for losses in visual attention or manual dexterity through adaptive visual cues, alternative modalities, and situationally calibrated feedback.

6.1.5 Hedonic UX dimensions emerge from the meaningful integration of interactions with the environment. The hedonic UX dimensions evaluated in our experiments, such as *Stimulation* and *Novelty*, were appreciated at levels either similar or inferior to those in the control, Earth-like condition (Figure 5). Enhancing the felt experience across these dimensions related to pleasure, enjoyment, and subjective satisfaction, can address psychological well-being, foster engagement, and create meaningful interactions for users engaging in ICE environments. However, this desideratum may prove particularly difficult at the design level, given that ICE conditions are physically and psychologically challenging. Therefore, new interaction techniques are necessary to support UX across hedonic dimensions without undermining the pragmatic ones. One example is addressing emotional connection through gamification by including playful elements in the interaction, such as achievement badges or rewards, as well as fostering social connectivity through special communication features involving bases on Earth or with crewmates to enhance emotional bonding. At this level, we recommend: ⑥ enhancing hedonic UX by embedding interactions within a meaningful, enriching, and rewarding context for users. This involves integrating interaction design with habitat design (where interaction and environment are interconnected at a profound level evoking ubicomp-style interactions), emphasizing the benefits of collaborative work in isolated and confined environments (where teamwork and collaboration are encouraged whenever possible), and connecting UX design with techniques that support and promote well-being practices (where the latter dissimulate into the former, surpassing user conscious attention).

6.2 Theoretical Foundations for Studying UX in ICE Environments

Our exploration of UX in a simulated extraplanetary environment marks the beginning of more investigations in this area. To support such future work, we believe that theoretical developments are essential to build models of UX relevant to ICE environmental conditions, formulate and test hypotheses in new experiments, and evaluate UX under the unique physical and psychological constraints present in unfamiliar and unconventional environments. In the following, we suggest potential developments based on existing theoretical frameworks [22,63,69] for understanding user performance and experience on Earth, which we align with the design implications outlined in the previous subsection, and provide suggestions for extending them to extraplanetary environments.

6.2.1 Ability-based design. One of the most popular and encompassing design frameworks in accessible computing is Wobbrock *et al.*'s [69] Ability-based Design (ABD) approach. Unlike other frameworks, such as user-centered design [17], the specific focus on abilities aligns ABD with our goal. Although originally introduced in the context of accessible computing, ABD can be applied to users of various abilities, including users that employ their abilities in new environments, such as those characterized by ICE concerns. ABD leverages seven principles: *ability*, *accountability*, *availability*, *adaptability*, *transparency*, *performance*, and *context*. For example, by following the *ability* principle, designers focus on abilities, not disabilities, *i.e.*, what users can do instead of what they cannot. For example, walking or working in a bulky astronaut suit (see Figure 1) are examples of constraints that diminish one's sensory and motor abilities, developed within Earth's environment. Thus, the ABD principles could generalize well to extraterrestrial environments through user interfaces that provide *assistance* (our implication ①) and *resistance* (implication ②). Both *assistance* and *resistance* emphasize users' abilities to effectively engage with and successfully complete tasks, with the former offering targeted support toward a specific goal, and the latter preserving successful behavior across tasks and goals. Moreover, *adaptability* (implication ③), has been previously explored in SpaceCHI [45] through a generative theory proposal for extraterrestrial habitats characterized by high-risk, uncertainty, and dynamic situation development.

6.2.2 Reality-based Interaction. The effect of the environment on interaction design has been examined in the scientific community with several frameworks. Of these, one that is relevant to our scope is Jacob *et al.*'s [22] Reality-Based Interaction (RBI), which attempts "to make computer interaction more like interacting with the real, non-digital world" (p. 201). To this end, the framework considers four themes: (i) *naïve physics* (common sense knowledge about the physical world), (ii) *body awareness and skills* (awareness of one's body and skills for controlling the body), (iii) *environment awareness and skills* (sense of surroundings and skills for manipulating and navigating within the environment), and (iv) *social awareness and skills* (for interacting with others), respectively. *Naïve physics*, represented by the informal perception of basic physical principles, *e.g.*, gravity, friction, velocity, is inherently dependent on the planet. Although RBI subsumes the design of the natural interaction [21], the meaning of "natural" is likely to vary significantly in environments with different physical characteristics, *e.g.*, interacting with a device under microgravity conditions [11]. A more proper conceptual approach might be non-natural interaction design [64] to contrast, in the context of SpaceCHI, users' expectations of interacting in the Earth environment with those on other planets. From this perspective, both pragmatic and hedonic UX dimensions of interacting with computer systems in unconventional environments could be improved (our implications ⑤ and ⑥), as non-natural interaction design specifically emphasizes the unconventional, surprising, and unfamiliar across all elements of the context of use. Beyond the natural physical reality of Earth, the altered appearance and modified behavior of extraterrestrial environments require interaction design that embraces and integrate this non-natural context through inconstancy, inconsistency, and inaction [64]. *Environment awareness*

