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RESEARCH ARTICLE

Well-Being and Life-Support on the Moon and Beyond

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ABSTRACT

A future prospect is humanity's evolution in outer space. This paper investigated the change of paradigm from survivability to well-being of crews in social isolation and physical confinement as experimented in three simulated missions with life-support systems. We introduced the concepts by related definitions and we analyzed data by the ethological approach. It is based on a quantitative description of specific social interactions and facial expressions in daily life activities. We discussed the results showing the beneficial effects of multicultural crews and crew's food production from the mock-up habitat's greenhouses. That draws a broad space ecosystem including ecological, physiological and psychological life-supports responding to new needs, solutions and techniques to apply on Earth, Moon or Mars.

Keywords: Ethology, human health, isolated and confined environment, space mission.

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1. Introduction

In our contemporary world, humanity on Earth is living in changing ecological and social environments. One of the factors is climate disruption with the need to exploit natural resources available on the Mother Planet and to mitigate planetary boundaries. A favorable consequence for the terrestrial population is the continuous search for supports and solutions to improve the quality of life in order to achieve sustainable development. Another factor is societal with novel remote interpersonal communications and virtual assistants in most parts of the world. As a result, human societies manifest coping responses, invent adaptive strategies and conceive innovative technologies with the ultimate goal of living well individually and collectively. At the same time, humans need to build an adequate ecosystem. Such an issue becomes the new challenge of manned missions in the space environment. Our previous findings have shown that men and women manifest personal and social behaviors in a positive way in these challenging conditions. The mixed-gender and mixed-culture crews adapt through a systemic, dynamic, synergetic and salutogenic process (Tafforin *et al*., 2023). The new objective of our research is to focus on the well-being of crewmembers in relation to life-support systems. The future applications will be to find countermeasures for efficient use on the Moon and beyond with potential use on Earth.

The concept of well-being has various meanings according to a physiological, psychological or technological approach. It implies physical health, mental health and behavioral health. It is also related to various good life outcomes and an optimistic state of mind with successful functioning and subjective satisfaction at the family level, at the relationship level, at the professional level, at the economic level, etc. We propose to emphasize the human health in its multiple facets.

A cross-national review of the association between physiological markers and well-being suggests possible roles for serotonin, cortisol and immune system (De Vries *et al*., 2022). Biomedical screening prior to spaceflight is made to prevent physical health risks (Krittanawong *et al*., 2023). The main hazards of the extraterrestrial environment are exogenous, due to cosmic radiation and reduced gravity, and endogenous, due to social isolation and physical confinement. During the missions, regular exercise and low body negative pressure sessions help to prevent illness. Most of biological measures remained stable after a year aboard the International Space Station (ISS) (Garrett-Bakelman *et al*., 2019). So fitness was maintained but repetitive exercises are boring. The distraction factor attenuates these effects in extended periods of time (Tafforin, 2024a). In the last decade, exploratory qualitative methods of food-related well-being have shown strong association with physical health (Ares *et al*., 2014). Food is of paramount importance in daily life activity both for energy supply, nutritional needs and also for the enjoyment of social gatherings, ritual events in monotonous living conditions such as interplanetary travel. To compensate for the bland food in space, it will be necessary to grow fresh food on the Moon or Mars (Mane, 2024) to stimulate the taste receptors. A physiological definition of well-being could be the result of major biological balances, met energy needs, pleasurable sensory stimulations and playful motor training.

