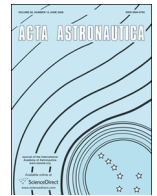




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# Humanly space objects—Perception and connection with the observer<sup>☆</sup>

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## ABSTRACT

Expanding humanity into space is an inevitable step in our quest to explore our world. Yet space exploration is costly, and the awaiting environment challenges us with extreme cold, heat, vacuum and radiation, unlike anything encountered on Earth. Thus, the few pioneers who experience it needed to be well protected throughout their spaceflight. The resulting isolation heightens the senses and increases the desire to make humanly connections with any other perceived manifestation of life. Such connections may occur via sensory inputs, namely vision, touch, sound, smell, and taste. This then follows the process of sensing, interpreting, and recognizing familiar patterns, or learning from new experiences. The desire to connect could even transfer to observed objects, if their movements and characteristics trigger the appropriate desires from the observer. When ordered in a familiar way, for example visual stimuli from lights and movements of an object, it may create a perceived real bond with an observer, and evoke the feeling of surprise when the expected behavior changes to something no longer predictable or recognizable. These behavior patterns can be designed into an object and performed autonomously in front of an observer, in our case an astronaut. The experience may introduce multiple responses, including communication, connection, empathy, order, and disorder. While emotions are clearly evoked in the observer and may seem one sided, in effect the object itself provides a decoupled bond, connectivity and communication between the observer and the artist-designer of the object. In this paper we will discuss examples from the field of arts and other domains, including robotics, where human perception through object interaction was explored, and investigate the starting point for new innovative design concepts and future prototype designs, that extend these experiences beyond the boundaries of Earth, while taking advantage of remoteness and the zero gravity environment. Through a form of emotional connection and design, these concepts will focus on the connection and brief emotional bond between a humanly animate object in space and a co-located observer in spaceflight. We conclude that beyond providing creative expressions for humanly contacts, these experiences may also provide further insights into human perception in spaceflight, and could be tested on the International Space Station, and serve as a stepping-stone towards use on long-duration spaceflight to Mars.

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## 1. Introduction

Our desire to explore the world around us will soon take us to distant parts of our solar system beyond Low Earth Orbit (LEO). These plans, including human exploration of

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Mars, are both exciting and dangerous, while long-duration spaceflight can be also lonely and lack stimulation or variety. Aside from being costly, future explorers will encounter extreme environmental conditions, from the extreme cold of space, heat from the Sun, vacuum, zero gravity, and both solar and galactic radiation. Human habitats during the Earth to Mars transit, and on the surface of Mars must provide protection for these explorers, which can be addressed through appropriate technological and engineering means. Over the past five decades significant research effort have been dedicated to also understand physical and psychological challenges of spaceflight. These studies mostly focused on the medical and technological aspects while the human factors and humanly connections have been less explored, especially on long-duration spaceflight lasting for years. At the same time, isolation and monotony heighten the senses and increase the desire to make connections with humanity and with any other manifestation of life. These necessary psychological connections may occur via sensory perception, including vision, touch, sound, smell, and taste. The sensory input is then interpreted through cognitive processes, where it is categorized into familiar or new patterns and experiences [29].

At times, this desire to connect could even transfer to non-living observed objects, if their movements and characteristics trigger the appropriate recognitions and responses from the observer. Visual or other sensory stimuli, such as lights and movements of an object, may create a perceived real bond with an observer. It can also evoke the emotion of surprise or confusion, when the expected behavior of the object changes to something no longer predictable or recognizable. Designers and artists, the target audience for this paper, can build physical characteristics, behavior patterns, and autonomy into objects and artifacts, which can benefit and entertain astronauts on long-duration spaceflight. The experience may elicit physical and emotional responses from the observer, including the feelings of communication, connection, empathy, order, and disorder. Through a form of artistic expression and design, future concepts could focus on the connection and brief emotional bond between a humanly animate object in space and a co-located observer in spaceflight. When we extend the observer-object framework to three actors, and include the designer, we can identify a decoupled bond that includes connectedness and communication, between the designer or artist, and the observer through the object. The scale of an artifact could vary from a small interactive object to a large multi-component and fully immersive system, for example a space habitat. Beyond the artistic expression of the designer-artist through an object or artifact, and the resulting experiences by an astronaut, experimentations in human-object interactions may provide further insights into human perception and cognition during spaceflight.

In this paper we will first introduce a range of foundational concepts, such as tacit knowledge by Michael Polanyi [28], cognitive development by Jean Piaget [27,29], cybernetics and its circularity by Norbert Wiener [32], variety by William Ross Ashby [3], and affordances by James Gibson [6,7] and Don Norman [22,23]. We will use these to discuss underlying considerations that may benefit future designers

and artists. In the next step we will provide contemporary examples from artists, designers, engineers, and other domains and draw attention to various aspects of their works that align with principles and approaches considered in our conclusion. The examples include: the Light and Space movement by James Turrell, Robert Irwin and Doug Wheeler [13]; multi-sensory viewer experiences by Olafur Eliasson [5], Nelly Ben Hayoun [1], and Anna Hill [30]; space-related artistic interpretation and scientific visualization by Richard Clar [2], and Dan Goods [8]; the creation of a new schema through animated mechanisms by Theo Jansen [11]; connecting the designer and the observer through design experiences, and performances by Ayako Ono [24], Mariko Mori [14]; emotional design and user experience by Ortíz Nicolás [25]; robotic collaborations with the observer and empathy by Guy Hoffman [9]; robotic interactions with the astronauts and the space environment at NASA-JSC [20]; habitats as large and immersive interactive environments at NASA [21]; and science fiction as a vision to the future.

These examples and the subsequent discussion can serve as a point of departure for conceiving new artistic and design concepts, and future prototype designs, which may extend these experiences beyond the boundaries of Earth, while taking advantage of remoteness and the zero gravity environment. Prior to infusion into long-duration spaceflight to Mars, these experimentations could be performed on the International Space Station (ISS), through the ISS utilization program.

## 2. Foundational concepts

Artists and designers create artifacts, which interact with the observer, thus communicating through the object. Through this communication knowledge is transferred. But the process also raises several interesting questions. For example: what do we know? How do we know what we know? What is real? Who decides what reality is? Or more specifically: what is the minimum desirable level of daily humanly interaction on long-duration spaceflight? Does this vary between different cultures, races, sexes, life stages, and other factors? These are just some of the fundamental questions that drive our understanding and search for meaning. Over our human history branches of philosophy were dedicated to answering them, which also included other connected and derived fields. In connection with our paper's topic, we will briefly discuss foundational concepts, including Polanyi's tacit knowledge [28], Piaget's schema [27,29], Wiener's cybernetics [32], and Gibson's affordances [6,7]. These introductions will be brief, but aim to establish the main concepts while subsequently discussing art and design examples, and some principles that can contribute to the design of new artifacts for the space environment, interacting with the astronauts, the observer.

### 2.1. Tacit knowledge

In his book, titled "Tacit dimensions", Michael Polanyi introduced the term "tacit knowledge" as opposed to explicit knowledge [27]. As Polanyi stated: "we can know more than we can tell". He discussed Meno's paradox by

Plato, about the search for a solution to a problem, where we either know what the problem is, then we know the solution, or we do not know what the problem is, then we wouldn't know what we are looking for. Tacit knowing addresses this hidden knowledge. Tacit knowing could account for (a) a valid knowledge of a problem, (b) the person's capability to pursue it, guided by its sense to approaching its situation, and (c) a valid anticipation of the yet indeterminate implication of the discovery arrived at in the end. Polanyi also discusses the hierarchy and emergence of knowledge. We have underlying unprocessed and interconnected pieces of information, which we may call intuition or gut feeling. Tacit knowledge is unarticulated and intuitive, that can't be communicated easily. It can be acquired only through experience within a relevant context. It is considered a personal knowledge, but it can be transformed into explicit knowledge by codifying, articulating or specifying it. Connecting experiences with tacit knowledge can play an important role for the designer in the design process, where prototyping can result in new insights and the emergence from tacit to explicit knowledge. It can also play a role for the observer when looking at the actions of the designed object.