and skills refer to navigating within and altering one's environment, which require different skills on Earth and outside-Earth planets. The transfer of skills at an interplanetary dimension can be achieved in part through adaptive behavior and performance [45] and in part through adaptive interfaces [69], suggesting a process of "mediation." The primary reality, serving as the substratum for all interactions, emerges as key to aligning users' expectations of what is natural with the environment's actual appearance and behavior. Reducing the *décalage* between users' expectations and the environment's reality can positively impact UX across both pragmatic and hedonic dimensions. Next, we discuss another framework that explicitly emphasizes computer-mediated perception and action.

6.2.3 Sensorimotor Realities. Sensorimotor Realities [63] (SRs) represent a technology-agnostic framework for computer-mediated perception and action with an interaction design perspective by capitalizing on three key elements: (i) the heterogeneity of human sensorimotor abilities, (ii) the diversity of extended reality worlds, and (iii) the mediation of perception and action through computers. In this context, interaction represents an act of mediation, as follows. The *sensory mediation* and *motor mediation* dimensions specify the nature and amount of mediation that affects perception and action. The *virtuality* dimension represents the amount of virtual content presented to the user. The *imaginarity* dimension represents the degree to which mental imagery is needed for effective operation in the world. Finally, *body augmentation* specifies the use of wearables to mediate sensation and action, while *environment augmentation* specifies the integration of sensing, processing, and visualization technology in the physical environment to mediate sensorimotor abilities. The concept of "mediation," key to the SRs design approach, is directly relevant to extraterrestrial contexts of use where interactions are performed in specific conditions of equipment that mediate abilities, e.g., astronaut suits as human augmentation in space exploration [15] and, correspondingly, an emerging practice of astronaut-oriented design [2].

Mediation provides the context for automatic interactions in ICE environments (our implication ④) by shifting routine tasks from the user's focused attention and active engagement to the periphery of both sensory and motor processes. In this sense, mediation encompasses all processes that, being exocentric to the user and attributable to devices or the environment, influence intrinsic perception and action, thus creating the premises for improving both pragmatic (implication ⑤) and hedonic (implication ⑥) UX dimensions. The former is supported through concrete assistance that increases user efficiency in unfamiliar environments, while the latter arises from the ability of mediation to create meaningful integrations between interaction and environment. Furthermore, beyond *body augmentation*, mediation is achieved through *environment augmentation* due to specialized equipment used for navigation, exploration, and sustaining life in an extraterrestrial environment [35,57]. Through the lens of mediation, both user sensorimotor abilities and their perception of the environment's characteristics, particularly ICE ones, can be dynamically reshaped. Thus, along with ability-based design [69] and reality-based interaction [22], sensorimotor realities [63] provide a theoretical foundation for exploring interaction frameworks for planetary environments beyond Earth.

6.3 Limitations and Future Work

There are several threats [65] that might have influenced the results of our experiments, which we discuss in the following.

In terms of *external validity*, both our experiments were conducted at MDRS, a state-of-the-art facility designed to replicate Mars analog conditions as closely as possible. However, despite the fidelity of this setting, significant differences exist compared to the actual Martian environment, such as Mars' gravity being 38% of Earth's, a Martian day lasting 24 hours and 40 minutes, and the average temperature being of -63°C . Thus, our empirical results should be interpreted with the understanding that they reflect a partial simulation of Mars. Nevertheless, despite these differences, a wide range of conditions were simulated with high fidelity at MDRS—particularly aspects related to feelings of isolation and confinement, perceptions of a vast uninhabited terrain, and the restrictions imposed by wearing and manipulating heavy and bulky equipment, all of which were present in the simulation.

Regarding *internal validity*, our crew size was limited to six analog astronauts per experiment, because of logistical constraints at MDRS. This aspect presents a significant limitation to both the statistical power and generalizability of our findings. For example, crew members with different physical training, psychological profiles, or technical backgrounds may evaluate their UX in patterns that differ from those observed in our sample. Moreover, the small sample size prevented us from performing inferential statistical analyses and, instead, we focused on descriptive statistics and identifying trends in how the various UX dimensions evolved over time. Nevertheless, even this preliminary information is valuable for understanding differences with respect to Earth-like settings and can serve as a foundation for future investigations. Furthermore, our experiments focused solely on graphical and haptic interactions, excluding other modalities, devices, and platforms. While these two modalities are representative of Mars missions, future work should expand the scope of UX evaluation in extraplanetary environments to more diverse application types and interaction devices. At a methodological level, the integration of physiological and cognitive measures, such as stress biomarkers and cognitive load assessments, will enable a more comprehensive understanding of how ICE environments affect the UX of interactive systems.