A review of measures of positive mental health identified happiness as a state characterized by pleasurable feelings on several dimensions (Iasiello *et al*., 2024). The behavioral correlates of feeling well in everyday situations are more significantly frequent smiles (Gardiner *et al*., 2022). They are the facial expressions of positive affects, emotions and moods that also refer to cheerfulness and friendliness. These mental processes can enrich the experience and build the resilience of individuals to respond positively through their personal capacity and to respond cooperatively within social contexts. In space psychology, an assessment of external crew communication during simulated lunar missions found a convergence of styles between male and female crewmembers and an increase in social cohesion (Supolkina *et al*., 2021). Narrative analysis of a simulated mission to Mars reports that cultural heterogeneity is beneficial for an isolated and confined crew (Poláčková Šolcová *et al*., 2016). Discussion about food was an enjoyable topic regarding cultural habits and celebration rituals. They strengthened good team spirit. Spirituality and humanism can provide a sense of purpose and meaning to deal with challenging life conditions. Astronauts are animated by such motivation (Kanas, 2020) and used humor to cope with stressful events (Brcic *et al*., 2018). In an analog environment, personal values would decrease for the benefit of social interest values (Ma *et al*., 2019). A psychological definition of well-being could be the result of personality traits and in-collective abilities to be happy as a beneficial state. It prevails in pleasant feeling, good mood, positive affect and joyful emotion.

Techniques for creating suitable habitat first require the inhabitants to meet their basic needs. In the case of lunar settings and more distant habitable planets, well-being is achieved while living on limited energy, water and food, while being protected from radiations, hostile climates, periods without sunlight, and while relying on remote communication, safety and autonomy from Earth. Some best practices are studied in polar bases in Antarctica but also in thriving protocols in small habitats such as the Mars Desert Research Station (MDRS) (Poulet & Doule, 2014) and the Hawaii Space Exploration Analog and Simulation (HI-SEAS) (Dunn Rosenberg *et al*., 2022). In particular, in habitats comprising ecological life-support systems such as the Lunar Palace 1 (Hao *et al*., 2023) and the EDEN ISS (Zabel *et al*., 2020), plant cultivation should be both a fresh food supply system and a source of well-being in the greenhouse. New needs are now turning to the comfort of the interior of space stations. Studies of the lighting inside a mock-up of an hygiene area showed the effect of correlated color temperature on the best emotion and satisfaction levels providing insights for novel operational facilities (Jiang *et al*., 2022). Digital technologies leading to positive outcomes for human space exploration are premised on design principles that support well-being (Smith *et al*., 2023). The idea of a Moon village that gathers all these findings and integrates the human group at the heart of the system is the final goal of living well in a self-sufficient and self-organized micro-society. A technical definition of well-being would be the result of comfortable living conditions offering the best designs and technologies to meet the basic and pragmatic human needs. This is done in social harmony and ecological balance on any habitable planet and in adequate life-support systems.

The concept of life-support has evolved in great proportion. Since the early days of human space exploration, when Neil Armstrong, Buzz Aldrin and Michael Collins spent 8 days together in the Apollo 11 modules (apart from crew separation for walking on the lunar surface), living conditions were reduced to freeze-dried food, limited water and stored waste. A full oxygen atmosphere was maintained and the carbon dioxide produced by the crew's breathing was removed immediately. Life-support is a set of techniques that enable the crew to survive in inhospitable environments and provide key management (Tamponnet *et al*., 1991). Some of them are protective (radiation protection, fire control, thermal and pressure control) and mandatory. Others bring necessary elements that can either be supplied (oxygen, water, food) and stored (carbon dioxide, grey water, waste) or regenerated (Fig. 1).

As crew size, crew diversity and mission duration increased (Fig. 2), life-support system progressively evolved from an open-loop, non-regenerative status to a closed artificial ecosystem via physical/-chemical and then biological techniques. They could use transported resources during interplanetary flights or in-situ resources once on the planet. When dealing with a Moon village or Mars settlement, the success of manned missions imposes a paradigm shift from survivability to well-being. This applies directly to the life-support system, both individually and socially. Some benefits for the entire population of a planetary base require food quality and food variety, a less inconvenient recycling