## 2.2. Cognitive development

The theory of cognition and human intelligence development was first constructed by Jean Piaget, a Swiss developmental psychologist [27,29]. While Piaget's focus was to discover the developmental stage theory of children, he also addressed the nature of knowledge, including its acquisition, construction and use. Children think about the world around them differently from adults, as they learn and acquire knowledge differently through cognitive development. For example, in this process—at times—they may talk to animals and inanimate objects, and attribute life to them. Piaget labeled this animism. He also explored other concepts about childhood development processes, related to logic, language, space and time, and play, among others. Piaget contributed experience and interaction as key elements of cognitive child development. Through a constructivist approach, he theorized that knowledge is developed gradually, in stages, and by constructing and understanding of the world through sensory experiences and interactions. Alignments and discrepancies with building blocks of intelligent behavior and knowledge (schemata) influence interpretation and learning.

A schema organizes categories of information and the relationships within Piaget [27]. In one's mind each schema relates one aspect of the observed world, which can be artifacts, actions, or abstract concepts. The interaction between the object and the observer is achieved through sensory perception, which includes three distinct interconnected elements: (1) the object itself; (2) the observer's sensory system (including vision, auditory (hearing), somatic sensation (touch), gustatory (taste), olfaction (smell) and vestibular (balance/movement)); and (3) the neural pathways of the brain involved with sensory perception. Cognitive processes include perceiving, remembering, believing, and reasoning. These steps may evoke emotions, which constantly intertwine with cognition. Interactions between the object

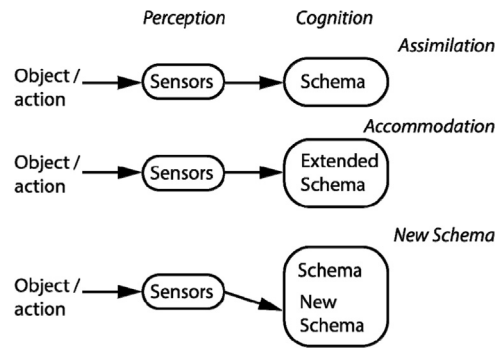


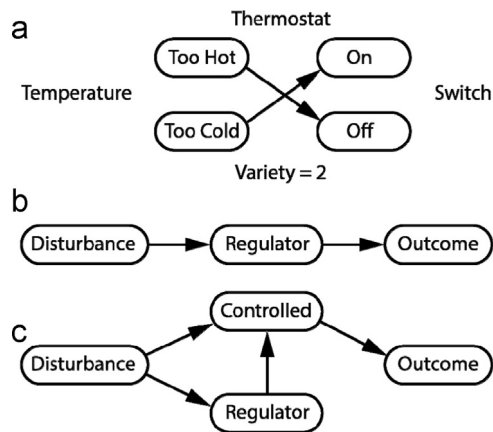
Fig. 1. Illustration of sensory perception and cognition, including assimilation, accommodation and creating a new schema.

and the observer are achieved through three complementary processes, namely assimilation, accommodation, and creating a new schema. In the case of assimilation, interaction with the object is approached through previous experiences of the observer, and if there is an alignment, then the new experience will become part of the existing schema. Accommodation requires revision of the old schema to fit the new experiences. When these two approaches do not work, the observer is required to create a new schema to interpret the new experience (see Fig. 1). The sequential process of assimilation, accommodation and creating a new schema is part of the process of experiencing and learning, and may evoke a range of emotions in the observer, including surprise, joy, and frustration. Designers and artists utilize this approach, either consciously or subconsciously, and build it into their artifacts. We could also use this approach for humanly space objects.

## 2.3. Cybernetics

Cybernetics can be described through its circularity. The father of cybernetics, Norbert Wiener, defined it as “the scientific study of control and communication in the animal and the machine” [32]. It is a multidisciplinary approach for the exploration of regulatory and control systems, including their constraints, potentials, and structures. It can be used in closed signal loops, where an action of an object in the system generates a response in its environment, which could trigger a feedback loop, resulting in a circular causal relationship. This interaction is relevant in the design phase of an object, where prototyping cycles provide this iteration loop, and may converge towards an optimal outcome. Another circularity exists as the observer tries to interpret the object's actions through continuous sensory sampling, thus accumulating knowledge about the object. Design thinking, systems thinking, and integrative thinking, including scenario prototyping, can stimulate new ideas, resulting in an emergence of tacit knowledge to communicable knowledge, and new options (also when relevant, strategic advantage).

In the cybernetics framework, variety describes the total number of distinct states of a system. This could be further illustrated through Ashby's law of requisite variety by William Ross Ashby (see Fig. 2), which states that “variety can destroy variety”. Specifically, in order for a system to effectively control another, it must have at least as much variety as the system it is to control, otherwise the



**Fig. 2.** Ashby's law of requisite variety. (a) Illustration of the requisite variety of a thermostat; (b) the role of the regulator (e.g., an engineer) in the variety of a linear disciplinary system; and (c) the role of the regulator (e.g., the designer/artist) in the variety of a multi-disciplinary system.

control is considered restrictive. As an example, we can consider a thermostat, with an on and off switch. If the temperature is too hot it switches off, and if it is too cold, it switches on. The variety of the regulator is 2, resulting in 2 states for the controlled (Fig. 2a). For a linear disciplinary field, such as engineering, the variety is tightly controlled, and the disturbance—or the problem to be solved—is filtered by the regulator's degree of variety, resulting in a well-defined outcome (Fig. 2b). This is a typical approach used at NASA during technology development projects, as discussed below for the robotics and habitats project examples. Designers on the other hand can introduce an iterative and integrated system level approach, thus broadening the requisite variety to achieve a more optimal design (Fig. 2c). In this paper we discuss systems with three actors. It includes the designer, the artifact, and the observer, where the designer acts as a regulator, and the message is communicated to the observer through the requisite variety of the artifact as a medium. (The requisite variety of an object is defined by the regulator.) Consequently, the designer is key to influence the perception of the observer, while the experience of the observer is defined by the interaction between the artifact and the observer's schema. In effect, the process of regulation is similar in character to the shaping of perception. (Note: the theorem of a good regulator was conceived by Roger C. Conant and W. Ross Ashby [3], and considered central to cybernetics.)

#### 2.4. Affordances

The term “affordance” was introduced by the American psychologist James Gibson in his article, titled “The Theory of Affordances” [7]. It refers to one or multiple opportunities or possibilities for interaction, provided by a particular object or environment. These action possibilities can be measured objectively in a latent environment, and does not have to be known or recognized by the observer. Also, they do not have to be visible, perceivable or even desirable. Affordances are always expressed through their dependences on the observer. They are circular relationships, relating some types of

