

Might as Well Be on Mars: Insights on the Extraterrestrial Applicability of Interaction Design Frameworks from Earth

Jean Vanderdonckt

Université catholique de Louvain
Louvain Research Institute in
Management and Organizations
Louvain-la-Neuve, Belgium
jean.vanderdonckt@uclouvain.be

Radu-Daniel Vatavu

MintViz Lab, MANSiD Center
Ștefan cel Mare University of Suceava
Suceava, Romania
radu.vatavu@usm.ro

Julie Manon

Cliniques universitaires Saint-Luc
Institut de recherche expérimentale et
clinique, Neuro Musculo Skeletal Lab
Brussels, Belgium
julie.manon@uclouvain.be

Michael Saint-Guillain

Université catholique de Louvain
Institute of Information and
Communication Technologies,
Electronics and Applied Mathematics
Louvain-la-Neuve, Belgium
michael.saint@uclouvain.be

Philippe Lefevre

Université catholique de Louvain
Institute of Information and
Communication Technologies,
Electronics and Applied Mathematics
Louvain-la-Neuve, Belgium
philippe.lefevre@uclouvain.be

Jessica J. Marquez

NASA Ames Research Center
Moffett Field, CA, USA
jessica.j.marquez@nasa.gov

ABSTRACT

As humanity expands its reach into the Cosmos, the imagination-sparking prospect of colonizing other planets, such as Mars, becomes increasingly tangible. However, establishing livable environments on Mars necessitates robust and efficient computer systems, and thus design knowledge for highly usable interactions that match users' abilities under the unique challenges posed by other planets' environments. In this work, we connect to current interaction design frameworks, such as Ability-based Design, Reality-based Interaction, and Sensorimotor Realities, to assess their suitability beyond Earth. Furthermore, we present insights from the user experience of interactive systems on Mars through observations collected during a mission at the Mars Desert Research Station. We use our findings to propose future research on interaction frameworks with extraterrestrial and interplanetary applicability.

CCS CONCEPTS

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

KEYWORDS

Extraterrestrial, Mars mission, interaction design, user interface design, design frameworks

ACM Reference Format:

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)*, May 11–16, 2024, Honolulu, HI, USA. ACM, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3613905.3650807>

1 INTRODUCTION

Prospective colonization of other planets is an endeavor that presents many technical challenges, among which robust interactive computer technology to sustain life, work, and communication in environments with characteristics vastly different from Earth. The intersection of this endeavor with the HCI community is SPACECHI [27, 28], an initiative that delineates an area of scientific exploration where established methods, techniques, and approaches from within HCI are applied to support missions and discoveries in space exploration. Examples include designing user interfaces for interactive computer systems meant to be used in extraterrestrial environments by focusing on specific human factors [18], software [3], and hardware [29] and dealing with specific systems and human-related challenges, such as communications delays, reduced sensory input and motor output, and physiological effects that extraterrestrial environments may have on humans [12].

However, interaction design that satisfies all these constraints remains an elusive endeavor at the moment. Even with design guidelines in place for crew user interfaces, such as those available in the NASA's Human Integration Design Handbook (HIDH) [20], the multi-faceted experience of operating an interactive system on another planet with different gravity conditions [7] or of the mere act of eating [24], are yet to be fully understood.

In this work, we scrutinize contemporary interaction design frameworks that capitalize on concepts of *ability* (i.e., what users can do) and *environment* (i.e., what is the environment like in which users engage in the interaction). Our working hypothesis is that, despite the varying environmental conditions that affect the ability of users to interact with computer systems on different planets, the principles, rules, and laws inherent in such frameworks should hold to some extent or be proportionally relative to the same interactions that take place on Earth, considered as a baseline [31].

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).
CHI EA '24, May 11–16, 2024, Honolulu, HI, USA
© 2024 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-0331-7/24/05
<https://doi.org/10.1145/3613905.3650807>



Figure 1: How transferable is knowledge enabled by interaction design frameworks from Earth when computer systems are meant for contexts of use specific to other planets’ environments? In this work, we examine several frameworks, originally proposed within an Earth-centered perspective, for interaction with computer systems on other planets with a case study involving Mars. Note: this photograph was taken during our mission at the Mars Desert Research Station (MDRS).