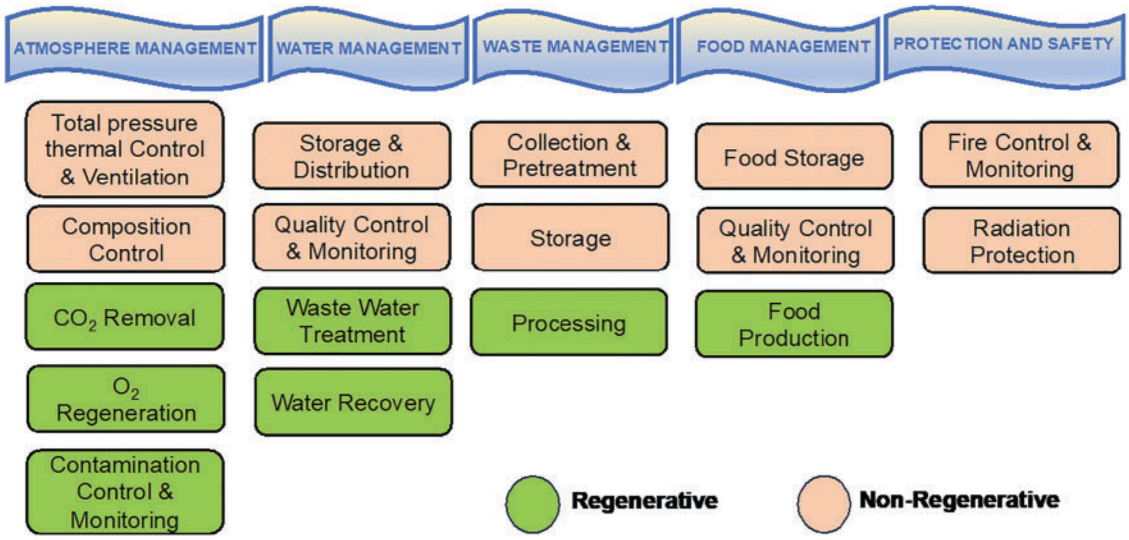

Fig. 1. Basic techniques of life-support.

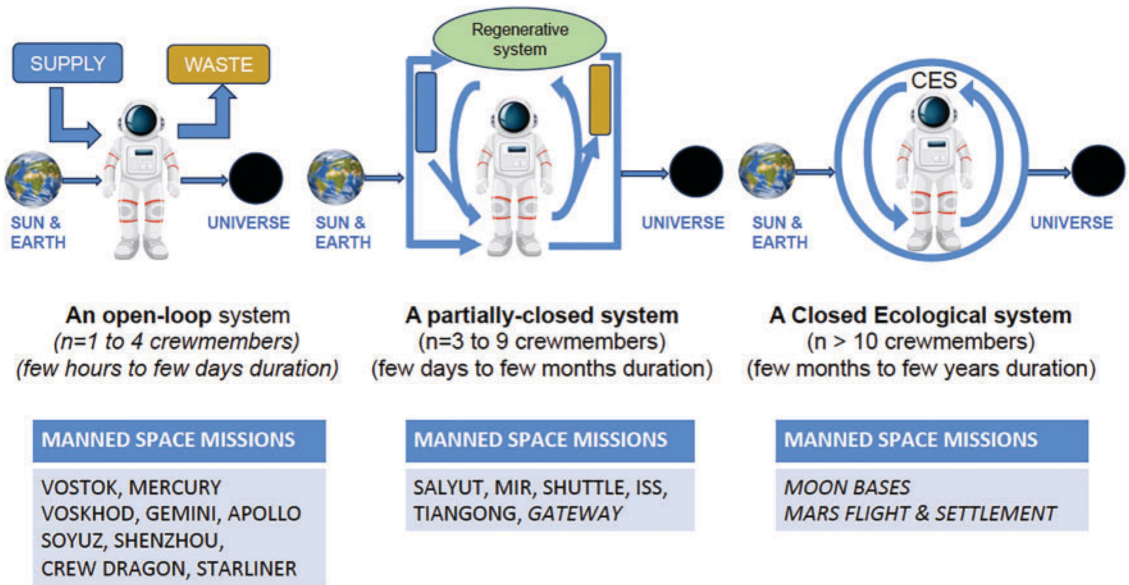

Fig. 2. Evolution of life-support according to crew size and mission duration.