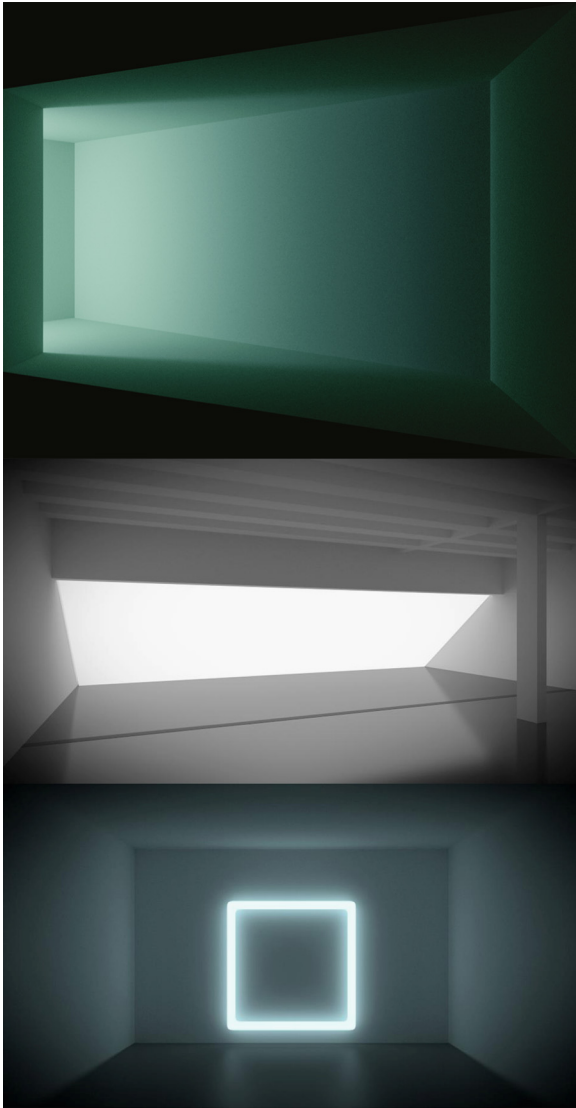
attributes of the environment to interactivity potential by an agent, which in turn aligns and relates back to the environment, which has relevant affordances. For example, a high bookshelf provides affordance for a tall person. The same bookshelf is out of reach for a child, without having the same affordance. The concept of affordance has been very influential in a number of fields, including design, visualization, human–computer interactions, ergonomics, and others. It also influenced how we consider visual perception. Looking at it from the environmental psychology point of view, perceiving the environment leads to action, and affordances provide clues for the observer, indicating possibilities for an immediate action without requiring sensory processing. For example, a lamp-post provides an affordance of walking into it, while the moving observer subconsciously can avoid the collision based on existing knowledge of the potential outcomes. (Gibson's breakthrough idea was the realization that “our heads are in the world” as our interpretation and construction of it are triggered by affordances, rather than “the world is on our heads” as it is perceived.) Other examples include buttons, knobs and levers, where the observer instinctively knows how to operate them.

Don Norman developed an extended view of the concept of affordance, assuming dependence on culture, prior knowledge, and personal expectations [23]. Compared to Gibson, Norman uses perceived affordances (which may not even actually exist), where the appearance of an artifact could provide critical clues about it. Norman also introduced signifiers to guide the observer about how to interact with the object and utilize its affordances. His combination of affordances and signifiers could make an action easy or difficult.

Designers have to consider how to create a perceivable conceptual model to fit the artifact into the observer's schema; what type of guidance should be provided about its usability; and how to align the artifact's affordance to the knowledge of the observer, especially if the observer has not seen the artifact before. The designer/artist can also introduce “false affordance”, where no affordance is implied, but no action is possible (e.g., having a thin wire chair that does not support any weight). Design feature can also connote cultural differences, differentiation or entertainment. Another option is using “hidden affordance” where the information about the affordance is not available (e.g., a hidden drawer). This approach could be a useful tactic on a long-duration spaceflight, slowly revealing hidden affordances to enable continuous stimulation from humanly space objects. They could be stimulated over time or by user expertise, and even by boredom levels.

#### 3. Contemporary examples from artists, designers, and engineers

The fields of arts, robotics, user experience design, human factors, habitat design, and related space technologies are too broad to provide a concise overview in this paper. Instead, we have chosen a number of representative examples to illustrate contemporary work from arts, design, and engineering, related to interactions between the observer, the object and the artist or designer. The listed examples link also the designer with the observers through the underlying concepts listed in Section II. In this paper we can differentiate between art and



**Fig. 3.** Blender3D renderings by T. Balint after: (top) James Turrell, “Wedgework” (1969); (middle) Robert Irwin, “Slant/Light/Volume” (1971); and (bottom) Doug Wheeler, “M669” (1969).

design (a) about space (where space can be either volumetric or a location above and beyond Earth), (b) for space on Earth, and (c) in space. These considerations could include art, design, and entertainment at any scale, from a small artifact to a whole space habitat.

### 3.1. Light and space by James Turrell, Robert Irwin and Doug Wheeler

The Light and Space movement originated in Southern California in the 1960s. It focused on the perception of light, large volume, and scale. To highlight these goals, it typically used a combination of glass, fluorescent light, neon, and reflective surfaces with resin and cast acrylic. The artists played with light directionality, shadows, combination or natural and artificial lights, transparency, translucency and reflectivity. They often incorporated the latest technologies



**Fig. 4.** “Weather Project” (2003) by Olafur Eliasson, installed at Tate Modern’s Turbine Hall, London.

from the aerospace industry, engineering and technology, and benefited from the proximity of these industries in Southern California. The movement consisted of a large group of artists, including James Turrell, Robert Irwin and Doug Wheeler (see Fig. 3).

Through their works, the artists investigated sensory deprivation or overload, which resulted in extreme retinal responses by the observer. They used light to create abstract shapes, without using actual materials. In turn this allowed the observer to perceive the light and shapes without over-emphasizing the physical aspects of an actual object. This representation highlighted the idea that the world around us is a mental image, perceived and interpreted by the human mind [13]. On long-duration spaceflight we could employ similar effects and approaches inside a multifunctional habitat to interact with the astronauts and create diverse moods between various modes, including work, rest, and exercise.

### 3.2. Multi-sensory observer experiences by Olafur Eliasson, Nelly Ben Hayoun, and Anna Hill

Olafur Eliasson is a Danish-Icelandic artist known for his large-scale installations, employing—often in combination—natural agents (e.g., light), elemental materials (e.g., water), and environmental conditions (e.g., temperature) to stimulate and enhance the viewer’s experience. For example, his



Fig. 5. “The Soyuz Chair” (2009) by Nelly Ben Hayoun.

“Weather Project” was installed at the Turbine Hall of the Tate Modern, London, in 2003 (see Fig. 4). In this project, Eliasson created a fine mist in the air, installed a large circular sun-like disc on the interior wall, made up of hundreds of monochromatic lamps, radiating a yellow-orange light. Furthermore, the ceiling of the hall was covered with a huge mirror, allowing the visitors to see themselves from afar through the mist and in the orange light. This panoramically immersive experience included an abstractionist translation of the schema of a sunset. The mist provided a measure to sense the immense volume, while the mirror helped the observer to interact with the environment [5]. On long-duration spaceflight the habitat volume is constrained. Changing the perception about volume and mood could benefit the physiological and psychological wellbeing of the astronauts.

Nelly Ben Hayoun is an experience designer and award-winning director. She works with leading scientists and engineers, to devise subversive events and experiences. Her Soyuz Chair project [1] was developed in collaboration with the astronaut Jean Pierre Haignere. This installation accurately provided an immersive experience to the observer through the reproduction of all 3 stages of a Soyuz rocket launch. The chair oriented the observer into a reclined position, facing the sky. It included a headset for the sound, a control panel to select between a single stage or all 3 stages of a launch, and speakers to simulate the vibration (see Fig. 5). While spaceflight to date is limited to about 500 people only, such installations could translate these experiences to a broader audience.

Anna Hill is an interactive artist, who earned an MA in Fine Art Sculpture from RCA. She integrates science, imagination, and indigenous knowledge to promote emotional connection to our environment, and works with astronomical science through interdisciplinary collaborations with

space scientists, architects, designers, and communications experts. She founded the company Space Synapse Systems Ltd., and participated in the European Space Incubator Initiative, which included a feasibility study funded by the European Space Agency. The goal was to communicate the human experience of space travel to the public. The study included a Symbiotic Sphere for space interaction design; a Remote Suit to share the space experience with the wearer; the Space Synapse System to share telemetry from space-based satellites, probes, and astronauts to Earth; and participatory platforms for educational outreach, interactive exhibits, and for the online community [30].