We are thus interested in the applicability and reusability of established interaction frameworks for their capacity to transfer design knowledge from Earth’s particular environment to contexts of use specific to other planets. That is to say, what is the extent to which interplanetary transfer of interaction design can be facilitated by Earth-originating and bounded conceptual and design frameworks? To this end, we resort to Ability-Based Design (ABD) [39], an effective framework for interactive technology that matches users’ abilities, and Reality-Based Interaction (RBI) [13], a framework for designing interactions phenomenologically centered on the experience of the “real world.” We also adopt the more recent perspective of Sensorimotor Realities (SRs) [35], a framework that connects abilities with computer-supported environments, including virtual and augmented ones. In support of our explorations, we also present insights from observations collected during a 12-day mission at the [Mars Desert Research Station \(MDRS\)](#), a space analog facility that supports Earth-based research in pursuit of human space exploration; see Figure 1 for a photo taken during this mission.

2 RELATED WORK

SPACECHI [27,28] represents a recent initiative of the HCI scientific community to support human physical and mental performance in extraterrestrial 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” [27, p. 1]. SPACECHI places emphasis on 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 during the space mission.”¹

Research contributions to SPACECHI have addressed a wide palette of topics, including crew collaboration and tools for mission planning [41], human-system resilience and design for maintainability in deep-space missions [19], participatory design for space systems engineering [21], human-robot interaction in extraterrestrial missions [16], food experience design for space travel [24], and examinations of the influence of extraterrestrial conditions, such as microgravity, on human factors and design of interactive systems of various kinds; see [7,8,15] for a few examples. The user experience of space interactions has also been addressed in the scientific literature. For example, Saint-Guillain *et al.* [29] evaluated twelve UEQ+ scales [30] during a simulated Mars mission. Nilsson *et al.* [22] reported qualitative findings, from interviews with astronauts and space experts, regarding the capabilities of virtual environments to facilitate user-centered approaches to operational performance and human factors in relation to system design for space missions. We

¹<https://spacechi.media.mit.edu>

refer the readers to Ekblaw *et al.* [5] for more examples of research at the intersection of HCI, pervasive computing, and space, and Lee *et al.* [14] for a vision of an interplanetary metaverse intended to connect users from Earth and Mars.

The recent interest of the HCI community in contributing to humanity’s quest for space exploration sets the context for our work. To the best of our knowledge, current interaction design frameworks, originally developed within the Earth-centered perspective, have not been examined for their transferability to outside-Earth environments. These include, for example, frameworks that focus on users’ abilities [39], the environment [13], or both [35], which we discuss in Section 3. Note that our focus is on the high-level paradigmatic nature of these frameworks, which goes beyond mere design guidelines. Regarding the latter, NASA’s Human Integration Design Handbook [20] provides an extensive set of guidelines for crew interface with workstations, architecture, habitation facilities, and extravehicular systems next to information about human physical and cognitive capabilities. For example, the properties of well-designed crew interfaces, according to [20], are represented by usability, simplicity of visual design and operation, consistency of elements, style and interaction, and legibility of text and graphics, respectively. An example of the latter is “Displays should be legible under all expected spaceflight conditions where reading/interpretation of the displayed information will be required” [20, p. 905]. Such specific guidelines fall outside our scope, whereas we are instead interested in high-level paradigms that accommodate interactions in various environments, including extraterrestrial ones. To address the limited exploration in this space, we connect in the following section to current frameworks relevant to the concepts of “ability” in relation to users and the physical characteristics of the “environment” or “reality” within which users operate.

3 INTERACTION DESIGN FRAMEWORKS THROUGH THE PRISM OF EXTRATERRESTRIAL APPLICABILITY

In this section, we discuss interaction design frameworks relevant to our scope due to their emphasis on one or both key elements of the contexts of use [2,4] of extraterrestrial applicability: (i) *users*, explored in the following through the prism of their abilities, such as the ability to hold steady a handheld device and touch accurately on its screen, and (ii) *environments*, described in terms of their characteristics, e.g., 3.71m/s^2 gravity on Mars vs. 9.81m/s^2 on Earth.

3.1 Ability-based Design

One of the most popular and encompassing frameworks in accessible computing that explicitly highlights *ability*—as opposed to *disability*—and, consequently, directly relevant to our scope of investigation is Wobbrock *et al.*’s [39] Ability-based Design (ABD) approach. Unlike other accessible design frameworks, such as user-centered design [10], the specific focus on abilities aligns ABD with our goal, since “Just as user-centered design shifted the focus of interactive system design from systems to users, ability-based design attempts to shift the focus of accessible design from disability to ability” [39, p. 9:1]. Although originally introduced in the context of assistive technology and accessible computing, ABD can also be

applied to users of various abilities, including users without diagnosed disabilities in the strict sense of the word [40]. 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. Following *adaptability*, designers create interfaces that dynamically adapt to users’ abilities. Follow-up ABD developments include [23,38].