of feces and urine, and a powerful atmosphere revitalizing infrastructure. One promising avenue is a Bioregenerative Life-Support System (BLSS) integrating multitrophic aquaculture that converts waste into fish food (Przybyla, 2021). Aquariums can enhance perceptions of the value of natural ecosystems and consequently increase health benefits (Cracknell *et al*., 2016). Research on BLSS is compartmentalized such as Micro-Ecological Life-support System Alternative (MELISSA) which is broken down into four main processes based on bacteria bioreactors and food production (Godia *et al*., 2024). An innovative Controlled Ecological Life-support System (CELSS) that integrates the human group should meet the requirements for biological autonomy while confined and isolated from the original biosphere. Sustained daily tasks in greenhouses and life-support systems appeared to be more efficient than brief physical exercise to counteract psychophysiological deconditioning (Yuan *et al*., 2019).

To further advance in our conceptual paradigm, we investigated the CELSS platforms which provide appropriate experiments in space to address the relationship between life-support and well-being. We applied the ethological approach to behavioral health. Our working hypotheses are that social interactions and facial expressions are relevant behavioral indicators of well-being in daily life activities, and that life-support as part of a broad ecosystem is a beneficial solution for isolated and confined human groups in space.

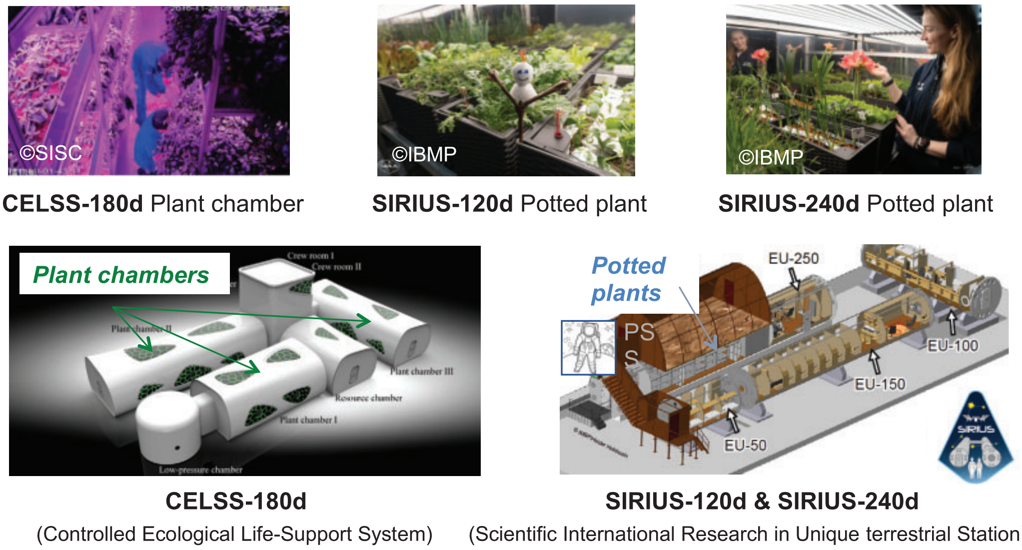

Fig. 3. Multi-chamber facilities with plant chambers or potted plants as elements of life-support.

2. Method

The methodological tools used in ethology, the science of behavior, are based on observing, describing and quantifying the spontaneous individual and inter-individual behavior from video recordings in any situation that takes into account the relationship between the humans and their environment. The method is detailed in Tafforin (2024b). Within the whole behavioral repertoire, we choose to monitor the duration of cooperative social interactions and the frequency of positive facial expressions during shared meals in the multi-chamber facilities as experimental scenarios of daily live in manned missions (Fig. 3).

