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Time Architecture

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Abstract. Living in an artificial environment without access to the natural solar light, has a strong influence on the circadian clock of humans. Light is the most powerful synchroniser of human internal biological clock. The environmental conditions, however, are different in an extraterrestrial environment, such as in low Earth orbit, deep-space or on other planets. The exposure to the sunlight in space is influenced by the specific location of the habitat in relation to the Sun, as well as by specific habitat system, determining the amount of the crew's exposure to radiation. Therefore, disruptions in sleep-wake cycles have been common among astronauts. In addition, the lack of sunlight is known to induce Seasonal Affective Disorder (SAD), manifesting through fatigue, concentration and memory problems, decreased mood and obesity. In this paper we discuss the importance of considering time in architectural design as the crucial element to recover natural environment conditions in isolated interior spaces. We propose generic architectural tools for an artificial environment in order to influence an astronaut's perception of time. To regulate the biological clock of an astronaut, a specific lighting system for isolated environments is introduced. The projected simulation will be looped in a 24-h period, in order to regulate astronaut's circadian rhythm and create straightforward reference of the time of day. The light will be installed and tested in the M.A.R.S. analogue habitat in Poland.

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1 Introduction

In relativistic context, time cannot be separated from the three dimensions of space. In humans, timekeeping systems, called biological clocks, continuously synchronise sleep and activity cycles to rotation and revolution of the Earth. Biological clock consist of the central pacemaker neurons in the hypothalamus and autonomous or semi-autonomous peripheral pacemakers in other parts of the body, like the gut, heart or liver (Fig. 1). The biological clock is reset by environmental factors, mainly by light. Light signals represent the most important synchronization of timegiver (Zeitgeber). In addition, a variety of external stimuli such as temperature, nutrient availability or social interactions, may contribute to phase resetting of the circadian clock. The timing system is based on 9 major clock genes expressed by clock cells (period, frequency, timeless, clock, cycle, double-time, shaggy, vrille, par domain protein 1ϵ, casein kinase 2). Cyclic expression of these genes is based on interlocking transcriptional and translational feedback loops, which generate circadian oscillations that drive output pathways and rhythmic behavior such as locomotor activity, feeding, mating, etc. [25, 26]. Circadian rhythms control body temperature, heart activity, hormone secretion, blood pressure, oxygen consump-

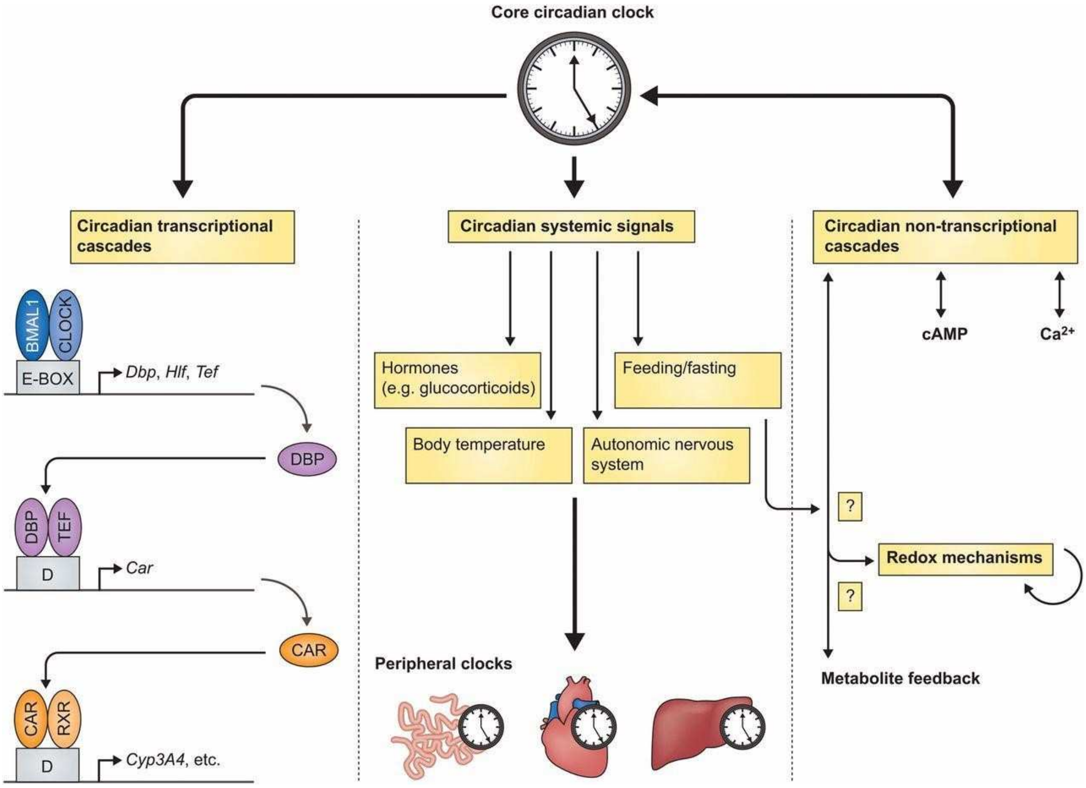

Figure 1. *The cellular regulation of clock-controlled processes can be achieved by direct clock gene expression via transcriptional cascades (left), systemic signals such as hormones, metabolic products and body temperature (center), and post-transcriptional cascades to propagate circadian signals to physiology, and vice versa (right). Credit: [18]*

tion and metabolism [14].

