42nd International Conference on Environmental Systems
15 - 19 July 2012, San Diego, California

AIAA 2012-3615

Lighting of space habitats: Influence of color temperature on a crew's physical and mental health

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The aim of this paper is to establish the importance of proper lighting in space habitats by analyzing the optical effects of light on human beings, with regard to the consequences for mental and physical health and influences on the performance of their activities. It also seeks to establish possible solutions through the use of specific types of lighting in space habitats. The light field is studied both technologically and psychologically. Inadequate artificial lighting directly affects people's health and alters biological and psychological processes. The temperature of the light alters the circadian rhythms, causing physical and psychological disorders in the human body that affect health. The period of time spent on the International Space Station is becoming increasingly longer, up to six months, and the crew must remain in an isolated living and work environment that is very different from life on Earth. The environment where these various activities are performed, including the lighting of said environment, should be appropriate and contribute to the physical and mental comfort of the users. In this paper we identify the need to incorporate variable wavelength lighting systems, in contrast to the type of lighting currently in use, based on scientific studies conducted on the influence of light on mental and physical health of humans and space psychology, particularly in studies on crew isolation. The study places special emphasis on the color temperature of a light source, as it determines the influence on the psychology of human beings, especially when isolated in space.

I. Introduction

THE study of lighting within the different habitats of civilizations has revealed its importance in issues relevant to human activities. Light is clearly related to human biological functions, and therefore architecture has historically focused its efforts on providing both shelter and adequate lighting, giving its residents a suitable place to perform their activities. In space architecture the union between lighting engineering and psychological environment is more than important, in fact it is essential, due to the hostile and difficult physical and psychological conditions when crews are isolated. Traditionally, lighting systems have been studied from an eminently technical, easily measurable perspective: lux minimum per activity to be performed, adequate wavelength lighting, arrangement of the light and energy consumption. However, two new psychophysiological features, the influence of light on humans and the circadian system, stand as essential factors. It is necessary, therefore, to review the existing lighting systems in the most hostile environments, including space habitats, and in particular the International Space Station (ISS), to ensure a proper state of well-being for the crew, for prolonged exposure to the current static lighting used in these systems can alter human biological functions, which in turn generates consequences for mental states.

"Light is really the source of all beings" Louis Kahn, architect.

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II. Light and psychophysiology

Light exerts a beneficial effect on human skin. Our ancestors used heliotherapy as a treatment for diseases and as a health benefit, a natural method which has been replaced and forgotten following the invention and use of penicillin in the nineteen-thirties. Today there is more appreciation[1] for natural light as a health benefit, thanks to numerous biological and medical studies. In these studies, the discovery of additional nerve connections from recently-detected novel photoreceptor cells in the eye connected to the brain (melanopsin molecule is the photopigment responsible for ipRGC[234]-*intrinsically photosensitive Retinal Ganglion Cells*- phototransduction), show that the eye is not only an organ of vision, but that light also regulates and controls a wide range of biological processes. These are particularly related to the control of our biological clock and to the balance of certain important hormones that regulate light-dark rhythms. This demonstrates that health, well-being, and alertness are all influenced by light.

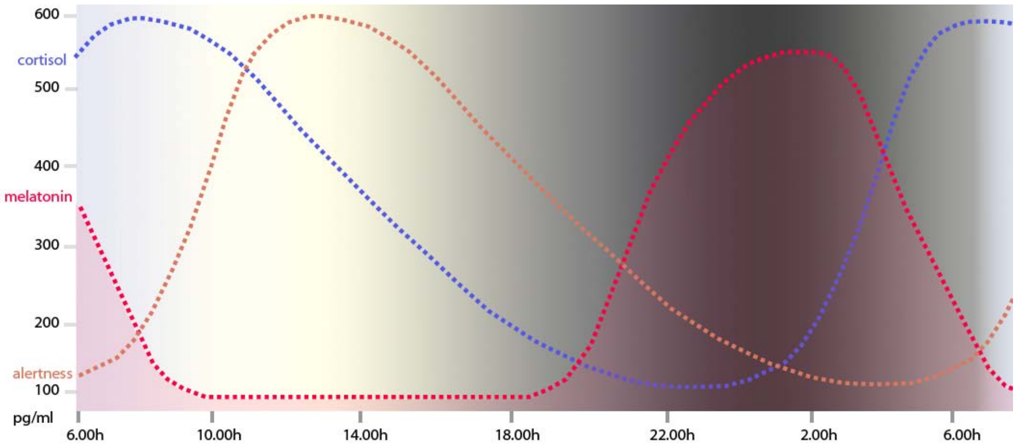


Figure 1. Human biorhythms (alertness, cortisol and melatonin) for a natural 24hour light/dark cycle[5];