The CELSS-180d experiment took place at the Space Institute of South China (SISC) in Shenzhen and simulated a 180-day duration interplanetary journey to Mars and back. It included 40-minute delayed communications with Earth. The habitat housed one woman and three men of the same Chinese nationality. It consisted of 8 interconnected modules: three large plant chambers, two crew cabins, one low pressure plant chamber, one life-support chamber and one resource chamber. The facility had functions of crew working and living quarters, greenhouse, food production, atmosphere control and waste recovery using plants and microorganisms as central recycling components. In the present study we analyzed video data collected once a month at lunchtime in the kitchen.

The SIRIUS-120d and SIRIUS-240d experiments are part of the Scientific International Research in Unique Terrestrial Station (SIRIUS) program conducted at the Institute for Biomedical Problems of the Russian Academy of Science (IBMP-RAS) in Moscow and simulated a 120-day and a 240-day mission to the Moon respectively, with transits, docking to the future orbital station (Gateway) and landing on the lunar surface. During SIRIUS-120d, the habitat housed three women and three men of three nationalities, American, Russian and Emirati. During SIRIUS-240d, it housed two women and three men of two nationalities, American and Russian. The facility consisted of 4 interconnected modules: the module EU-100 for medical and psychological works, the module EU-150 for living quarters, the module EU-250 for food storage, potted plants growing and waste disposal. The module PSS Planetary Surface Simulator had the function of Extra Vehicular Activities (EVA). For a comparative analysis, we selected video data collected once a month at breakfast time in the kitchen and for a longitudinal analysis we used all the data collected twice a month.

The independent variables studied are crew activity (plant chambers, potted plants), crew composition (culture) and mission duration (extended periods of time). The dependent variables are behavioral expressions of well-being. All the participants gave their consent to the study after approval by the relevant ethic committees in each country.

3. Results and Discussion

Processing the occurrence of observed behaviors is the specific phase of the ethological approach. We give a quantitative description of relevant events in terms of action verbs. Fig. 4 displays the rate per minute of facial expressions as indicators of well-being (main item is "smiling"). They were analyzed in a temporal dynamics according to space mission related crew composition and life-support related crew activity. The results show a decreasing frequency of this positive expression over time with a