For *construct validity*, our within-subject approach could be restructured as a between-subject design to mitigate potential learning effects that might influence evaluations in consecutive sessions. Finally, in terms of *conclusion validity*, we ensured all crew members received uniform training before their mission. However, this training was not comparable to the extensive and intensive preparation of real astronauts, spanning months of physical and psychological effort. Future work could address these threats by incorporating larger samples of analog astronauts who undergo more intensive training and experience more realistic simulations of extraplanetary conditions, if technologically available.

Lastly, a final limitation regards the emotional cost endured by our participants while operating in the ICE environment, an aspect that we did not evaluate or consider in this work. However, future examinations could look at how emotional factors interact with physical and psychological stressors to offer a more comprehensive understanding of the UX of interactive computer systems in such

environments. The ethics of designing such experiments—where conditions are challenging and potentially significantly more demanding than those of our study—involves careful consideration of participant well-being and risk mitigation, going beyond simple informed consent. We recommend continuous monitoring and support mechanisms that should be in place to address any adverse effects that may arise during the experiment.

7 Conclusion

We reported in this work empirical findings from two experiments conducted in an extraplanetary simulated environment, reflective of challenging ICE conditions, to evaluate various UX dimensions involved by interacting with graphical and haptic user interfaces. Our results indicated that environmental stressors, of either a physical or psychological nature, affect UX with various patterns and help us conclude that interactions designed for such environments need to be tailored to exceptional usage conditions. We also proposed future developments based on extending interaction frameworks developed within an Earth perspective to extraplanetary environments. We envision further research to replicate, consolidate, and refine the implications of our experiments as well as to extend them through evaluations in actual ICE environments or more realistic simulations, such as actual space missions or polar expeditions. We believe that our findings represent a first step towards understanding UX in unconventional environments, where interactive computer technology plays a crucial role in supporting work and well-being. We also plan to compare different interaction modalities equipped with different devices to determine which one seems the most appropriate to accomplish a given task, without causing interference with other modalities already involved, such as the speech modality used for communication. Finally, we also want to compare the preference expressed by analog astronauts for performing these tasks with performance measures, such as the pragmatic measures reported in this article.