Lighting[6] determines how we see surrounding objects and therefore how we perceive them, generating sensations and thoughts which vary depending on the individual; each one of us will have a different perception of the world because we are all different in terms of sense of sight, culture, and experience. Humans have common values with respect to light: performing a given activity with inadequate lighting creates discomfort or inconvenience, and artificial light or light changes alter our circadian rhythms influencing our alertness, performance, and sleep patterns. The human circadian rhythm period varies from 23.5 to 24.7 hours, with an average of 24.2 hours among healthy adults[7]. It needs to be reset[8] exactly 24 hours each day to keep an appropriate relationship with the environment. We can consider light as being the biggest indicator, powered by daily ocular stimulus, which allows us to reset the circadian rhythm.

Life habits[9] have changed drastically in the relatively recent past compared with the evolutionary history of humans. Our ancestors spent more time outdoors than we do today. Each day the light-dark cycle synchronizes the physiology and behavior controlled by our internal clocks[10], since human hormones vary in synchronicity with the variation in daylight. That's why this fact was considered essential in this research. At the ISS, where light is constant throughout the workday, synchronization of the hormones with the variation of light is canceled. Thus we can say that "static" artificial light[11] alters both our hormonal and our circadian rhythm**s.**

The following figures compare the wavelengths of natural and artificial light in a work environment.

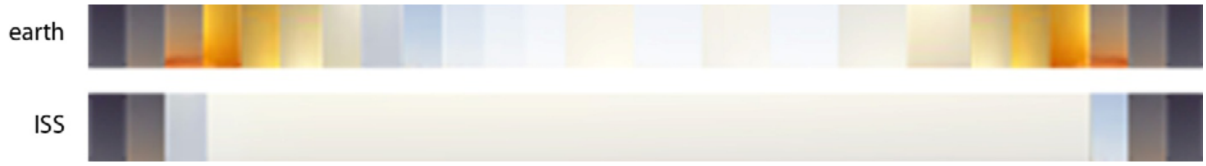


Figure 2. Color variation of light throughout the day.

For thousands of years[12] humans lived and worked conditioned by sunlight, with a light intensity varying according to the time of day and season. For people who work indoors, color variation of natural light throughout the spectrum is nonexistent. This difference is especially acute in the International Space Station (ISS).

The effect of light on the human body[13] is physiological and psychological. One the one hand daytime light increases cortisol levels (a sunlight dependent hormone responsible for alertness) and makes us more active. At night high melatonin levels in the blood help us to sleep. Moreover, recent studies involving the melanopsin molecule have found that specialized photosensitive ganglion cells are also involved in this process. Melanopsin is most sensitive to short-wavelength (blue portion of the spectrum) visible light (max 480 nm) [14] and studies on humans have concluded that it has a direct influence on resetting the timing of the circadian rhythm by suppressing nocturnal melatonin production[15]. This kind of hormone acts as a biochemical marker of night and is currently associated with sleeplessness[16], being directly related to alertness[17].

Light is also used effectively as a cure[18] for people suffering from seasonal affective disorder[19] (SAD), shift-work or jet-lag, caused by a lack of light during the winter or the desynchronicity of the light-dark cycle. Through the use of light and darkness, circadian rhythms can be changed in order to help people adapt to a new time zone, night shifts, or to combat falling levels of alertness in the afternoon (depending on the timing of light exposure, light can both advance the clock to an earlier time or delay it to a later time). Furthermore, light has a strong influence on people’s moods[20]. When performing a particular activity, such as reading, a non-appropriate light makes us feel uncomfortable. But sometimes, for the same activity, color light levels deemed acceptable will vary according to the time of day. Reading during the day requires plenty of white ambient light, but at night, the same activity requires a warm, low-intensity ambient light and a cold or warm white light focused on the book. The implementation[21] of lighting systems that do not mimic sunlight, as well as the use of stable prolonged artificial lighting that does not follow natural light patterns promotes feelings of sadness or irritability, feelings related to a biological and physiological human response to artificial lighting[22].