### 3.3. Space-science art and visualization by Richard Clar and Dan Goods

Richard Clar is a new media interdisciplinary artist, and an early pioneer of art-in-space, who began work in this field in 1982 with a NASA-approved concept for an art-payload for the Space Shuttle. His work titled “COLLISION II: an orbital debris constellation sculpture” [2] depicts 192 orbital debris objects in LEO from all space-faring nations. The orbits were calculated by a supercomputer, and set against the 10,000-objects space debris catalog. The video, produced by the Naval Research Laboratory, depicts a 12 h period, viewed from LEO and geosynchronous orbits (see Fig. 6). The work communicates the negative impact of space exploration as our activities spread outside the boundaries of Earth.

Dan Goods is the Visual Strategist at NASA’s Jet Propulsion Laboratory, in Pasadena, CA, and has his own art practice through public and private art commissions around the world. He graduated from the Art Center College of Design, Pasadena, CA. In his “Hidden Light” project (2005), the goal was to communicate the

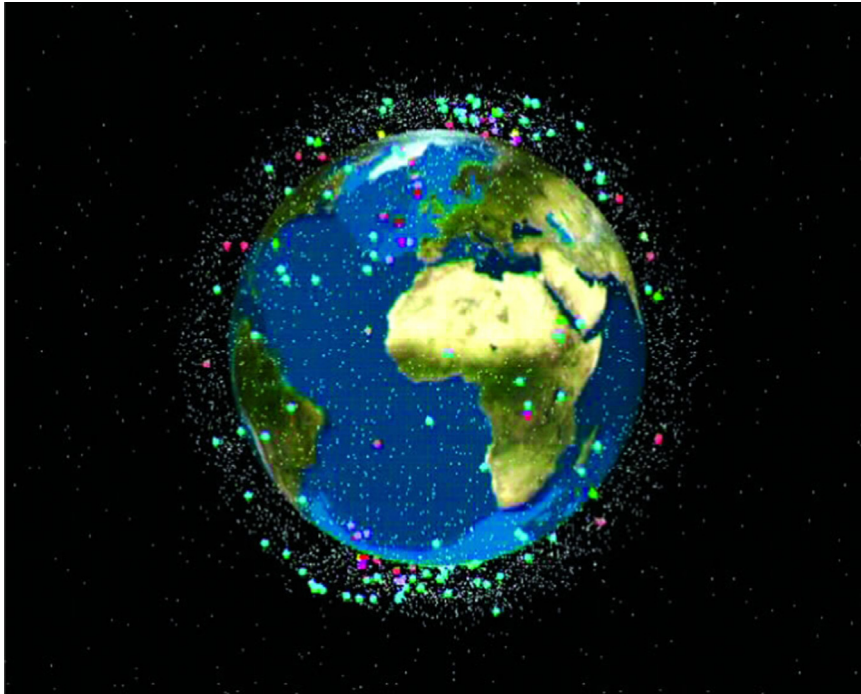


Fig. 6. "COLLISION II: An orbital debris constellation sculpture" (2003) by Richard Clar.



Fig. 7. "Hidden Light" project (2005) by Dan Goods.

difficulties of terrestrial planet finder missions, where the light of a planet is obscured by the billion times brighter sun it is orbiting. The installation demonstrates the concept of "seeing the unseen", by projecting a movie of planets to a large wall surface and at the same time over-projecting a much brighter pixelated movie that is reminiscent of the active solar surface (see Fig. 7). In effect, the image of the "sun" washes out the image of the planets. As the observer walks in front of the "sun projector", the human shadow on the wall blocks out the sun's image and reveals the much dimmer image of the planets. Shadows from more people reveal more of the planetary movie images. This interactive display communicates knowledge in an abstract form about scientific and technology principles, and involves the observer with the observed events, as a regulator. In a cybernetic sense, there is a circular loop

between the observer and the observed. The observer acts as a regulator, and with the projection of shadows refines the interpreted knowledge. The activity is also entertaining, and lends itself for other activities, including shadow play, which may or may not have been considered by the artist at the initial conception of the installation [8]. Visualization of scientific principles about space is important to communicate knowledge clearly to a broader audience in a direct or stylized manner.

#### 3.4. Creating a new schema through animated mechanisms by Theo Jansen

Theo Jansen is a Dutch artist who is building large self-animated truss mechanisms, known as "Strandbeest" (see Fig. 8). As Jansen stated in a BMW car commercial: "The walls between art and engineering exist only in our minds." His creations have built-in artificial intelligence to avoid obstacles by course adjustment upon detection. These Strandbeests, while clearly machines, resonate with the observer as their movements, hesitations evoke recognition within the observer's schema of animals. The perception chain may sweep through multiple phases. At first it captures the familiar movement within an existing schema, followed by an attempted accommodation within a schema. Once recognized as an outlier, a new schema is created for this multi-legged, moving, still lifeless, but animal-like animated object, which falsely projects self-awareness [11]. Blurring reality between what is alive and what is not may provide exciting stimuli to astronauts, and exemplifies the process of creating a new schema.



Fig. 8. A “Strandbeest” by Theo Jansen.



Fig. 10. “Wave UFO” (1999–2002) by Mariko Mori.



Fig. 9. “Space Musical Instruments—Cosmic Seeds” project (2009–12) by So Negishi and Ayako Ono; a pair of musical instruments flown on the ISS.

### 3.5. Connecting the designer and the observer through space inspired artifacts by Ayako Ono and Mariko Mori

Ayako Ono is working in the fields of fine arts, design, architecture, and behavior science, in which she holds a Ph.D. Her project, titled “Space Musical Instruments—Cosmic Seeds”, was co-designed with a metal artist, So Negishi, in 2009 [24]. It consisted of a pair of musical instruments suitable for weightlessness. The instruments were called “Ellipsoid Bell” and “Fractal Bell” (see Fig. 9). The project was selected by the Japan Aerospace Exploration Agency (JAXA) under the Cultural and Artistic Utilization of the International Space Station (ISS/Kibo) theme. This pair of musical instruments was played on the ISS by Daniel C. Burbank, the Expedition 30 commander, on February 10, 2012. One of the two pieces of music was composed by Jaakkoo Saari, called “Dream Starts”, and the other by Akira Takahashi, titled “Kiyoraka na sora”. The astronaut played the music multiple times for 15 min and improved his skills beyond the procedure manual. The performance included both procedural play and improvisations. The project combined a physical artifact, which was both an artistic object and an interactive instrument. It provided textural and

auditory interaction with the observer. The object and the sound linked the observer to both the designers and the composers, who were spatially and temporally disconnected. Through the performance the astronaut had a direct connection with Earth and its culture. Similar objects could provide entertainment on long-duration spaceflights.

Over the past century technological innovation drove societal advancements, especially in first world countries [4]. The Japanese artist, Mariko Mori, used state of the art (SoA) technologies, including advanced materials (with a fiberglass exterior and polyurethane interior), software, and biofeedback control of images, to create an interactive experience through a terrestrial installation, called “Wave UFO” (see Fig. 10). The inside of the installation, accommodating three people at a time, morphs to body shapes. The installation measures 34 by 17 by 14 ft. In its futuristic shape, form and functionality the object represents a Buddhist vision of Nirvana [14]. Objects and installations of this type are thought-provoking and contemplative, while connecting the artist with the observer through interactive experiences.