According to WHO [40], disability results from the interaction between health conditions and a range of environmental and personal factors, and “is part of being human and is integral to the human experience.” Moreover, the effect of the environment on the experience and extent of disability is significant, where inaccessible environments are barriers to participation and engagement. In contrast, abilities represent human potential, according to ABD [39]. While the term “environment” encompasses many factors, including social ones [40], we are interested in the physical constraints of extraterrestrial environments, demanding more effort from users to engage in specific actions. 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. From this perspective, the ABD principles, where interactive systems adapt to match existing abilities, can generalize well to extraterrestrial environments. Adaptability, especially, has been previously addressed by Parsons *et al.* [26] in SPACECHI with a generative theory proposal for HCI design in extraterrestrial habitats characterized by high-risk, uncertain, and dynamic situation development, i.e., “due to the dynamic, uncertain nature of work in complex sociotechnical systems, designers cannot imagine and plan for every possible use case of their artifacts; thus adaptations at the ‘sharp end’ of use are inevitable” (p. 2).

3.2 Reality-based Interaction

The effect of the environment on interaction design has been examined with several frameworks, of which we use Jacob *et al.*’s [13] Reality-Based Interaction (RBI) due to its explicit centering on “reality”—not just as a physical environment, but also as perception of the environment. RBI relates to design that attempts “to make computer interaction more like interacting with the real, non-digital world” (p. 201). To this end, the RBI 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 [11], the meaning of “natural” is likely to vary significantly in environments with different physical characteristics, e.g., interacting with a device under microgravity conditions [8]. A more proper conceptual approach might be non-natural interaction design [36] to contrast, in the context of SPACECHI, users’ natural expectations of interacting in the Earth environment vs. other planets. *Environment awareness and skills* refer to navigating within and

Table 1: Comparison of Earth and Mars on just a few characteristics reveals two significantly different physical environments.

Characteristic (unit of measurement)	Earth	Mars
Distance from the Sun (10^6 km)	150	228
Gravity (m/s^2)	9.81	3.71
Atmospheric pressure (kPa)	101.3 (at sea level)	0.6–1.0 (average)
Day length (hours)	24	24.6
Orbital period (Earth days)	365	687
Atmosphere	Nitrogen (78%), Oxygen (21%)	Carbon Dioxide (95.3%), Nitrogen (2.7%)
Surface temperature	−89°C to 58°C	−125°C to 20°C
Magnetic field	yes	no (weak residual magnetic field)
Presence of liquid water	abundant	evidence of past liquid water
Radiation protection	protective atmosphere and magnetic field	thin atmosphere, limited magnetic field
Communications delay to Earth (minutes, one way)	–	22.4

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 [26] and in part through adaptive interfaces [39], as discussed in the previous section, suggesting a process of “mediation” to support interaction between users and computer systems. Next, we discuss another framework that explicitly emphasizes computer-mediated perception and action.

3.3 Sensorimotor Realities

Sensorimotor Realities [35] (SRs) represent a technology-agnostic framework for computer-mediated perception and action with an interaction design perspective, i.e., “Sensorimotor Realities (SRs) are dynamic, continuously changing manifestations of the reality subjectively experienced by a computer system user as the result of associating sensory perception and motor action that are mediated by wearable devices and smart environments” (p. 687). SRs capitalize 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 that can be characterized in a six-dimensional space, 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 *imaginariness* 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. Follow-up developments of the SRs framework include [36,37].

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 [9] and, correspondingly, an emerging practice of astronaut-oriented design [1]. Furthermore, beyond *body augmentation*, mediation is achieved across the *environment augmentation*

dimension due to specialized equipment used for navigation, exploration, and sustaining life in an extraterrestrial environment [19,32].

3.4 Summary

We reviewed three interaction design frameworks through the prism of user abilities, environment physical characteristics, and the interdependence between mediated abilities and environments in which those abilities are used. Our findings indicate a potential for interplanetary applicability of these frameworks in their specific dimensions of *ability*, *adaptability*, *body and environment awareness*, *body and environment augmentation*, respectively. However, it is important to note the specific nuance that, while abilities remain consistent as they are reused through mediation in new contexts of use, the physical environment undergoes radical changes. Thus, the delta of effort in leveraging one’s abilities to engage in a specific interaction on Earth compared to another planet is determined by unequal changes in these two elements of the context of use—abilities and environment,—at the interplanetary scale. Next, we present empirical insights with a measure of the relative user experience on Mars vs. Earth, where the latter is the baseline.