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References

- [1] Paul T. Bartone, Gerald P. Krueger, and Jocelyn V. Bartone. 2018. Individual Differences in Adaptability to Isolated, Confined, and Extreme Environments. *Aerospace Medicine and Human Performance* 89, 6 (June 2018), 536–546. <https://doi.org/10.3357/AMHP.4951.2018>
- [2] Leonie Bensch, Tommy Nilsson, Paul de Medeiros, Florian Dufresne, Andreas Gerndt, Flavie Rometsch, Georgia Albuquerque, Frank Flemisch, Oliver Bensch, Michael Preutenborbeck, and Aidan Cowley. 2023. Towards Balanced Astronaut-Oriented Design for Future EVA Space Technologies. In *Proceedings of 3rd International Conference on Human-Computer Interaction for Space Exploration (SpaceCHI 3.0)*. MIT Media Lab, Boston, MA, USA, 10 pages. <https://elib.dlr.de/201717/>
- [3] Gaëlle Calvary, Joëlle Coutaz, David Thevenin, Quentin Limbourg, Laurent Bouillon, and Jean Vanderdonckt. 2003. A Unifying Reference Framework for Multi-target User Interfaces. *Interacting with Computers* 15, 3 (2003), 289–308. [https://doi.org/10.1016/S0953-5438\(03\)00010-9](https://doi.org/10.1016/S0953-5438(03)00010-9)
- [4] Giovanni A. Cavagna, P.A. Willems, and N.C. Heglund. 1998. Walking on Mars. *Nature* 393, 636 (1998). <https://doi.org/10.1038/31374>
- [5] Rashi Chandra. 2024. Predictive UX: Anticipating User Actions with Machine Learning. <https://insights.daffodilsw.com/blog/predictive-ux-anticipating-user-actions-with-machine-learning>
- [6] William J Clancey. 2006. Participant Observation of a Mars Surface Habitat Mission Simulation. *Habitation* 11, 1 (2006), 27–47. <https://doi.org/10.3727/154296606779507132>
- [7] Charles L.A. Clarke, Gordon V. Cormack, Jimmy Lin, and Adam Roegiest. 2017. Ten Blue Links on Mars. In *Proceedings of the 26th International Conference on World Wide Web (WWW '17)*. International World Wide Web Conferences Steering Committee, Republic and Canton of Geneva, 273–281. <https://doi.org/10.1145/3038912.3052625>
- [8] Joëlle Coutaz, James L. Crowley, Simon Dobson, and David Garlan. 2005. Context is Key. *Commun. ACM* 48, 3 (2005), 49–53. <https://doi.org/10.1145/1047671.1047703>
- [9] Anind K Dey. 2001. Understanding and Using Context. *Personal and Ubiquitous Computing* 5 (2001), 4–7. <https://doi.org/10.1007/s007790170019>
- [10] Ariel Ekblaw, Juliana Cherston, Fangzheng Liu, Irmandy Wicaksono, Don Derek Haddad, Valentina Sumini, and Joseph A. Paradiso. 2023. From UbiComp to Universe-Moving Pervasive Computing Research Into Space Applications. *IEEE Perv. Comp.* 22, 2 (2023), 27–42. <https://doi.org/10.1109/MPRV.2023.3242667>
- [11] Sands Fish. 2018. How To Design Interplanetary Apps. Medium. <https://sandsfish.medium.com/how-to-design-interplanetary-apps-22ebefec097d>
- [12] Sands Fish. 2022. Orientation-Responsive Displays for Microgravity. In *Proceedings of the SpaceCHI 2.0 Workshop, Advancing Human-Computer Interaction for Space Exploration at CHI 2022 (SpaceCHI 2.0)*. MIT Media Lab, MA, USA, 5 pages. <https://drive.google.com/open?id=1BUQDkbt6tSCJ759Z00FuaEmm6Af5h2z9>
- [13] Sands Fish and Nicole L'Huillier. 2018. Telemetron: A Musical Instrument for Performance in Zero Gravity. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '18)*. NIME Community, 3 pages. https://www.nime.org/proceedings/2018/nime2018_paper0066.pdf
- [14] Murielle Florins, Francisco Montero Simarro, Jean Vanderdonckt, and Benjamin Michotte. 2006. Splitting rules for graceful degradation of user interfaces. In *Proceedings of the ACM Int. Conference on Advanced Visual Interfaces (AVI '06)*. ACM, New York, NY, USA, 59–66. <https://doi.org/10.1145/1133265.1133276>
- [15] Marcin Frackiewicz. 2023. *The Role of Human Augmentation in Space Exploration*. LIM. <https://ts2.pl/en/the-role-of-human-augmentation-in-space-exploration>
- [16] Gregory Goth. 2012. Software on Mars. *Commun. ACM* 55, 11 (nov 2012), 13–15. <https://doi.org/10.1145/2366316.2366321>
- [17] John D. Gould and Clayton Lewis. 1985. Designing for usability: Key principles and what designers think. *Commun. ACM* 28, 3 (mar 1985), 300–311. <https://doi.org/10.1145/3166.3170>
- [18] Marc Hassenzahl, Sarah Diefenbach, and Anja Göritz. 2010. Needs, affect, and interactive products – Facets of user experience. *Interacting with Computers* 22, 5 (2010), 353–362. <https://doi.org/10.1016/j.intcom.2010.04.002>
- [19] Sandra Häuplik-Meusburger and Sheryl Bishop. 2021. Introduction to ICE. In *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing, Cham, 1–8. https://doi.org/10.1007/978-3-030-69740-2_1
- [20] Andreas Hinderks, Dominique Winter, Martin Schrepp, and Jörg Thomaschewski. 2019. Applicability of User Experience and Usability Questionnaires. *Journal of Universal Computer Science* 25, 13 (2019), 1717–1735. https://www.jucs.org/jucs_25_13/applicability_of_user_experience/jucs_25_13_1717_1735_hinderks.pdf
- [21] Linda Hirsch, Jingyi Li, Sven Mayer, and Andreas Butz. 2022. A Survey of Natural Design for Interaction. In *Proceedings of Mensch und Computer (MuC '22)*. ACM, New York, NY, USA, 240–254. <https://doi.org/10.1145/3543758.3543773>
- [22] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. 2008. Reality-based Interaction: A Framework for Post-WIMP Interfaces. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 201–210. <https://doi.org/10.1145/1357054.1357089>
- [23] Lauren Blackwell Landon, Grace L. Douglas, Meghan E. Downs, Maya R. Greene, Alexandra M. Whitmire, Sara R. Zwart, and Peter G. Roma. 2019. The Behavioral Biology of Teams: Multidisciplinary Contributions to Social Dynamics in Isolated, Confined, and Extreme Environments. *Frontiers in Psychology* 10 (2019), 20 pages. <https://doi.org/10.3389/fpsyg.2019.02571>
- [24] Lauren Blackwell Landon, Jessica J. Márquez, and Eduardo Salas. 2023. Human Factors in Spaceflight: New Progress on a Long Journey. *Human Factors* 65, 6 (2023), 973–976. <https://doi.org/10.1177/00187208231170276>
- [25] John Leach. 2016. Psychological factors in exceptional, extreme and torturous environments. *Extreme Physiology & Medicine* 5, 7 (2016). <https://doi.org/10.1186/s13728-016-0048-y>
- [26] Lik-Hang Lee, Carlos Bermejo Fernandez, Ahmad Alhailal, Tristan Braud, Simo Hosio, Esmée Henricke Anne de Haas, and Pan Hui. 2022. Beyond the Blue Sky of Multimodal Interaction: A Centennial Vision of Interplanetary Virtual Spaces