### 3.6. Emotional design and user experience by Ortíz Nicolás

Emotional design relates to the hierarchy of user needs, from functionality, through usability, to pleasure [12]. Connecting to the pleasure element of this hierarchy, Ortíz Nicolás (from the Imperial College, London) reported a foundational investigation on pleasant user experiences through human–object interactions [25]. Through four empirical studies, he characterized the observer’s pleasant experiences with an object. He identified 25 positive emotions and ranked them through the perspectives of both observers/users and designers, and four relevant connected issues for product design. The four issues were: frequency and preference of the experience (from the side of the observer/user), and preference and difficulty of elicitation (from the side of the designer). Designers highly ranked the emotions of: curiosity, joy, surprise, confidence, inspiration, fascination, satisfaction and pride. Observers/users’ ranking of emotions included: satisfaction, inspiration, joy, amusement, and relaxation. Infrequent emotions that affected only one side were: lust and worship. He



found that there is limited knowledge in the field about the difficulty of eliciting positive emotions through durable objects. Ortíz categorized three levels for arousal and for pleasantness of emotions. For arousal these were: exciting, neutral and calm emotions. For pleasantness he included pleasant, quite pleasant and very pleasant emotions. In addition, he addressed triggers, appraisal structures, thought-action tendencies, and thematic appraisals of the emotions. These findings are also reported in [26]. The knowledge gained from this research could inform and help designers and artists improve tools and processes to better convey positive emotions and experiences through their designs, from smaller scale objects/artifacts to full habitats. Emotional design could play an increasingly important role on long-duration spaceflight, where astronauts experience isolation, monotony, stress, and fatigue.

### 3.7. Robotic collaborations with the observer and empathy by Guy Hoffman

Guy Hoffman is an Assistant Professor in the School of Communication at IDC Herzliya, and co-director of the IDC Media Innovation Lab [9]. His studies and research in human–robot interaction at MIT and the Georgia Institute of Technology, computer science at Tel Aviv University, and animation at Parsons School of Design, NYC, provided a solid foundation for subsequent research in human–robotic interaction (HRI), collaboration, robotic cognition, anticipation and timing in HRI, multi-agent decision processes (MDP), non-verbal communication, entertainment, theater, musical performance robotics, and non-humanoid robotic designs. Dr. Hoffman's pioneering work on a human–robot joint theater performance, and improvising real-time human–robot jazz duet was combining technology with human–robotic interactions. For the theater performance [10] he used a robotic desk lamp (see Fig. 11a), that served as a non-anthropomorphic, collaborative robotic platform. With 5 DOF (degrees of freedom) a robotic arm mounted lamp evoked a personal relationship with the human partner, without resorting to human-like features. Similarly, working with Gil Wainbert at the Georgia-Tech Center for Music Technology, another non-anthropomorphic robot, Shimon, was performing collaboratively with a human in an improvisational jazz performance (see Fig. 11b), and in another case the robot collaborated with a rap artist [31]. The movements, timing, and gestures of the lamp and the robot as they interacted with the human companion evoked compassion, empathy, and the feeling of collaboration, which would be important considerations on long-duration spaceflight.

### 3.8. Robotic Interactions with the astronauts and the space environment at NASA

Over the past few years NASA has been developing two humanoid robots, Robonaut 2 (R2) and Valkyrie (R5). R2 (see Fig. 12) was developed by researchers at NASA's Johnson Space Center (JSC), in collaboration with General Motors and Oceanering [20]. This state-of-the-art (SoA) humanoid robot is highly dexterous, and consists of a number of systems, including vision, image recognition, sensors, tendon hands, control algorithms, and it has a strong technology spin-off



Fig. 11. Guy Hoffman's non-anthropomorphic robots. (a) The “Confessor” theater performance with the AUR lamp [10] and (b) collaborative performance with the robot “Shimon” [9].

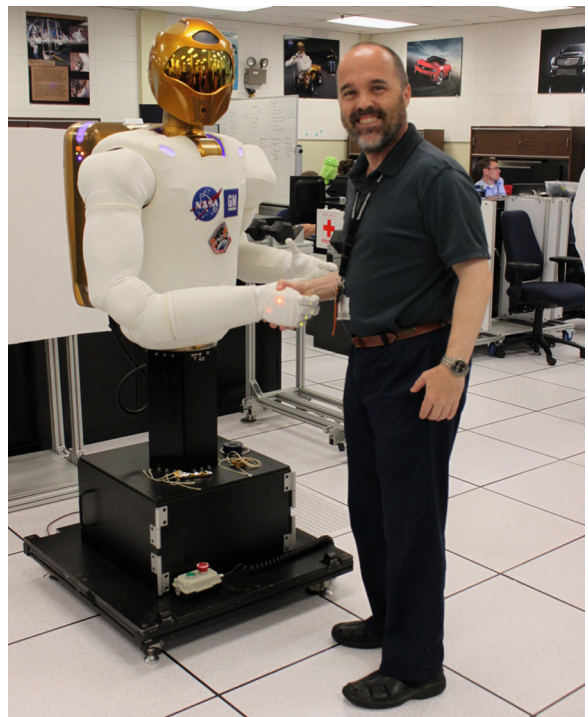


Fig. 12. NASA's Robonaut 2 humanoid robot with T. Balint at the Johnson Space Center.

potential to other fields. With its appropriate built-in safety measures, it can work alongside humans on the ISS, and perform repetitive tasks, from cleaning of rails to measuring air quality at various points of the station. The R2 upper torso recently received its legs, allowing it to move around inside

the ISS. The next-generation robot, NASA's Valkyrie (R5), is a 1.9 m tall, 125 kg, 44 DOF, battery-powered humanoid robot (see Fig. 13). It is also built at JSC, in partnership with the University of Texas, and Texas A&M, and with funding contribution from the state of Texas. Valkyrie was designed to perform perception-intensive, dynamic, and dexterous tasks during the DARPA Robotic Challenge on December 12, 2013. The task were performed semi-autonomously, where the robot generated a point cloud of its environment, and sent it to the team for analysis. Based on the results, the team relayed back sufficient information to the robot to autonomously carry out an appropriate action sequence. Both Robonaut 2 and Valkyrie were designed from an engineering point of view, to be functional in their environments and carry out their prescribed actions efficiently. These robots were not designed for the same type of human-machine interactions as Guy Hoffman's non-anthropomorphic robots, or for the types of emotional design discussed by Ortiz et al. [26] and Ortiz [25]. However, if we plan to explore distant planetary destinations with a combined crew of humans and robots, more human-centered interfaces would be desirable.

### 3.9. Habitats as large and immersive interactive environments at NASA

Over the past five decades there have been many space and surface habitat designs; some of them are shown in Fig. 14. Today the only operating space habitat is the International Space Station, shown in Fig. 15. Long-duration space flight to Mars drives the needs for crew



Fig. 13. NASA's Valkyrie (R5) humanoid robot.

habitation capabilities, which in turn trickles through the whole mission design [16–18]. Crew habitation modules are required during the cruise phase from the Earth to Mars and back (Fig. 16), and also on the Martian surface for which a ground demonstrator is shown in Fig. 17 [21]. These multi-purpose habitation modules could be rigid or inflatable. They must support diverse operational modes, including working, sleeping, eating, exercising, communicating, resting and entertaining. They also have to provide a safe environment that enables the crew and the system to respond to medical, environmental, technical, and other emergencies. Thus, the habitable volume must be large enough to execute the necessary tasks and to provide a psychologically acceptable space for the long period of confinement. The Design Reference Architecture 5.0 documents only briefly touch upon these requirements, including sensory stimulation to offset the physically and socially monotonous environment; monitoring systems to track cognitive performance; devices to mitigate fatigue, work overload and circadian misalignment; and communications tools accounting for time delays. The primary discussions in the DRA 5.0 focus on engineering solutions to solve life support, environmental protection and habitat design from a technological and engineering point of view. In addition, NASA and other national space agencies studied the psychological and medical impact of the space environment on the crew throughout the course of long-duration spaceflight [15]. Consequently, an opportunity exists for designers to address the multi-disciplinary aspects of such multi-functional habitats, targeting it from an integrated system level human-centered approach, rather than from a technical perspective.