4 INSIGHTS FROM A SIMULATED MARS ENVIRONMENT

To complement our theoretical examination of interaction design frameworks for interplanetary applicability, we conducted an empirical exploration of the user experience of interacting with two computer systems on Mars. We chose Mars because it is the most accessible planet from Earth, while also unique in the solar system with very diverse and complex geology;² see Table 1. Thus, Mars presents challenging constraints for interaction design by featuring a significantly different physical environment compared to Earth:

- *Gravity and atmospheric pressure.* The gravity ratio between Mars and Earth is $3.71/9.81=0.38$, while pressure ratio is $1/101.3=0.0098$. The effects of reduced gravity (by 62.2%) and pressure (Mars has barely 1% of Earth’s pressure) on human body movement have yet to be fully understood [25].
- *Climate.* Mars experiences extreme temperatures with averages ranging from −125°C to 20°C. In addition, its thin

²NASA Mars Exploration. Why Mars?, <https://mars.nasa.gov>

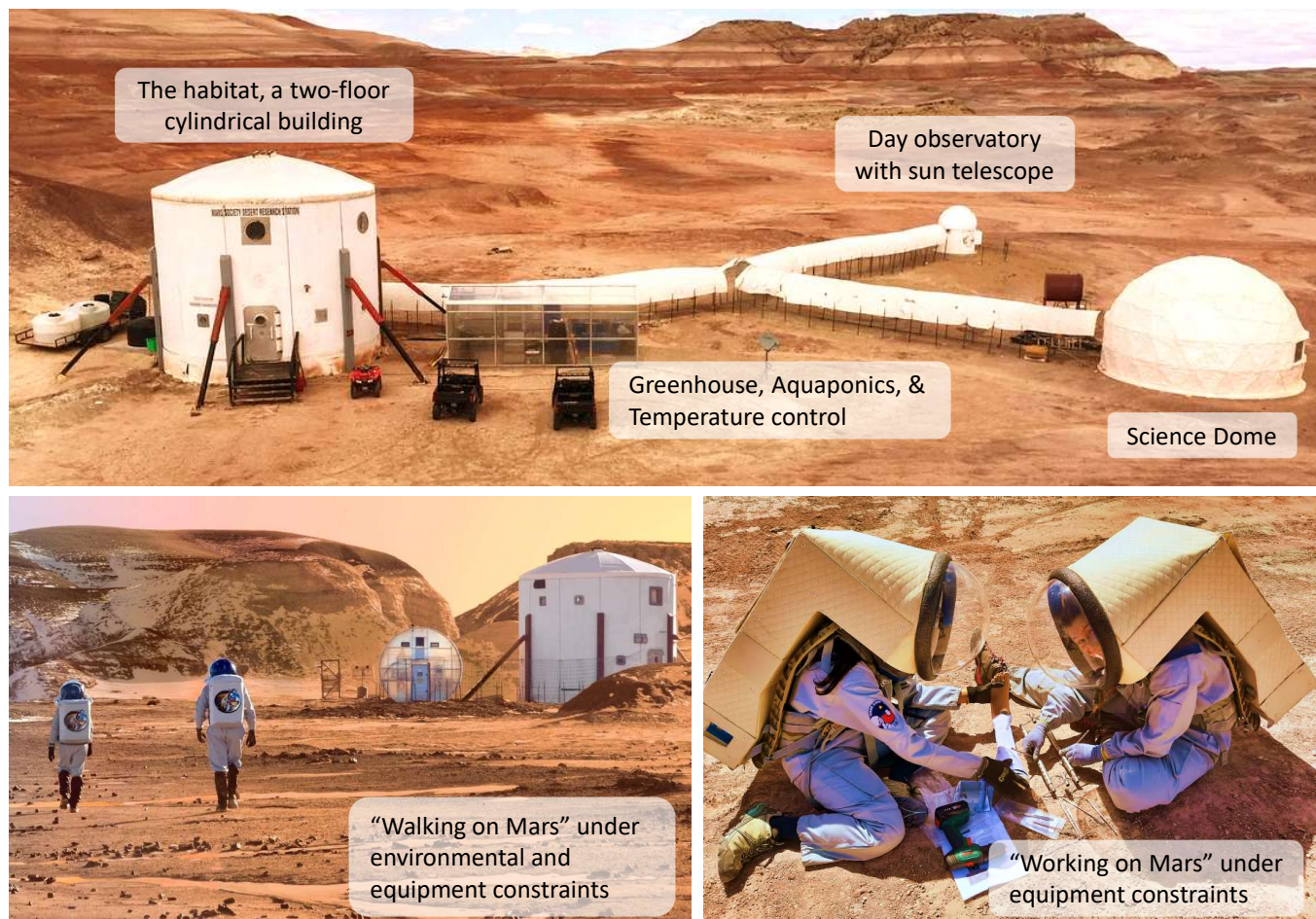


Figure 2: The MDRS environment where the Mars mission was simulated (top) and examples of outdoor exploration (bottom).