- in Turn-based Metaverse. In *Proceedings of the ACM International Conference on Multimodal Interaction (ICMI '22)*. ACM, New York, NY, USA, 648–652. <https://doi.org/10.1145/3536221.3558174>
- [27] Lauren B. Leveton, Camille Shea, Kelley J. Slack, Kathryn E. Keeton, and Lawrence A. Palinkas. 2009. Antarctica Meta-analysis: Psychosocial Factors Related to Long-duration Isolation and Confinement. In *Proceedings of Human Research Program Investigators Workshop*. Universities Space Research Association. <https://doi.org/citations/20090007551>
- [28] Shu-Yu Lin and Katya Arquilla. 2022. Quantifying Proprioceptive Experience in Microgravity. In *Proceedings of the SpaceCHI 2.0 Workshop, Advancing Human-Computer Interaction for Space Exploration at CHI 2022 (SpaceCHI 2.0)*. MIT Media Lab, MA, USA, 5 pages. <https://drive.google.com/open?id=14adCKB1U5m2-0kiL9BL02rD6-uUkoavd>
- [29] Rhema Linder, Chase Hunter, Jacob McLeomore, Senjuti Dutta, Fatema Akbar, Ted Grover, Thomas Breideband, Judith W. Borghouts, Yuwen Lu, Gloria Mark, Austin Z. Henley, and Alex C. Williams. 2022. Characterizing Work-Life for Information Work on Mars: A Design Fiction for the New Future of Work on Earth. *Proceedings of ACM Human-Computer Interaction* 6, GROUP, Article 40 (jan 2022), 27 pages. <https://doi.org/10.1145/3492859>
- [30] Adrian Lubitz, Octavio Arriaga, Teena Hassan, Nina Hoyer, and Elsa Andrea Kirchner. 2022. A Bayesian Approach to Context-based Recognition of Human Intention for Context-Adaptive Robot Assistance in Space. In *Proceedings of the SpaceCHI 2.0 Workshop, Advancing Human-Computer Interaction for Space Exploration at CHI 2022 (SpaceCHI 2.0)*. MIT Media Lab, MA, USA, 5 pages. <https://drive.google.com/open?id=1OMi3vs8VNtFSbRXNvV8PH-vsXzZu75ub>
- [31] Julie Manon, Vladimir Pletser, Michael Saint-Guillain, Jean Vanderdonck, Cyril Wain, Jean Jacobs, Audrey Comein, Sirga Drouet, Julien Meert, Ignacio Jose Sanchez Casla, Olivier Cartiaux, and Olivier Cornu. 2023. An Easy-To-Use External Fixator for All Hostile Environments, from Space to War Medicine: Is It Meant for Everyone's Hands? *Journal of Clinical Medicine* 12, 14, Article 4764 (2023), 16 pages. <https://doi.org/10.3390/jcm12144764>
- [32] Julie Manon, Michael Saint-Guillain, Vladimir Pletser, Daniel Miller Buckland, Laurence Vico, William Dohney, Sarah Baatout, Cyril Wain, Jean Jacobs, Audrey Comein, Sirga Drouet, Julien Meert, Ignacio Sanchez Casla, Cheyenne Chamart, Jean Vanderdonck, Olivier Cartiaux, and Olivier Cornu. 2023. Adequacy of in-mission training to treat tibial shaft fractures in mars analogue testing. *Scientific Reports* 13, Article 18072 (2023). <https://doi.org/10.1038/s41598-023-43878-1>
- [33] Jessica J. Márquez and Mary L. Cummings. 2008. Design and Evaluation of Path Planning Decision Support for Planetary Surface Exploration. *Journal of Aerospace Computing, Information, and Communication* 5, 3 (2008), 57–71. <https://doi.org/10.2514/1.26248>
- [34] Jessica J. Márquez, Lauren Blackwell Landon, and Eduardo Salas. 2023. The Next Giant Leap for Space Human Factors: The Opportunities. *Human Factors* 65, 6 (2023), 1279–1288. <https://doi.org/10.1177/00187208231174955>
- [35] Kaitlin R. McTigue, Megan E. Parisi, Tina L. Panontin, Shu-Chieh Wu, and Alonso H. Vera. 2023. How to Keep Your Space Vehicle Alive: Maintainability Design Principles for Deep-Space Missions. In *Proceedings of SpaceCHI 3.0, A Conference on Human-Computer Interaction for Space Exploration (SpaceCHI 3.0)*. MIT Media Lab, MA, USA, 8 pages. https://human-factors.arc.nasa.gov/publications/SpaceCHI2023_Maintainability.pdf