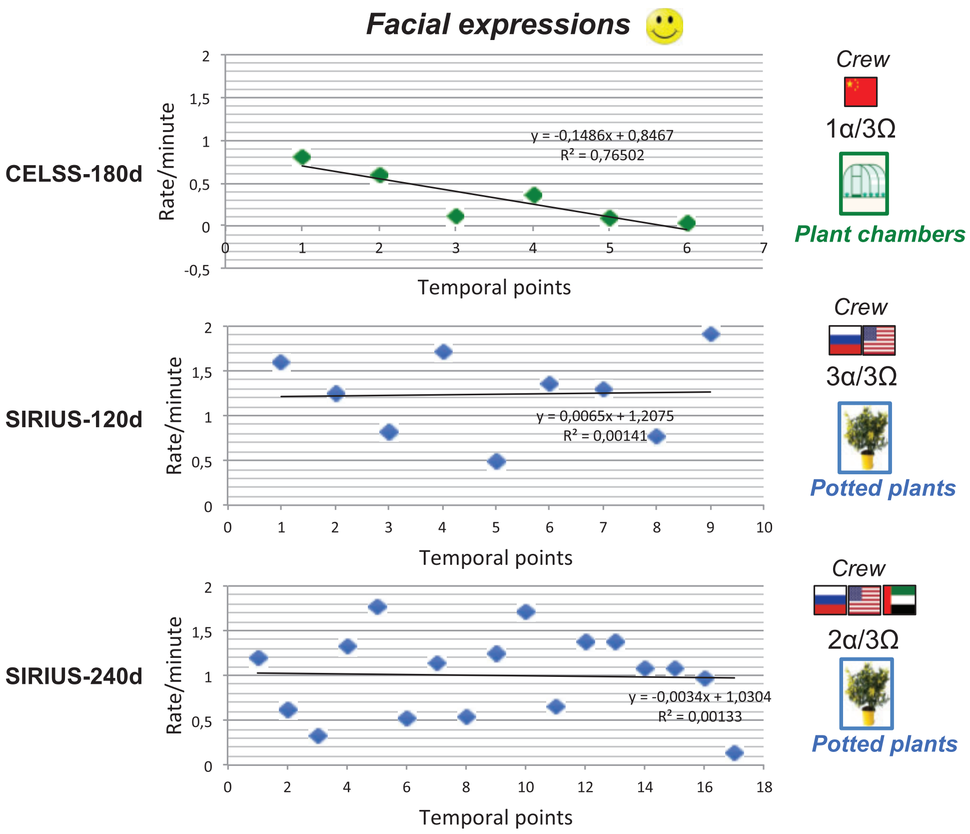

Fig. 4. Facial expressions by crew composition and crew activity over time.

significant correlation index ($R^2 = 0.8$; $p < 0.001$) during the CELSS-180d experiment. It simulates a Mars mission with a monocultural crew (Chinese), with no EVA but with major activities in the greenhouse designed by four plant chambers in the multi-module facility. This confirms the key feature of diversity in the crew composition (Tafforin, 2024a) and highlights the need for diverse life-supports, possibly exacerbated by remote and delayed communications with the ground. There is no significant correlation between the SIRIUS-120d and SIRIUS-240d experiments. First, this highlights that there is no dependency between the time variable and positive facial expressions whether the mission duration is of 120 days, 180 days or 240 days. Our previous work has shown cyclic or periodic behavioral variations over time (Tafforin *et al.*, 2023). This is found again in the scattered time points. We could also interpret the scattergrams regarding the multicultural crews (American-Russian or American-Russian-Emirati) as a positive impact on the well-being of the social group, along with episodic potted plants growing activities. SIRIUS scenarios simulated Moon missions with EVA, which could also be beneficial in the absence of greenhouse activity.

Fig. 5 displays the mean duration of social interactions as an indicator of well-being (the focus was on object manipulation among each other and a relevant item was "food sharing"). The results show a significantly high level of this cooperative interaction during the CELSS-180d experiment compared to the SIRIUS-120d and SIRIUS-240d experiments. It is a behavioral pattern that only occurred according to fresh food offerings in the greenhouse. The event unfolds as if fresh food production from crew activities in the plant chambers was beneficial to the ecological life-support.

Considering the overall definitions of well-being given in the introduction, how can humans optimize the part of life-support that addresses physiological, psychological and technological needs in social isolation and physical confinement? Fig. 6 displays a solution that integrates space crews into the interfaces. The multi-system provides crewmembers with oxygen, water, energy and food for survivability along with exercise against sensory-motor deconditioning, protection against environmental hazards, treatment against medical illness and others. It also provides means about behavioral health for adaptability such as privileging actions and interactions being verbal or non-verbal against negative emotions and others. Fig. 7 displays some possibilities of countermeasures nested in a broad ecosystem. With the aim of improving quality life inside the habitat, examples of benefit-related solution are a virtual natural landscape with fragrant natural flowers, familiar bird songs, fish farming aquarium, greenhouse gardening, a palette of flavors and a robot companion. Outside the habitat, it concerns remote communications with the Crew Control Center (CCC) on the ground and EVAs in space. Each solution or technique can be adapted and implemented on Earth, on the Moon and beyond.

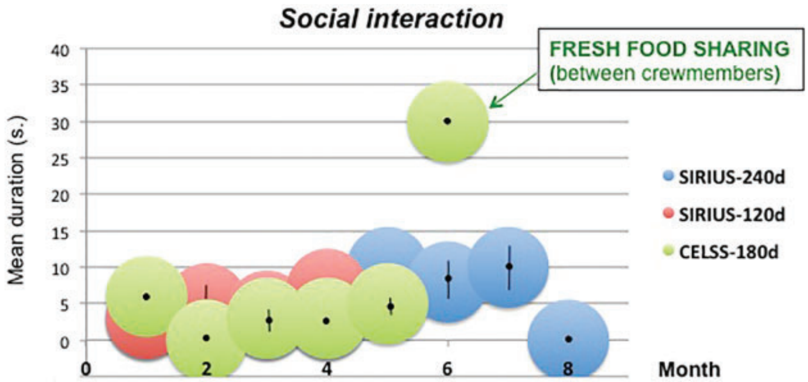

Fig. 5. Social interactions according to fresh food offerings in the greenhouse.