atmosphere is composed mainly of carbon dioxide and provides minimal insulation for human habitation [12]. As Mars lacks any magnetic field or shield to protect against solar and cosmic radiation, prolonged exposure to its environment can have detrimental effects on human health [29]. Thus, engaging in tasks on Mars’ surface requires appropriate equipment, which inevitably limits body movement and dexterity.

- *Dust storms.* Mars is known for intense dust storms that can cover the entire planet and last for weeks, therefore restricting solar-powered equipment and visibility.
- *Communications delays.* The distance between Earth and Mars induces a communications lag of roughly 22.4 minutes, making remote control, message exchange, and interplanetary applications [6] technically challenging [3].
- *Technological and logistic challenges.* Transporting humans and supplies to Mars and sustaining human life on the planet pose significant challenges. Thus, developing the necessary life support systems, habitats, and transportation infrastructure is crucial for the prospect of colonizing Mars.
- *Diminished visual perception.* Being farther from the Sun, Mars receives about half the sunlight compared to Earth,

which has negative effects on circadian rhythms, well-being and visual perception, e.g., reddish sunlight [18].

- *Psychological stress.* Extended Mars missions involve prolonged isolation and limited social interaction and communication with Earth and, thus, may negatively impact the cognitive performance [17,18].

Although in situ evaluations of interactive systems are not possible on Mars, in-lab examinations can be conducted in terrestrial environments [33] where conditions similar to those of the physical environment of Mars are reproduced. One example is the [Mars Desert Research Station](#), a facility situated in the Utah desert featuring a Jurassic-Cretaceous geologic landscape that looks Mars-like to its visitors; see Figure 2, top for an overview of the MDRS environment and facilities consisting of a two-story cylindrical building (the habitat), day observatory, greenhouse, and a dome for conducting scientific activities. We conducted a Mars mission at MDRS with a crew composed of eight trained analog astronauts (two women and six men, aged between 22 and 34 years old) over a continuous period of twelve days; see Figure 2, bottom for several photographs taken during the mission.

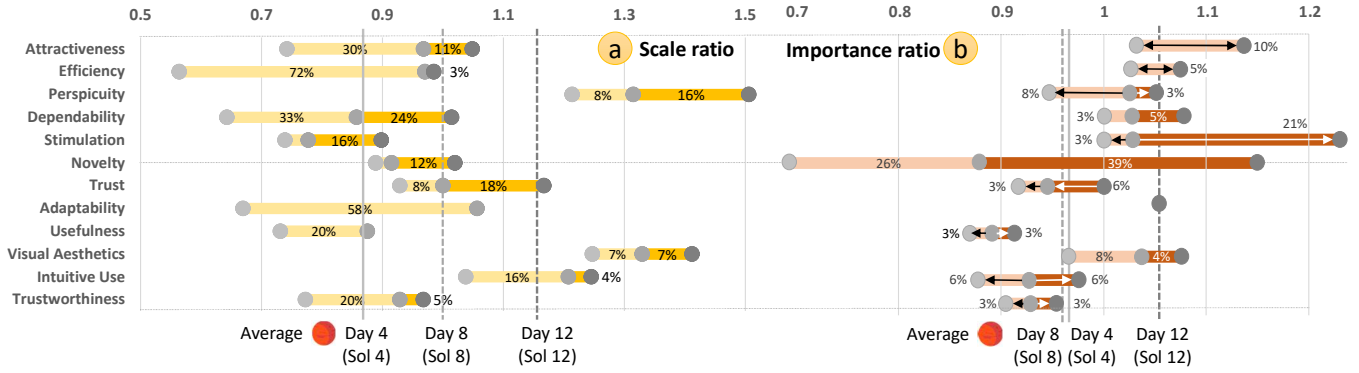


Figure 3: Dumbbell plot of the evolution of user experience (a) and importance (b) ratios after four, eight, and twelve days.