### 3.10. Science fiction

Science fiction in literature, visual arts, and media has long been a beacon for projecting our imagination and expressing potential futures. They represent technologies in a human context, and highlight how they can transform our lives for better or worse. Many of the predictions are already around us, from rockets to computers, visiting distant planetary destinations or looking back on earth from geostationary satellites. These ideas also influenced design esthetics, user interface and interaction designs, style, form, function, philosophy, ethics, and provided both hope and fear about our future. The examples are too numerous to list in this paper, but we could highlight a few, from Isaac Asimov's three laws of robotics from the short story "Runaround" (1942), through Stanley Kubrick's HAL 9000 and the Space Station in the film "2001: A Space Odyssey" (1968), to Ridley Scott's vision of the future in the film "Blade Runner" (1982) based on Philip K. Dick's short story "Do Androids Dream of Electric Sheep" (1968).

## 4. Discussions

The examples from the previous sections illustrate a range of examples of how we can account for affordances, tacit knowledge, perception and linked schema, and the circularity of cybernetics to achieve a constructivist middle ground between the physical world and its interpretation

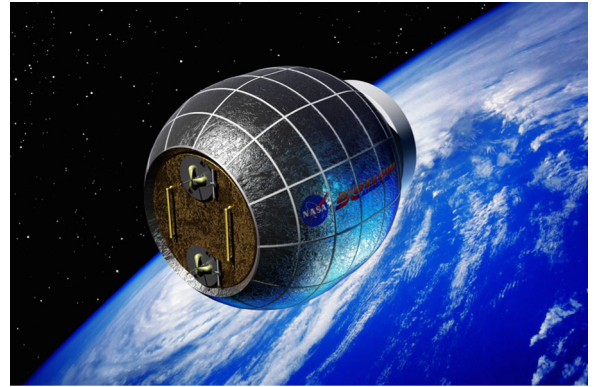
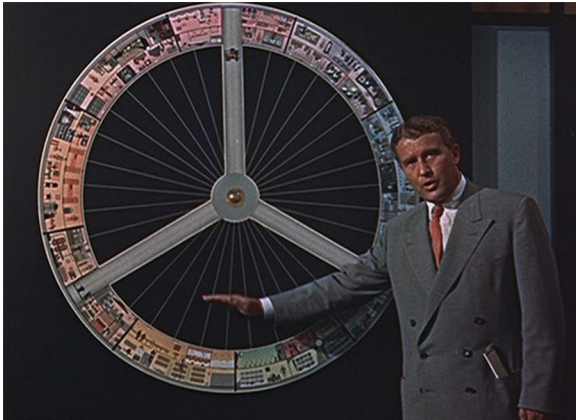


Fig. 16. Bigelow's expandable (inflatable) activity module concept.

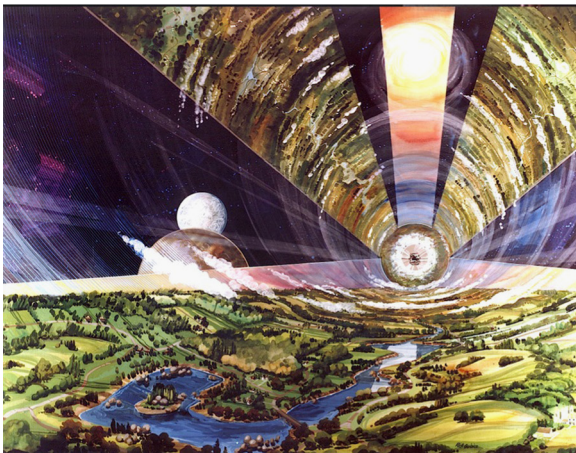


Fig. 17. NASA's X-hab ground demonstrator for a Mars surface module habitat.

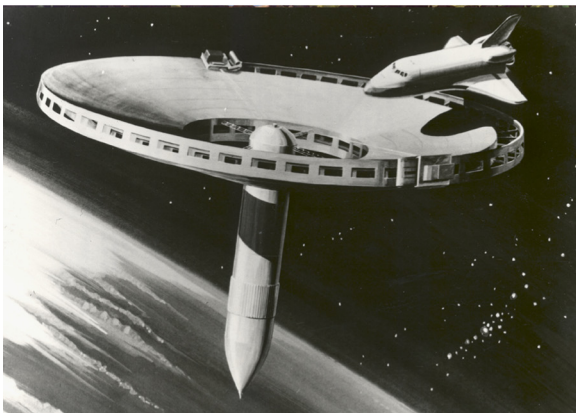


Fig. 14. NASA's early space station designs from the 1950s and the 1970s.

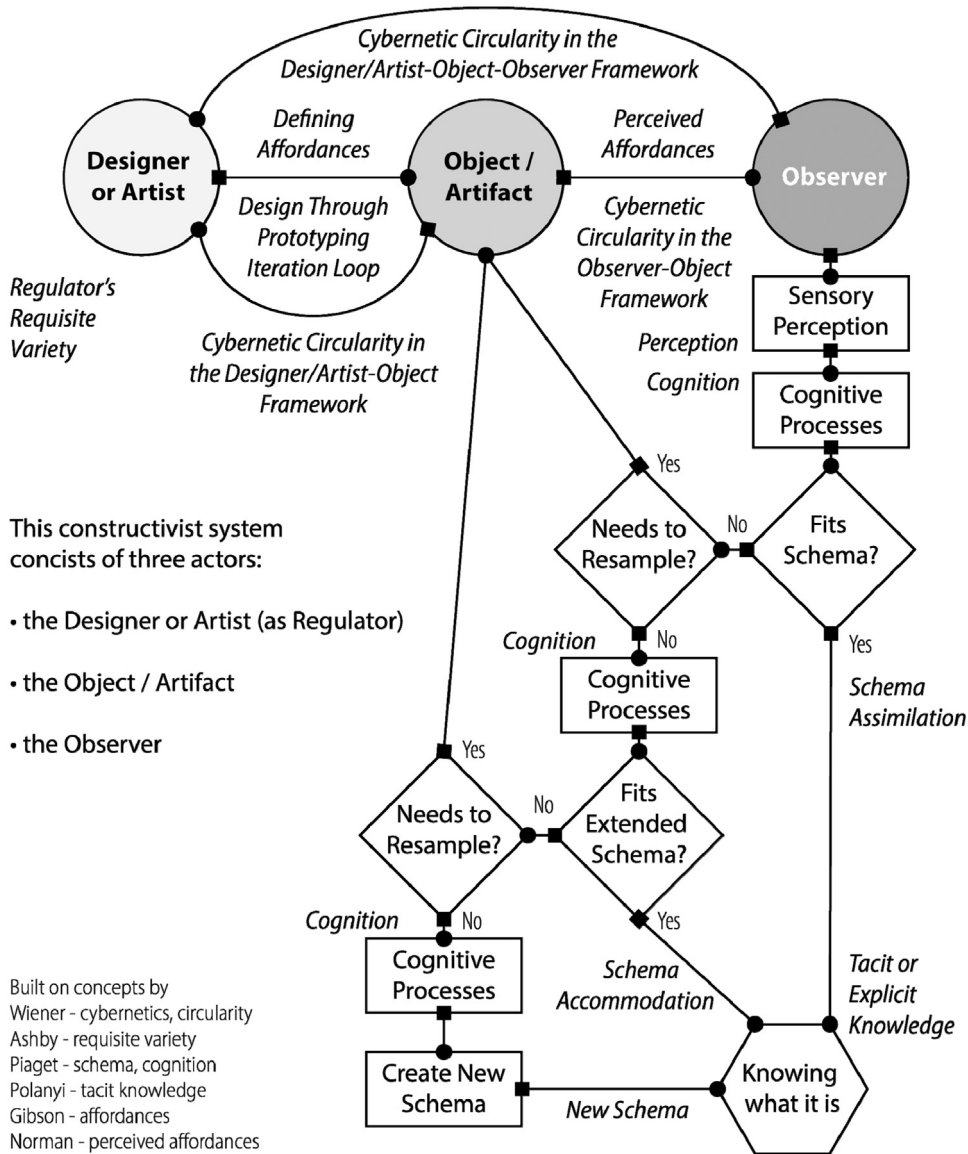


Fig. 15. The International Space Station, today's only operating space habitat at Low Earth Orbit.