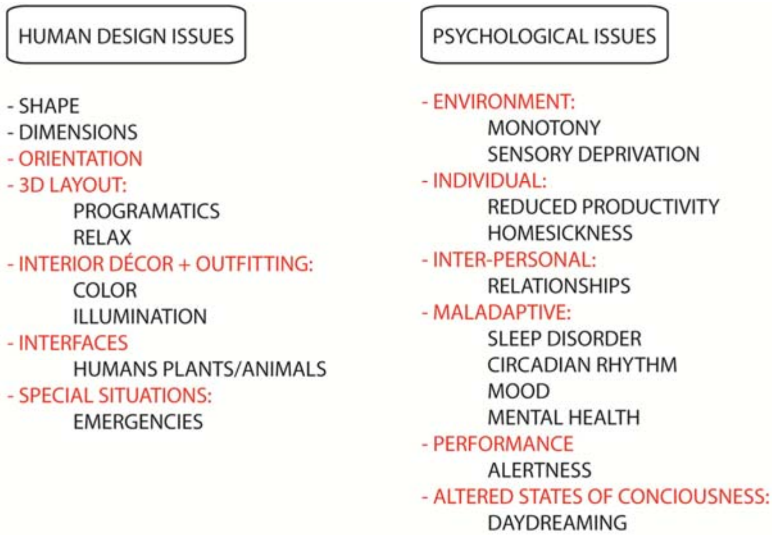


Figure 3. Human design issues that can affect crew psychology and effects of habitat design on behavior in long-duration confinement in extreme environments. [23]

There is no variability of natural light in space habitats, where so far only illuminated fluorescent light has been used; lighting can vary only in quantity but not in color temperature. This study focuses on replacing actual lighting with LED lighting, which creates more light intensity with the same energy expenditure and offers a wider range of wavelengths equivalent to those found in natural lighting. Regardless of the lights used, the problem of artificial lighting in these habitats is exacerbated because life takes place in an indoor, artificially-lighted closed space, with the same light color throughout the day. This creates a sense of confinement and disturbs the connection with the daily cycle of light in nature. On the ISS the few windows are facing "down" toward the Earth, and its daily cycle of light consists of an invariable white artificial light. They observe 16 sunsets each day, and the corresponding dark areas, when located on the night side of the Earth. This seems unnatural.

In these habitats, isolation and such close relationships with other human beings can create stress and interpersonal problems[24], and it is known that the interior design of space habitats improve the well-being of the crew. In future long-duration missions to the Moon or Mars, both for the journey as in the planetary habitat, this aesthetic function becomes even more important, because not only must they satisfy the basic survival functions of the crew, but also take into account their physiopsychology to reduce the effects of stress. "Human Factors Engineering[25]" is a term that encompasses a number of technical factors such as smells, food, noise, orientation, communication, temperature, sleep, hygiene, color, lighting, ergonomics, life support, among other things, and their countermeasures, both physiological and psychological. Although these factors are generally well studied quantitatively, we have often neglected their "qualitative" aspects, overlooking what we call "Environmental Psychology."

"Experience has shown that workers who work in remote and isolated places, or in high-risk environments analogous to Space produce undesirable symptoms: maladaptive behaviors and a decrease in performance associated with stress. Groups confined in places like Antarctic research stations, nuclear submarines, and underwater habitats have shown low morale, increased anxiety, sleep disturbances, fatigue, decreased productivity, hostility, and interpersonal conflict. The relationship between the 'habitat design' and 'crew psychology and behavior' must be deeply studied and applied" [26]. In future long-term space travel and stays (interplanetary travel, or settlements on the Moon or Mars) interior design of habitats will be essential for the physical and psychological well-being of the crew.

Light is a main factor in the physical and mental health of human beings, as it influences their circadian system. "*The warm white light (3,000 K) facilitates relaxation and improves wellbeing, while day-light (5,600 K) stimulates and activates the human body*." [27] The circadian rhythm of cortisol begins with sunrise, reaching its peak at about 9:00 a.m., when it starts to decline to its minimum level at 6:00 p.m., beginning again at 6:00 a.m. the next morning. "*However, this hormone is also produced when the body is subjected to any stress (physical, mental, emotional, spiritual, chemical, nutritional, electromagnetic or thermal)."* [28] Therefore space habitats not only have to control light in working hours to control melanopsin and cortisol and therefore alertness, but also try to reduce stress[29] by generating a more pleasant light environment, similar to the natural light cycle of the sun.