The crew members evaluated the user experience of ROMIE [29], an operation management application for robust advanced modeling and scheduling selected for its capabilities to optimize astronaut scheduling during their mission. To this end, we used the following twelve UEQ+ [30] scales in our study, which we chose due to their capability of covering a wide palette of UX aspects, from how visually appealing an application looks to how efficient it is to interact with it and how trustworthy its content is perceived, as follows:

- *Attractiveness* evaluates participants' overall impression of the application, i.e., do they like or dislike it?
- *Efficiency* evaluates participants' perceptions of being capable of completing tasks within the application without unnecessary effort.
- *Perspicuity* measures participants' impression about how easy it is to become familiar with the application, including the process of learning to use it.
- *Dependability* evaluates the impression of participants that they are the ones controlling the interaction in the application.
- *Stimulation* evaluates how exciting and motivating the application feels during use.
- *Novelty* measures the degree to which the application feels innovative and creative.
- *Trust* evaluates participants' impression that data entered into the application is safely processed and cannot be used to the detriment of the person providing it.
- *Adaptability* evaluates the impression of participants about how easily the application can be adapted to specific preferences.
- *Usefulness* measures the degree to which the application is perceived to bring advantages to the user.
- *Visual aesthetics* evaluates the degree to which the application has a nice and appealing visual look.
- *Intuitive use* measures participants' impression about the capability of the application to be used immediately without training, instructions, or help from others.
- *Trustworthiness of content* measures the impression of participants about the information provided by the application being reliable and accurate.

We refer readers to [30] for more details about these scales as well as for other scales of the UEQ+ framework that are useful in specific applications, such as haptics or acoustics. We employed the scales in Earth conditions before the mission (day 0) and in Mars conditions at different time points represented by four (Sol 4), eight (Sol 8), and twelve Martian days (Sol 12). Subsequently, we aggregated Mars' experience compared to Earth into one measure of UX transferability, following Clarke *et al.*'s [3] definition of relative effort, which we adapted to our specific application contexts involving UX measure α and planet π , as follows:

$$\text{UXT}(\alpha, \pi) = \frac{\text{Measure } \alpha \text{ evaluated on planet } \pi}{\text{Measure } \alpha \text{ evaluated on Earth}} \quad (1)$$

Using this formalism, $\text{UXT}(\alpha=\text{Efficiency}, \pi=\text{Mars})$ represents, for example, the relative perceived efficiency of interactions performed with a specific computer system on Mars relative to the corresponding user experience on Earth. Each UX measure was evaluated using ratings across 7-point Likert scales with labels, e.g., *Perspicuity* was evaluated in response to the question "In my opinion, handling and using the product are" and the following four scales: not understandable–understandable, difficult to learn–easy to learn, complicated–easy, and clear–confusing, respectively; see [30].

Figure 3a presents the evolution of several UXT ratios across four, eight, and twelve days, where one Sol is one Martian day. For example, $\text{UXT}(\text{Adaptability}, \text{Mars})$ starts at 0.67 at Sol-4, increases to 1.06 at Sol-8, and stays at 1.06 at the end of the mission. We observed this trend repeating for the other UXT measures, which surpassed threshold 1 at Sol-12 only. One exception is $\text{UXT}(\text{Efficiency}, \text{Mars})$, consistently lower than 1 (from 0.56 to 0.98), suggesting that the crew felt less efficient on Mars compared to Earth during the entire mission. $\text{UXT}(\text{Perspicuity}, \text{Mars})$, however, consistently exhibited values above 1 (from 1.21 to 1.51), revealing users' perceptions of interactions being easier to learn and use as the mission progressed. Overall, all UXT ratios evolved towards higher values as the mission progressed. However, this was not the case for their perceived importance; see Figure 3b. For example, the perceived importance of Stimulation started at 1.03 on Sol-4 and decreased slightly at 1.00 on Sol-8 before increasing to its maximum value, 1.23, on Sol-12. While the importance of Novelty was evaluated to be inferior on Mars compared to Earth, it increased from Sol-4 to Sol-12 by 26% and 39%, respectively. Adaptability remained consistent throughout

the entire experiment, yet perceived of higher importance when evaluated on Mars, a finding that supports prior theoretical developments on adaptive performance in SpaceCHI [26]. Finally, four of the UXT measures evaluated in our study (Trust, Usefulness, Intuitive Use, and Trustworthiness) were consistently rated as having lower importance when the interactions were performed in Mars conditions compared to Earth.