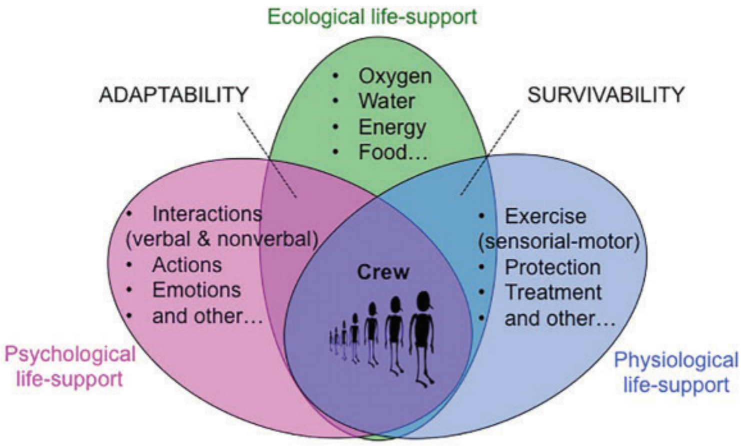

Fig. 6. Multi-system life-supports integrating space crews.

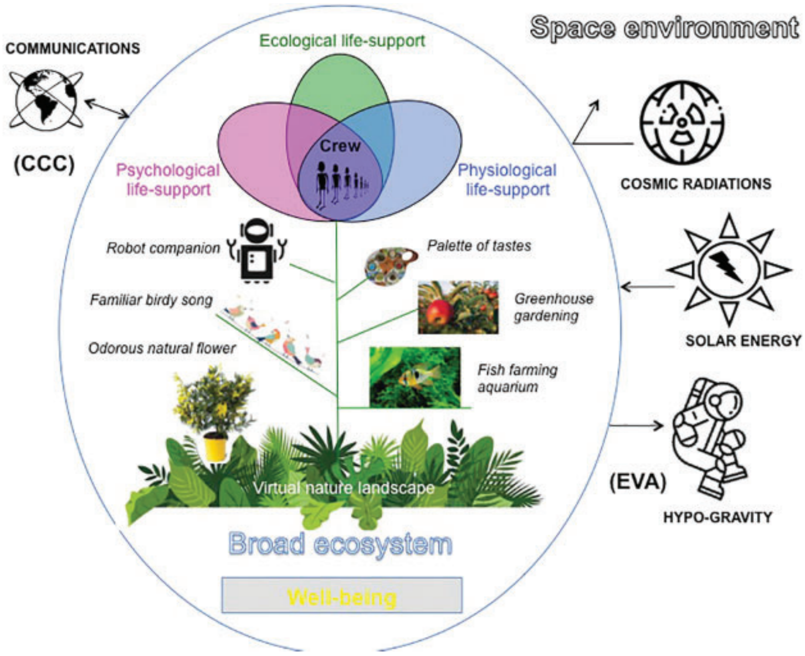

Fig. 7. Countermeasures for well-being in a broad space ecosystem with a multi-system life-support.

An ethological definition of well-being could be the result of being active, receptive and expressive in order to evolve well in an optimal and optimistic relationship with the natural and cultural environment. These are simple behaviors such as listening to a bird, gardening plants, eating a meal, looking at a landscape, communicating with others in real or virtual terms, and an infinity of individual and inter-individual actions adapted to any living situation.

4. Conclusion

Looking ahead to the next lunar and future interplanetary missions, the combination of psychological, physiological and ecological life-support must be considered in a broad space ecosystem that protects humans from extraterrestrial environmental hazards and contributes to the well-being of humanity in its positive evolution.

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Conflict of Interest

The authors declare that they do not have any conflict of interest.

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