- [36] Anna-Lena Meiners, Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2024. A Benchmark for the UEQ+ Framework: Construction of a Simple Tool to Quickly Interpret UEQ+ KPIs. *Int. J. Interact. Multim. Artif. Intell.* 9, 1 (2024), 104. <https://doi.org/10.9781/IJIMAI.2023.05.003>
- [37] Susmita Mohanty, Jesper Jørgensen, and Maria Nyström. 2006. Psychological Factors Associated with Habitat Design for Planetary Mission Simulators. In *Proceedings of Space Architecture Symposium: Space Human Factors (Space 2006)*. American Institute of Aeronautics and Astronautics, Reston, VA, USA. <https://doi.org/10.2514/6.2006-7345>
- [38] Michael Nebeling, Fabrice Matulic, Lucas Streit, and Moira C. Norrie. 2011. Adaptive layout template for effective web content presentation in large-screen contexts. In *Proceedings of the 11th ACM Symposium on Document Engineering*. ACM, New York, NY, USA, 219–228. <https://doi.org/10.1145/2034691.2034737>
- [39] Tommy Nilsson, Leonie Bensch, Florian Dufresne, Flavie Rometsch, Paul de Medeiros, Enrico Guerra, Florian Saling, Andrea Casini, and Aidan Cowley. 2023. Out of this World Design: Bridging the Gap between Space Systems Engineering and Participatory Design Practices. In *Proceedings of SpaceCHI 3.0, A Conference on Human-Computer Interaction for Space Exploration (SpaceCHI 3.0)*. MIT Media Lab, MA, USA, 9 pages. <https://spacechi.media.mit.edu/spacechi-2023-program>
- [40] Tommy Nilsson, Flavie Rometsch, Leonie Becker, Florian Dufresne, Paul Demedeiros, Enrico Guerra, Andrea Emanuele Maria Casini, Anna Vock, Florian Gaeremynck, and Aidan Cowley. 2023. Using Virtual Reality to Shape Humanity's Return to the Moon: Key Takeaways from a Design Study. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems (CHI '23)*. ACM, New York, NY, USA, Article 305, 16 pages. <https://doi.org/10.1145/3544548.3580718>
- [41] Marianna Obrist, Yunwen Tu, Lining Yao, and Carlos Velasco. 2019. Space Food Experiences: Designing Passenger's Eating Experiences for Future Space Travel Scenarios. *Frontiers in Computer Science* 1 (2019), 17 pages. <https://doi.org/10.3389/fcomp.2019.00003>
- [42] Laurent Opsomer, Frédéric Crevecoeur, Jean-Louis Thonnard, J. McIntyre, and Philippe Lefèvre. 2021. Distinct adaptation patterns between grip dynamics and arm kinematics when the body is upside-down. *Journal of Neurophysiology* 125, 3 (2021), 862–874. <https://doi.org/10.1152/jn.00357.2020>
- [43] Laurent Opsomer, Benoit Delhay, Vincent Théate, Jean-Louis Thonnard, and Philippe Lefèvre. 2023. A haptic illusion created by gravity. *iScience* 26, 7, Article 107246 (2023). <https://doi.org/10.1016/j.isci.2023.107246>
- [44] Lawrence A. Palinkas and Peter Suedfeld. 2021. Psychosocial issues in isolated and confined extreme environments. *Neuroscience & Biobehavioral Reviews* 126 (2021), 413–429. <https://doi.org/10.1016/j.neubiorev.2021.03.032>
- [45] Paul Parsons, Zixu Zhang, and Jackson Murray. 2022. Adaptive Performance: A Generative Theory for HCI Design in Extraterrestrial Habitats. In *Proceedings of the SpaceCHI 2.0 Workshop, Advancing Human-Computer Interaction for Space Exploration at CHI 2022 (SpaceCHI 2.0)*. MIT Media Lab, MA, USA, 4 pages. https://drive.google.com/open?id=1vYNe4HXcdVnMeNn0X_IXWn7hCUXIDOKU
- [46] Pat Pataranutaporn, Valentina Sumini, Ariel Ekblaw, Melodie Yashar, Sandra Häuplik-Meusburger, Susanna Testa, Marianna Obrist, Dorit Donoviel, Joseph Paradiso, and Pattie Maes. 2021. SpaceCHI: Designing Human-Computer Interaction Systems for Space Exploration. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA '21)*. ACM, New York, NY, USA, Article 96, 6 pages. <https://doi.org/10.1145/3411763.3441358>