These findings reveal different UXT trends in environments with different characteristics compared to Earth. The various UXT ratios, either below or above 1 (where 1 indicates equivalent UX on both Mars and Earth), suggest different ways in which the experience of interactions varies interplanetary. Note that the environment undergoes significant changes and, therefore, the interaction design must match user expectations of the new “reality” on another planet, following reality-based interaction [13]. However, the user’s abilities essentially stayed the same during the 12-day mission, directly transferring to another environment. Wearing specialized suits and living in unconventional habitats are examples of SRs [35] mediation that transpired in the different UXT trends and the relative importance of UX measures on Mars vs. Earth observed in our study. In this context, where direct transfer of ability-based design [39] may be interplanetary feasible, ability-mediating [35] approaches are equally needed.

Although our results are preliminary, they suggest the opportunity of extending the applicability of current interaction design frameworks that emphasize users’ abilities and environments’ characteristics—ABD [39], RBI [13], and SRs [35], developed within the Earth-centered perspective,—through the prism of *relative* user performance and experience. This possibility would enable designers to evaluate interactive systems under Earth conditions and subsequently apply transfer coefficients to estimate user performance or experience in another physical environment through *interplanetary models of interaction*. Such an approach has several implications for researchers and practitioners, including new research into interplanetary interaction design frameworks, development of interplanetary applications, and running user studies and conducting evaluations that capitalize on concepts of relative user experience and transfer of interaction knowledge, including natural modalities such as gesture-based interaction with computer systems [34], across different physical environments representing different contexts of use. However, while this hypothesis seems promising, it needs validation in further experiments to reveal whether the principles and rules of current interaction frameworks developed within a Earth-centered perspective transfer well, via proportional relativity, to other environments with the Earth considered as a baseline. Furthermore, the very notion of context of use [4] may need revisiting for new relevant dimensions in the interplanetary perspective.

5 CONCLUSION AND FUTURE WORK

Interaction design for computer systems meant for operation on other planets presents new challenges that require proper frameworks that feature interplanetary transfer of design knowledge, beyond mere user interface guidelines. In this work, we discuss three interaction design frameworks that present potential in this direction by emphasizing *users through their abilities and environments through their physical characteristics* as two key elements in

the context of the use of interactive interplanetary systems. We argue that as humanity advances in its quest for colonizing space, prioritizing research on interplanetary interaction design for computer systems intended to support life, work, and communications on other planets is key to ensuring the success and sustainability of the colonization endeavor. Interesting future work is extending current frameworks with dimensions for interplanetary transfer of design knowledge, such as to arrive at models that estimate user performance and experience with interactions performed in other planets’ environments with respect to Earth, e.g., in terms of relative performance effort or perceived experience. Participatory design scenarios conducted in specialized facilities, such as during missions at MDRS, are equally recommended. Furthermore, we look forward to more studies involving evaluations of interactions conducted in diverse physical environments, simulating physical constraints that would be experienced on other planets.

ACKNOWLEDGMENTS

This paper received support from the EU EIC Pathfinder-Awareness Inside challenge “*Symbiotik*” project under Grant no. 101071147 and from “Fonds de la Recherche Scientifique—FNRS” under Grant no. 40004991.

REFERENCES

- [1] 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 SpaceCHI 3.0, A Conference on Human-Computer Interaction for Space Exploration (SpaceCHI 3.0)*. MIT Media Lab, MA, USA, 10 pages. <https://spacechi.media.mit.edu/spacechi-2023-program>
- [2] Gaëlle Calvary, Joëlle Coutaz, David Thevenin, Quentin Limbourg, Laurent Bouillon, and Jean Vanderdonck. 2003. A Unifying Reference Framework for multi-target user interfaces. *Interacting with Computers* 15, 3 (06 2003), 289–308. [https://doi.org/10.1016/S0953-5438\(03\)00010-9](https://doi.org/10.1016/S0953-5438(03)00010-9)
- [3] 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 (Perth, Australia) (WWW '17)*. International World Wide Web Conferences Steering Committee, Republic and Canton of Geneva, CHE, 273–281. <https://doi.org/10.1145/3038912.3052625>
- [4] Joëlle Coutaz, James L. Crowley, Simon Dobson, and David Garlan. 2005. Context is key. *Commun. ACM* 48, 3 (mar 2005), 49–53. <https://doi.org/10.1145/1047671.1047703>
- [5] 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 Pervasive Computing* 22, 2 (2023), 27–42. <https://doi.org/10.1109/MPRV.2023.3242667>
- [6] Sands Fish. 2018. How To Design Interplanetary Apps. Medium. <https://sandsfish.medium.com/how-to-design-interplanetary-apps-22ebefec097d>
- [7] 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>
- [8] 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
- [9] Marcin Frackiewicz. 2023. *The Role of Human Augmentation in Space Exploration*. LIM Center. <https://ts2.pl/en/the-role-of-human-augmentation-in-space-exploration/>
- [10] 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>
- [11] Linda Hirsch, Jingyi Li, Sven Mayer, and Andreas Butz. 2022. A Survey of Natural Design for Interaction. In *Proceedings of Mensch Und Computer 2022 (MUC '22)*. ACM, New York, NY, USA, 240–254. <https://doi.org/10.1145/3543758.3543773>