by the observer. Consequently, when designing a new artifact the designer should consider one, multiple, or all of the principles discussed below, may it relate to a small object or the whole environment or habitat. (Note: throughout the discussions we are referring to an object not as an inanimate artifact, but a system capable of advanced performance and interactions via digital and other systems.) The design or artistic considerations could include, but are not limited to, the following attributes:

#### 4.1. Human–object interaction model with 3 actors

To illustrate the link between the designer or artist, the object or artifact, and the observer (for example an astronaut), we have created a simple constructivist system with 3 actors (see Fig. 18). We are proposing this interaction model, and will describe it below to illustrate how it connects with the foundational concepts discussed in Section II. The model also includes two sub-systems with two actors each, specifically the designer/artist and object/artifact system, and the observer/astronaut and object/artifact system. The observer interrogates the objects through sensory perception and relates to its movements and other characteristics to inner experiences (or schemata). The inquiry (or information sampling) consists of picking out clues from the object (e.g., via affordances, movements, colors). When a new experience from the



**Fig. 18.** A constructivist system with 3 actors: the Designer or Artist, the Object or Artifact, and the Observer (for example an astronaut). The model also includes two systems with two actors each, specifically the Designer/Artist and Object/Artifact system, and the Observer/Astronaut and Object/Artifact system.

interaction either fits into an existing schema or relates to the observer's tacit knowledge, an instantaneous connection may form. The longer and more sequentially or persistently the observer's schema aligns with the object's performance, the stronger the connection is. Furthermore, an expectation or desire may build in the observer to perpetuate this connection and anticipate the subsequent actions. At the same time the perception gap widens between the surprise element of the continuing connection with the object and the knowledge that the object's behavior is unpredictable—e.g., a leaf blown by the wind on the ground. If, however, the observer is interacting with a designed object, it may allow one to inquire into the mind of the designer by trying to resolve the puzzle that awaits, set up by the designer through the affordances of

the object. This decoupled system represents two loosely coupled connections. One between the designer and the object and another between the object and the observer. The clarity of the transferred information is also dependent on the shared knowledge base between the designer and the observer. Higher clarity may translate the designer's intention to the observer through the performance of the object. That is, the designer acts as a regulator, and the requisite variety and—real or perceived—affordances built into the object define the interactions and outcomes to be interpreted by the observer. The observer only sees the object's performance, as the designer is very likely both spatially and temporally decoupled from the observer and the performing object. A looser connection with the designer, or less restricting requisite variety,

may provide hints to the observer from the designer's perceptions, but it does not over-control the object, and allow for interpretation differences experienced from the observer. This adjustment of the object's requisite variety could change throughout the performance or interaction. For example, starting with a strong guidance, then transitioning into vagueness, or vice versa. From the designer's point of view, the processes of regulation of an object, that is the definition of its requisite variety, translates to the shaping of the observer's perception. From the observer's perspective, the recognition of the person (designer) in the performance (of the object) is a skill. One needs to recognize that a performance is being witnessed before trying to interpret it (see Fig. 18). The interaction between the designer or artist and the observer can be fully or loosely coupled, or decoupled. For example, during the prototyping iteration phase—consisting of divergence and convergence cycles—the designer may test the observer's response to the object, making the connection closely coupled. This allows the designer to identify various options and alternatives, and modify the object iteratively. The prototyping circularity helps align the schema of the designer with that of the observer. The designer acts as a regulator, and the requisite variety and affordances infused into the object results in the desired interpretation by the observer. In another case, the observer may provide feedback after the use of the object, which can give after-the-fact feedback to the designer, in a spatially and temporally decoupled manner. Here the designer is physically separated from the observer by large distances and time. The third option involves a fully decoupled connection, where the designer does not have any feedback from the observer at any point. This is the least desirable mode, as it does not transfer knowledge from the observer back to the designer that could be incorporated into future designs.

#### 4.2. Certainty versus uncertainty

The mind interprets the information, and creates a perception based on explicit or tacit knowledge formed around a schema. For example, as the observer looks at an object, he/she develops a mental construct about it. As a first impression, the observer relates the sensory information (visual, tactile, etc.) to previous knowledge (e.g., shape, color, texture, material etc.), then to other characteristics (e.g., behavior, movement). Is the collected information coherent? (E.g., an object is inanimate, while a living thing is animate.) When there is a mismatch, it causes the observer to feel an emotional or mental imbalance or non-equilibrium. This evoked uncertainty unbalances the already established and rigid schema for the object, which may not fit for the full framework, the schemata. In case of a mismatch, the observer may resample the object multiple times, or uses internal cognitive processes, until the experience fits to either an extended schema or a new schema (see Fig. 18). Clear communication is an important aspect of good design. If the method to use an object/artifact is not obvious, and the users cannot use it, it will be quickly ignored or even rejected. Thus the designer needs to include appropriate information about the usability and understandability of an object/artifact. Using a suitable schema (or conceptual

model), the observer/user can be guided through the usage by providing clues about correct usage. Good communication by the designer to the observer through the object is important where the goal is knowledge transfer. For this, affordances and signifiers can play an important role. An object can have both real and perceived affordances and these do not need to be the same! The designer/artist can design an object that either guides or misguides the observer. For example, visual clues (signifiers) in the form of arrows on the road can indicate an affordance to the observer, while the real road is not turning, thus misguiding the observer. This misguidance also builds on cultural references, related to the acceptance of road signs. As the object/artifact interacts with the observer, certainty or uncertainty may or may not be desired. For example, for a functional object uncertainty becomes a distraction. For an entertainment purposed object, uncertainty might be desirable, especially on long-duration spaceflight, where predictable repetition may decrease the desirability of the continuing interaction with the object.

#### 4.3. Spaceflight environment

During long-duration spaceflight the crew encounters extreme space environments (e.g., temperature extremes, microgravity, solar and galactic cosmic radiation, vacuum, zero gravity, and high-velocity micrometeorites), which in turn impact crew health, performance, psychology, and biological responses. Biological sciences, including psychology, psycho-sociology, human factors, and habitability, can play an important role in mitigating these environmental effects. Designers and artists also need to be aware of these circumstances when designing artifacts or habitable environments at any scale for human-object interactions. They could address stressors related to isolation, monotony, emotional conditions, cognitive effects, privacy, confinement, sensory and perceptual stimuli from various sources, multi-cultural and recreational aspects, microgravity, absence of natural time parameters, altered circadian rhythms, and physical effects on the crew. (A more exhaustive list of stressors is provided in [15].)

#### 4.4. Space habitats as large scale, full immersion interactive environments

On a large systems scale, space habitats represent key mission architecture elements for future human missions to Mars. These include habitable spaces during the flights to-and-from Mars, and also on the surface of Mars.

Habitats are highly integrated multifunctional spaces combining engineering systems, with incorporated advanced elements from the fields of Information and Communication Technologies (ICT). Throughout the mission these habitable volumes serve as shared multifunctional spaces for working, resting, exercising, socializing, playing, and communicating.

While it may seem that these technologies are unique to space exploration missions, they are deeply rooted in the human experience related to terrestrial habitats. On Earth, significant ongoing research effort is dedicated to cross-cutting and multi-disciplinary fields, such as architecture design; city design; design theory; design conflict

management; generative and parametric design; hybrid spaces design; process and product modeling; ergonomic human interfaces; and from ICT, augmented, virtual and mixed reality; information design; information design and modeling; multi-agent decision-support systems; sustainable green design systems; and user participation in design. Building Information Modeling (BIM) and Industry Foundation Classes (IFC) provide a bridge between these fields.

Many of these terrestrial research findings and advances could be explored and translated into human-centered space exploration environments. For example, approach similarities can be found between human-centered building architectures and space habitats; sustainable green design systems and Environmental Control and Life Support Systems (ECLSS). On long-duration space flights multi-functional hybrid space designs could play a significant role, due to habitable volume limitations.