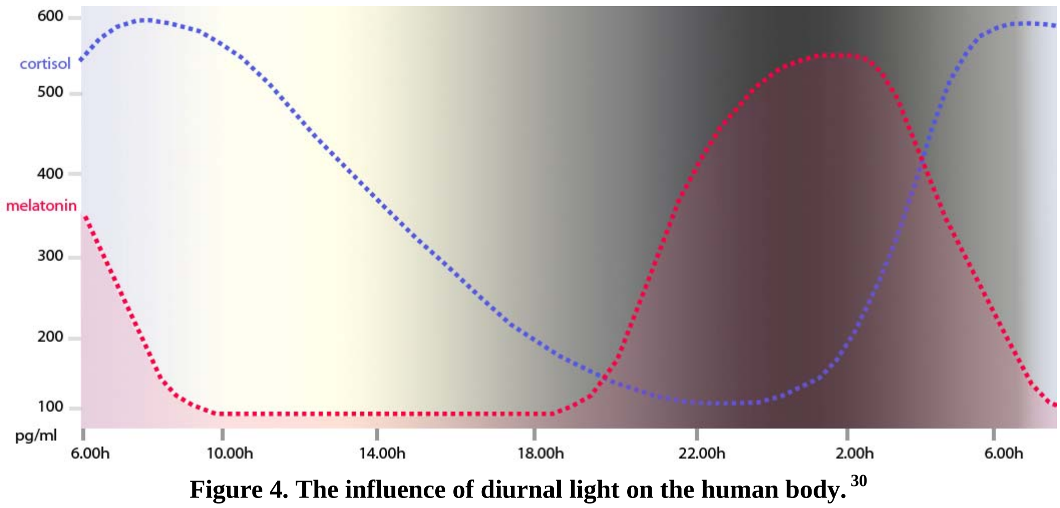


Figure 4. The influence of diurnal light on the human body. [30]

A long-duration short-wavelength light exposure is a potentially effective countermeasure for fatigue and low performance[31], particularly during biological night. Short-wavelength light is a highly effective wavelength for phase-shifting circadian rhythm, activating the nervous system[32]. However, utilization of such light exposure must be incorporated appropriately to avoid undesirable side effects on health and performance caused by altering light environments beyond normative conditions[33].

In the design of space habitats [34], there have been studies on energy efficiency, wavelength, light, and light intensity understood as constant light (throughout the day or during a particular activity), as well as on the location and angle of the light, the heat it generates, and the "white noise" it produces[35]. That is why we suggest, in addition to the aforementioned characteristics regarding lighting, to simultaneously control the amount and color of light in a variable way, which both naturally change throughout the day, and to create an environment that is similar to natural light in order to regulate circadian system and create a pleasant atmosphere for the crew, using dynamic lighting. This type of lighting would reproduce chromatic diversity and the intensity of natural light. Being able to vary the intensity at a given time, depending on the activity to be performed and the time slot would help to prolong alertness and therefore performance. In addition, color rendering of daylight that is adapted to the space habitat could also be adapted, depending on the origin and age preferences of the crew, using a choice of personal light, thus generating greater sense of control over the habitat.

III. Dynamic lighting

Figure 5. Color variation of light throughout the day.

Dynamic lighting[36] would apply natural lighting tonality and would vary in intensity, like in nature. Along with the seasons, the day-night cycle creates ever-changing[37] patterns of light during daylight hours. The aim here would be to reproduce those that benefit the crew. Nevertheless, it would be appropriate to adapt space lighting to those cycles that naturally provide 10-12 hours of daylight, thus avoiding the winter lighting cycle of limited daylight hours.

"The change of color temperature and light intensity is achieved by a combination of the luminous flux of two different lamps using a special optical technology. One of these lamps has a color temperature of 2600º K (warm white) and the other one 5600º K (cool white). The changing luminous flux of the lamp means that the color temperature can alternate perfectly between these two values."[38] Dynamic Lighting will help to improve the crew members' sense of well-being. If the crew can control their own space according to their needs, moods, and activities, and create exactly the right atmosphere, they will increase their performance and motivation. It has been proven[39] that dynamic light benefits concentration and therefore work performance.