- [47] Pat Pataranutaporn, Valentina Sumini, Melodie Yashar, Susanna Testa, Marianna Obrist, Scott Davidoff, Amber M. Paul, Dorit Donoviel, Jimmy Wu, Sands A Fish, Ariel Ekblaw, Albrecht Schmidt, Joe Paradiso, and Pattie Maes. 2022. SpaceCHI 2.0: Advancing Human-Computer Interaction Systems for Space Exploration. In *Extended Abstracts of the ACM Conference on Human Factors in Computing Systems (CHI EA '22)*. ACM, New York, NY, USA, Article 77, 7 pages. <https://doi.org/10.1145/3491101.3503708>
- [48] Vladimir Pletser and Bernard Foing. 2011. European Contribution to Human Aspect Investigations for Future Planetary Habitat Definition Studies: Field Tests at MDRS on Crew Time Utilisation and Habitat Interfaces. *Microgravity Science and Technology* 23 (2011), 199–214. <https://doi.org/10.1007/s12217-010-9251-4>
- [49] Jue Qu, Hao Guo, Wei Wang, and Sina Dang. 2022. Prediction of Human-Computer Interaction Intention Based on Eye Movement and Electroencephalograph Characteristics. *Frontiers in Psychology* 13 (2022), 16 pages. <https://doi.org/10.3389/fpsyg.2022.816127>
- [50] Michael Saint-Guillain, Jean Vanderdonck, Nicolas Burny, Vladimir Pletser, Tiago Vaquero, Steve Chien, Alexander Karl, Jessica Marquez, Cyril Wain, Audrey Comein, Ignacio S. Casla, Jean Jacobs, Julien Meert, Cheyenne Chamart, Sirga Drouet, and Julie Manon. 2023. Enabling astronaut self-scheduling using a robust advanced modelling and scheduling system: An assessment during a Mars analogue mission. *Advances in Space Research* 72, 4 (2023), 1378–1398. <https://doi.org/10.1016/j.asr.2023.03.045>
- [51] Inderpal S. Saluja, David R. Williams, Daniel Woodard, Janusz Kaczorowski, Ben Douglas, Philip J. Scarpa, and Jean-Marc Comtois. 2008. Survey of astronaut opinions on medical crewmembers for a mission to Mars. *Acta Astronautica* 63, 5 (2008), 586–593. <https://doi.org/10.1016/j.actaastro.2008.05.002>
- [52] Irene Lia Schlacht. 2011. Space extreme design - New ideas and approaches for space habitability. *Personal and Ubiquitous Computing* 15, 5 (2011), 487–489. <https://doi.org/10.1007/S00779-010-0320-X>
- [53] Irene Lia Schlacht and Henrik Birke. 2011. Space design - Visual interface of space habitats. *Personal and Ubiquitous Computing* 15, 5 (2011), 497–509. <https://doi.org/10.1007/S00779-010-0326-4>
- [54] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2017. Construction of a Benchmark for the User Experience Questionnaire (UEQ). *International Journal of Interactive Multimedia and Artificial Intelligence*. 4, 4 (2017), 40–44. <https://doi.org/10.9781/ijimai.2017.445>
- [55] Martin Schrepp and Jörg Thomaschewski. 2019. Design and Validation of a Framework for the Creation of User Experience Questionnaires. *International Journal of Interactive Multimedia and Artificial Intelligence* 5, 7 (2019), 88–95. <https://doi.org/10.9781/IJIMAI.2019.06.006>
- [56] Shivang Shelat, John A. Karasinski, Erin E. Flynn-Evans, and Jessica J. Marquez. 2022. Evaluation of User Experience of Self-scheduling Software for Astronauts: Defining a Satisfaction Baseline. In *Engineering Psychology and Cognitive Ergonomics*, Don Harris and Wen-Chin Li (Eds.). Springer International Publishing, Cham, 433–445. https://doi.org/10.1007/978-3-031-06086-1_34
- [57] David Smitherman and Andrew Schnell. 2020. Gateway Lunar Habitat Modules as the Basis for a Modular Mars Transit Habitat. In *Proceedings of the IEEE Aerospace Conference*. IEEE, USA, 1–12. <https://doi.org/10.1109/AERO47225.2020.9172540>
- [58] Peter Suedfeld. 2021. Applying Positive Psychology in the Study of Extreme Environments. *Journal of Human Performance in Extreme Environments* 6, 1, Article 6 (2021). <https://doi.org/10.7771/2327-2937.1020>
- [59] Andrew Terhorst and Jason A. Dowling. 2022. Terrestrial Analogue Research to Support Human Performance on Mars: A Review and Bibliographic Analysis. *Space: Science & Technology* 2022, 9841785 (2022), 18 pages. <https://doi.org/10.34133/2022/9841785>