There is also a complex and interdependent relationship between the astronauts and their environments. Information and communication technologies are vital to making the multi-year journey successful, and enjoyable. This is where new thoughts on the use of virtual, augmented and mixed reality designs, and emotional designs can make an impact beyond our current approaches, which are driven by engineering and technology solutions to address functionality and support human biology. Thus, novel human-centered approaches and applications can have terrestrial spinoffs to benefit the elderly and the disabled, and enhance the human experience, and augment functions and operations. ICT could also include smart objects and communicative objects. Current examples include automated inventory tracking, but with the rapidly improving terrestrial technologies and design interaction concepts, many of these could be translated to space use. Future examples could include interactive objects for entertainment, ranging from small scale to an interactive habitat.

Consequently, new insights could be gained through research by allowing experimentation around the parallels between terrestrial architectures, city designs, information and communication technologies, and projections to space habitats and human centered interactions and designs. The findings would be the results of the researcher's exploration, and may yield high-impact transformational approaches. This approach to a habitat design would be a departure from the current state of practice, which is still focusing primarily on technology solutions with modest advancement in the state of knowledge, lower impact, but at a lower risk, while notionally addressing the human element.

#### 4.5. Cultural aspects

On a spaceflight the crew might be international, where cultural conventions could play an important role. Some of these can be bridged through training and team building prior to the mission, but not all. This may result in perception differences between the various observers. Clear signifiers and perceived affordances, where the cultural and social conventions are overlapping, are important for the communication between the observers and their

interactions with objects. Suggesting that certain actions are possible is not an affordance (real or perceived), but a symbolic communication, which only works if the observer is familiar with the convention and understands it. This can be driven by the observer's schemata, and influenced by physical, logical and cultural constraints [23].

#### 4.6. Safety considerations

Any object designed by or for NASA, and to be used in space, has to adhere to the highest safety requirements. As defined in [19]: "Safety is NASA's highest priority. Safety is the freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. NASA's safety priority is to protect the following: (1) the public, (2) astronauts and pilots, (3) the NASA workforce (including employees working under NASA award instruments), and (4) high-value equipment and property. All research conducted under NASA auspices shall conform to this philosophy." These objects/artifacts need to operate in the extreme environment of space and in close proximity with the astronauts. Thus, the strong safety requirements introduce additional constraints for the designer, which may result in more complex and costly objects/artifacts, as they go through the required testing process in relevant environments.

#### 4.7. Temporal and spatial dimensions

Besides the temporal and spatial connectivity of the 3-actor system from a constructivist perspective (as discussed above), the designer can also consider the temporality and spatial dimensions of the object. This could include the duration and the rhythm of the experience, while the physical dimensions of the object can remain static or change dynamically. Furthermore, the scale can vary from a single small object/artifact to the full size complex and integrated space habitat.

#### 4.8. Movement versus stillness

Movement and stillness can be best described through Guy Hoffman's robots and their interactions with the observer. With the right movement, timing, rhythm or stillness the perceived connection between the observer and the object/artifact can be heightened and evoke strong emotions. It is considered separate from static and dynamic dimensions.

#### 4.9. Changing the meaning

In a multi-functional space environment—habitat—where resources are scarce and resupply is not an option, object might be designed for multiple uses and for various operational phases, such as work, relaxation, and entertainment. Consequently, objects could be designed with this in mind, and change their functions and meaning depending on when and how they are used. However, multiple uses, and different functions of an object using the same interactive connections

(e.g., buttons, screens) could lead to mistakes as ambiguous and unclear information is transmitted to the observer. It can also result in slips and mistakes, when the interactions with certain functionalities become automatic, and the observer does not pay appropriate attention to the function change [22].

#### 4.10. Visual impacts of light and dark

Inside a deep space habitat, extreme dark and light could be used to enhance space, volume and time perceptions. This can be localized to a small object/artifact, or the full environment. Light, colors, darkness, and shadows can have a deep emotional impact, evoking emotions in the observer from calmness to excitement. The terrestrial knowledge base on this topic is vast, and could be readily transferable to space-related designs.

#### 4.11. Abstraction

Abstraction could be used in multiple ways. It may mean the level of definition of a physical object, ranging from a highly detailed artifact to a non-anthropomorphic robot, or lights and shadows implying forms without actual materials, yet could be interpreted by the observer. Through interactions the meaning is negotiated, where part of the knowledge is carried by the artifact and part by the cognitive interpretation by the observer, which is also influenced by sensory perception.

#### 4.12. Immersive awareness

During interactions with the object, the observer's focus could narrow down to particular details, while blocking out the surroundings. In other cases the observer can be fully and panoramically immersed into the environment, not worrying about particular details. Shifting between focused and immersive experiences can enhance the evoked emotions in the observer. Artists, like Olafur Eliasson, use this approach in their designs. On long-duration spaceflight during the rest and relaxation periods a dynamically changing and emotionally connected immersive environment could be highly beneficial to the psychological wellbeing of the astronauts.

#### 4.13. Emotional design and empathy with the object

Examples for these attributes include the research of Ortíz Nicolás and the collaborative robotic designs of Guy Hoffman, discussed in the previous section. On long-duration spaceflight we need to go beyond engineering and technology solutions and cater to the psychological and emotional needs of the astronauts. This provides a fertile field for designers and artists targeting astronauts on long-duration space missions. However, we first need to gain acceptance from the engineering and technology community regarding the importance of these fields, and subsequently broaden our approach to include emotional designs in future space exploration plans and developments.

#### 4.14. Combined attributes

The individual attributes listed above can be combined to achieve a more complex experience for the observer. The attributes can be coherent, where the behavior is predictable, or not, which introduces uncertainty to the experience. For a working environment a predictable behavior is beneficial, while for entertainment purposes an unpredictable object behavior can heighten the experience.

### 5. Conclusions and future directions

In this paper we have provided a point of departure and an overview of some of the considerations for designers and artists, who are designing for the space environment from a perspective of human–object interaction. The outcomes may range from a single artifact to fully immersive integrated systems, such as a habitat. We have discussed fundamental concepts that can be beneficial to designers and artist, including tacit knowledge, cognitive learning, cybernetics, and affordances. We have also used contemporary examples from the fields of arts and design to illustrate these underlying concepts, which provided the basis for detailed discussions on the various attributes of a three-actor framework consisting of the designer or artist, the observer (in our case an astronaut), and the object or artifact.

In future work, we could design objects and artifacts for application in space, using the above considerations. These objects need to operate in the extreme environments of space, including vacuum, extreme temperatures, planetary atmospheres, radiation, and low gravity. The designs also have to account for safe operations. These objects can be created on the ground or in space, and target one or multiple sensors from our sensory perception. The sensory stimuli could be coherent or not, depending on the targeted impact on the observer. Due to the constrained resources on long-duration spaceflight, the object could be multi-functional and multi-purpose, when used in various habitability scenarios (e.g., during work, rest, entertainment, exercise). From the observer's point of view the interaction can be passive, where the object performs for the observer, or fully interactive. The affordances of the object could be highlighted using signifiers, or hidden, waiting for discovery by the observer during use. The object may interact with the environment and coded for certain behaviors. These behaviors and interactions with the observer and the environment are coded into the object by the designer. The built-in level of variety and control propagates from the designer through the object to the observer, driving certainty or uncertainty in the perceived behavior of the object.

For example, a robot—either humanoid or non-anthropomorphic—could mimic the actions and gestures of the observer in sync, store the movements in its memory then at a certain point start to move out of sync using these stored actions. This would initially create an expected, followed by unexpected interactions with the observer, and likely trigger emotional responses of amusement and surprise, and can result in some unpredictability and

inconsistency of the object's behavior as perceived by the observer.

Such designed objects and artifacts could be initially demonstrated on the International Space Station, as a stepping-stone towards use on long-duration spaceflight to Mars.

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