During working hours the pattern to be followed is as follows:

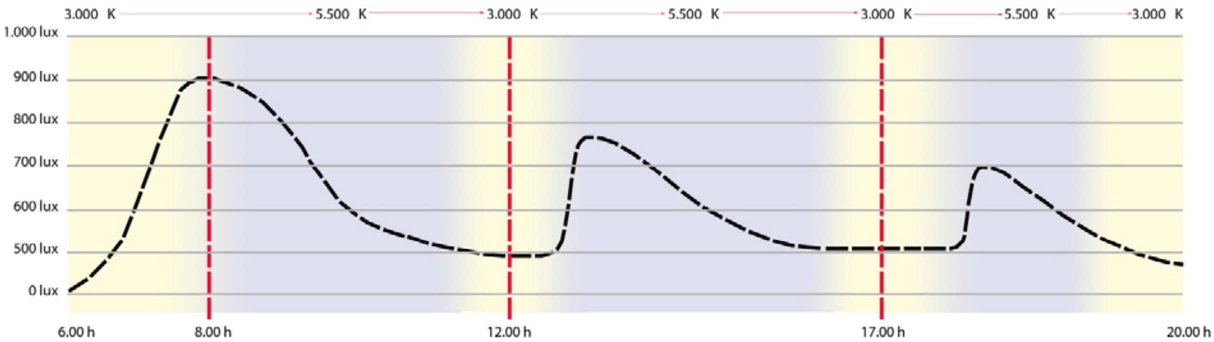


Figure 6. Example of a natural rhythm of activity.[40]

The day starts with a cold and crisp light. For lunch, the light level is reduced and warm light promotes relaxation. Subsequently the light level is raised and it is changed to a cooler, whiter light to counter drowsiness. At the end of the day, it is changed to a warm white light, to get us ready for the low light levels, characteristic of the afternoon-night time. This is combined with the general illumination, from the gradual switching on of the lights at 7:00 a.m. until to the gradual shutdown at 11:00 p.m.. Notwithstanding this option, there would also be lighting for emergency personnel or private lighting inside the cabin, for periods of relaxation. However there would be a lighting option for emergency situations or private staff rest-sleep cabins.

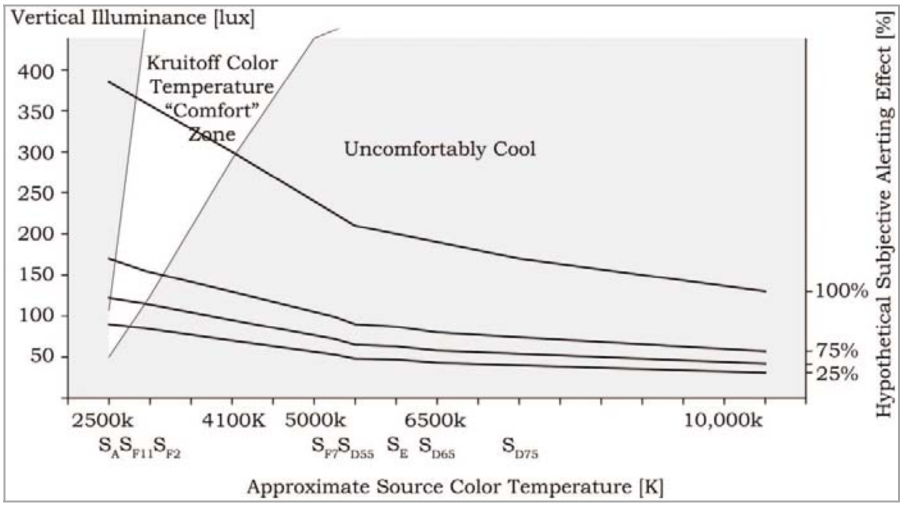
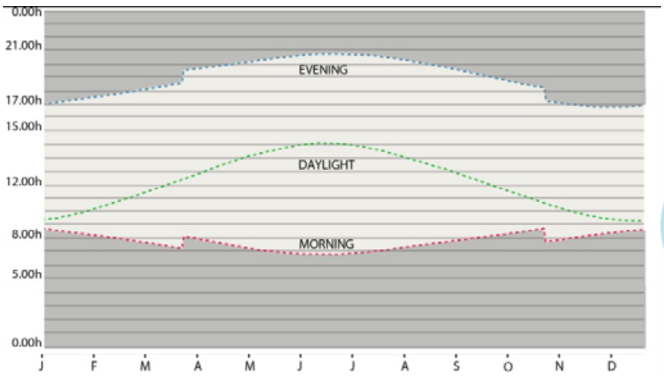