- [60] Martine Van Puyvelde, Daisy Gijbels, Thomas Van Caelenberg, Nathan Smith, Loredana Bessone, Susan Buckle-Charlesworth, and Nathalie Pattyn. 2022. Living on the edge: How to prepare for it? *Frontiers in Neuroergonomics* 3 (2022), 20 pages. <https://doi.org/10.3389/fnrgo.2022.1007774>
- [61] Jean Vanderdonckt, Gaëlle Calvary, Joëlle Coutaz, and Adrian Stanculescu. 2008. *Multimodality for Plastic User Interfaces: Models, Methods, and Principles*. Springer, Berlin, Heidelberg, 61–84. https://doi.org/10.1007/978-3-540-78345-9_4
- [62] Jean Vanderdonckt, Radu-Daniel Vatavu, Julie Manon, Michael Saint-Guillain, Philippe Lefevre, and Jessica J. Marquez. 2024. Might as Well Be on Mars: Insights on the Extraterrestrial Applicability of Interaction Design Frameworks from Earth. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. ACM, New York, NY, USA, Article 239, 8 pages. <https://doi.org/10.1145/3613905.3650807>
- [63] Radu-Daniel Vatavu. 2022. Sensorimotor Realities: Formalizing Ability-Mediating Design for Computer-Mediated Reality Environments. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality (ISMAR '22)*. IEEE, USA, 685–694. <https://doi.org/10.1109/ISMAR55827.2022.00086>
- [64] Radu-Daniel Vatavu. 2025. Non-Natural Interaction Design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '25)*. ACM, New York, NY, USA, 16 pages. <https://doi.org/10.1145/3706598.3713459>
- [65] Roberto Verdecchia, Emelie Engström, Patricia Lago, Per Runeson, and Qunying Song. 2023. Threats to validity in software engineering research: A critical reflection. *Information and Software Technology* 164 (2023), 107329. <https://doi.org/10.1016/j.infsof.2023.107329>
- [66] Sallie J. Weaver and Eduardo Salas. 2010. Training and Measurement at the Extremes: Developing and Sustaining Expert Team Performance in Isolated, Confined, Extreme Environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 54, 1 (2010), 90–93. <https://doi.org/10.1177/154193121005400120>
- [67] Bernhard Weber and Martin Stelzer. 2022. Sensorimotor impairments during spaceflight: Trigger mechanisms and haptic assistance. *Frontiers in Neuroergonomics* 3 (2022), 16 pages. <https://doi.org/10.3389/fnrgo.2022.959894>
- [68] Olivier White, Yannick Bleyenheuft, Renaud Ronsse, Allan M. Smith, Jean-Louis Thonnard, and Philippe Lefèvre. 2008. Altered Gravity Highlights Central Pattern Generator Mechanisms. *Journal of Neurophysiology* 100, 5 (2008), 2819–2824. <https://doi.org/10.1152/jn.90436.2008>
- [69] Jacob O. Wobbrock, Shaun K. Kane, Krzysztof Z. Gajos, Susumu Harada, and Jon Froehlich. 2011. Ability-Based Design: Concept, Principles and Examples. *ACM Transactions on Accessible Computing* 3, 3, Article 9 (apr 2011), 27 pages. <https://doi.org/10.1145/1952383.1952384>
- [70] World Health Organization. 2023. *Disability*. WHO. <https://www.who.int/news-room/fact-sheets/detail/disability-and-health>
- [71] Jimin Zheng, Shivang M. Shelat, and Jessica J. Marquez. 2023. Facilitating Crew-Computer Collaboration During Mixed-Initiative Space Mission Planning. In *Proceedings of SpaceCHI 3.0, A Conference on Human-Computer Interaction for Space Exploration (SpaceCHI 3.0)*. MIT Media Lab, MA, USA, 7 pages. <https://ntrs.nasa.gov/citations/20230008619>
- [72] Pierpaolo Zivi, Luigi De Gennaro, and Fabio Ferlazzo. 2020. Sleep in Isolated, Confined, and Extreme (ICE): A Review on the Different Factors Affecting Human Sleep in ICE. *Frontiers in Neuroscience* 14 (2020), 22 pages. <https://doi.org/10.3389/fnins.2020.00851>