- [12] Sandra Häuplik-Meusburger and Sheryl Bishop. 2021. *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer Nature, Cham. <https://doi.org/10.1007/978-3-030-69740-2>
- [13] 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 SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 201–210. <https://doi.org/10.1145/1357054.1357089>
- [14] Lik-Hang Lee, Carlos Bermejo Fernandez, Ahmad Alhilal, Tristan Braud, Simo Hosio, Esmée Henrieke 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 2022 International Conference on Multimodal Interaction (ICMI '22)*. ACM, New York, NY, USA, 648–652. <https://doi.org/10.1145/3536221.3558174>
- [15] 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>
- [16] 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>
- [17] 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>
- [18] 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>
- [19] 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
- [20] National Aeronautics and Space Administration (NASA). 2014. Human Integration Design Handbook (HIDH). Revision 1. <https://www.nasa.gov/organizations/ochmo/human-integration-design-handbook>
- [21] 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>
- [22] 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>
- [23] Amelie Nolte, Jacob Wobbrock, Torben Volkmann, and Nicole Jochems. 2022. Implementing Ability-Based Design: A Systematic Approach to Conceptual User Modeling. *ACM Trans. Access. Comput.* 15, 4, Article 34 (oct 2022), 26 pages. <https://doi.org/10.1145/3551646>
- [24] 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>
- [25] Laurent Opsomer, F. Crevecoeur, J.-L. Thonnard, J. McIntyre, and P. 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>
- [26] 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=1vYNe4HXcDVMMeNn0X_IXWn7hCUXIDOKU
- [27] 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>
- [28] 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 2022 CHI 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>
- [29] Michael Saint-Guillain, Jean Vanderdonckt, 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>
- [30] 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>
- [31] 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
- [32] David Smitherman and Andrew Schnell. 2020. Gateway Lunar Habitat Modules as the Basis for a Modular Mars Transit Habitat. In *Proceedings of the 2020 IEEE Aerospace Conference*. IEEE, USA, 1–12. <https://doi.org/10.1109/AERO47225.2020.9172540>
- [33] 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 (2022). <https://doi.org/10.34133/2022/9841785>
- [34] Radu-Daniel Vatavu. 2017. Characterizing gesture knowledge transfer across multiple contexts of use. *Journal on Multimodal User Interfaces* 11, 4 (2017), 301–314. <https://doi.org/10.1007/s12193-017-0247-x>
- [35] 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>
- [36] Radu-Daniel Vatavu. 2023. From Natural to Non-Natural Interaction: Embracing Interaction Design Beyond the Accepted Convention of Natural. In *Proceedings of the 25th International Conference on Multimodal Interaction (ICMI '23)*. ACM, New York, NY, USA, 684–688. <https://doi.org/10.1145/3577190.3616122>
- [37] Radu-Daniel Vatavu. 2023. Leveraging Sensorimotor Realities for Assistive Technology Design Bridging Smart Environments and Virtual Worlds. In *Proceedings of the 16th International Conference on Pervasive Technologies Related to Assistive Environments (PETRA '23)*. ACM, New York, NY, USA, 247–253. <https://doi.org/10.1145/3594806.3594834>
- [38] Jacob O. Wobbrock, Krzysztof Z. Gajos, Shaun K. Kane, and Gregg C. Vanderheid. 2018. Ability-based design. *Commun. ACM* 61, 6 (may 2018), 62–71. <https://doi.org/10.1145/3148051>
- [39] Jacob O. Wobbrock, Shaun K. Kane, Krzysztof Z. Gajos, Susumu Harada, and Jon Froehlich. 2011. Ability-Based Design: Concept, Principles and Examples. *ACM Trans. Access. Comput.* 3, 3, Article 9 (apr 2011), 27 pages. <https://doi.org/10.1145/1952383.1952384>
- [40] World Health Organization. 2023. *Disability*. WHO. <https://www.who.int/news-room/fact-sheets/detail/disability-and-health>
- [41] 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>