Figure 7. Alertness benefit from Illuminants and Color Temperature: Comparison of Various Light Sources.[41]

During resting hours, the crew could change the lighting color according to their city / culture of origin[42], thus creating a more familiar environment, maintaining light levels within their "comfort" zone, as shown in figure 8, which compares various lights according to color temperature, illuminance, comfort, and circadian efficacy assuming spectral neutrality of construction materials and biological temporal neutrality.



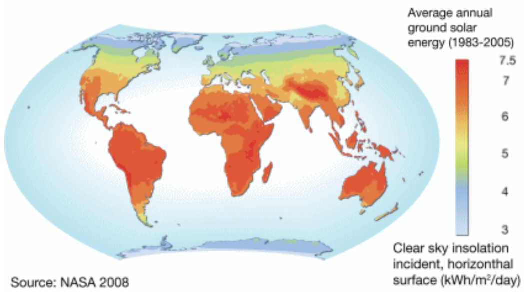


Figure 8. Daylight[43,44] on the geographical latitude of 40°;
Figure 9. Insolation-Lighting incidence on the earth.[45]

IV. Conclusions

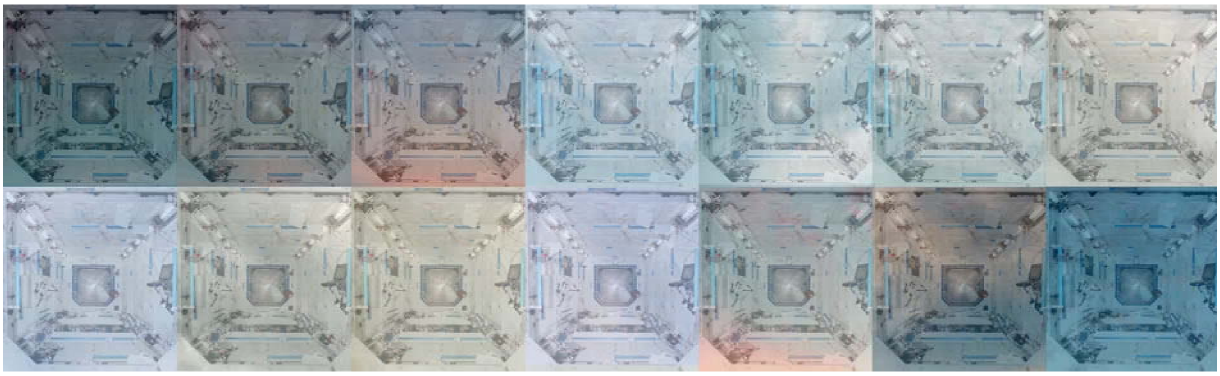


Figure 10. Approach to dynamic lighting in a space habitat. Original pictutre: Destiny laboratory.[46]

Circadian rhythms[47] are physiological responses of the human body's 24-hour cycles of light and darkness on Earth. This internal clock regulates hormones and other essential body functions, necessary for sleep (body temperature, heart rate, etc..). Natural light levels[48] range from 0.001 lux to 100,000 lux, the amount of light that is experienced on a starry night and a sunny day, respectively. It varies from 0° K to 12000º K in color temperature. If we subject the members of a space crew to a type of lighting that does not follow the wavelength changes that occur in natural light, their circadian cycles would be altered, in turn altering their physical and mental states.

The design of space habitats[49], especially for long-duration stays, must place special emphasis on space architecture and environmental psychology, complementing aerospace engineering, in order to reduce disease and stress on the crew. The role of space illumination is considered essential in this work, through the use of dynamic lighting. *"The dynamic changes in daylight have a positive influence on mood and stimulation[50]"*.

It would be appropriate to integrate a smart lighting system in aerospace habitats, which reproduce the wavelength changes found in the 24-hour daylight cycle, adapted to the activities performed by the crew.

We can select the crew according to their individual personalities to "minimize" problems between them. We can design interior spaces where people feel good and work well. But there is a final "intangible material" in habitat design that, depending on how it is applied, can create one psychological environment or another. This material is light, and it is vital to our rhythm of life.

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