Perturbation of circadian rhythms, mainly caused by prolonged exposure to artificial light, has been well-documented to interfere with numerous aspects of health, and to provoke pathological conditions, including metabolic diseases such as obesity and type 2 diabetes (T2D), cardiovascular diseases, thrombosis, or cancer and neurodegenerative disorders [28]. Moreover, chronic sleep and circadian disruption cause extensive inflammation, modulated cortisol levels and significantly increased C-reactive protein (CRP), tumor necrosis factor α (TNFα), and other inflammatory cytokine levels in plasma [15].

2 Existing Solutions to Simulate Sunlight

For greenhouses, aquaria and other bioreactors, lamps are developed to optimize conditions for efficient and healthy organism growth. Several MELiSSA (Micro-Ecological Life Support System Alternative managed by European Space Agency) studies have been performed to optimize light spectra for plant development. It is already clear that different climatic factors affect different biological processes. In the case of plants, temperature induces development (genetically programmed sequence of events during life cycle, formation of new organs, transitions from vegetative into flowering or fruiting phases), while light in combination with CO2 induces plant growth (morphology, elongation, leaf thickness, length and mass) [24]. The assembly based on the composition of several colors of LED lights obtains the best spectrum, for example Bridgelux LED's offer a coral grow lamp, where each light contains 112 x 1 Watt LEDs, red/blue/orange/white at 19:3:3:3 ratio. Such lamps are used not only to enhance growth, but also to stimulate flowering, seeding and fruiting (when blue and red light is provided simultaneously), increase vegetation periods (blue light), or to simulate sunlight during cloudy days [7]. An important advan-

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Figure 2. *CoeLux solutions. Examples of the window-shaped lamps imitating natural solar light source. Credit: [4]*

tage of LED technology over traditional light sources in sun simulators, such as xenon short-arc lamps and metal halide discharge lamps, is that it enables studying specific spectra and real time monitoring of light influence on molecular changes in living organisms. This control capability of precise spectral output and light uniformity will improve operating efficiency and research results. In addition, LED technology will decrease the operating and maintenance costs of the lighting system due to instant on/off and extended life of LEDs [30].

Sunlight simulants also meet increasing interest of architecture and lighting companies in order to increase human comfort, well-being and energy efficiency of buildings. Existing solutions come out from disruptive technologies, which change the way the space is designed and lit. It is possible to simulate daylight in interior spaces using lamps imitating dawn, dusk and even the movement of the sun. The exact biological effect of the simulator on human health, however, remains unclear and needs further investigation.

The solar simulators are characterized by specifications concerning spectral content, spatial uniformity and temporal stability. An output of a sun simulator is expressed in suns. 1 sun is typically defined as the nominal full sunlight intensity on a bright clear day on Earth, which measures 1000 W/m2. Examples of solar simulators are available from Abet Technologies [12], Eternal Sun [9], infinityPV [3], Newport Oriel [13], TS-Space Systems [5], Photo Emission Tech [19], Sciencetech [2], Spectrolab [6], ProPhotonix [30], WACOM [4]. One of the most developed and advanced technologies is provided by the CoeLux (Fig. 2). CoeLux technology is adjusted for all types of indoor architecture, where it can change the way spaces are experienced [1].

3 Lighting System for Spacecrafts

Guidelines for designing lighting system for a spacecraft could be found in a chapter about lighting from Human Integration Design Handbook published by NASA in 2014 [29]. The habitat lighting system design process must start with a clear statement of its function and task, the characterisation of its locations and orientation and architectural features which will meet all the requirements. On the International Space Station (ISS) fluorescent lighting panels are replaced with solid-state LED lighting modules that produce blue, white, or red light depending on the time. Fluorescent lamps with magnetic ballasts flicker at a normally unnoticeable frequency of 100 or 120 Hz. For some individuals suffering for example from vertigo [11], or chronic fatigue syndrome, such flickering can cause problems.

LED lighting, however, has no flickering, which makes it more similar to the sunlight. Shifting from blue to red light through an intermediate white stage could help to simulate the typical day/night cycle in the spacecraft. The blue lighting is meant to stimulate the retinal photopigment melanopsin, as well as the hor-

Light	**Protein**	**Function**
300-365 nm	Carotenoids, Vit. D, serotonin, cryptochromes	Synthesis
198-380 nm	Interleukin IL-1, Prostaglandins D2, E2, F2⊠, Endothelin 1, Tumor necrosis factor (TNF⊠), Fibroblasts growth factor (bFGF), NO, beta-endorphines, trans-urocanic acid	Synthesis
419-477 nm	Melatonin	Suppression
Intense light, about 10,000 lux	Cortisol	Suppression

Table 1. *Examples of proteins sensitive to different types of light. Light can either induce or suppress the synthesis of these proteins in eye, skin or brain [17, 31, 22, 27, 16].*

mone melatonin, which helps a person to feel more alert and awake. The shift to red lighting reverses the process and helps to encourage feelings of sleepiness. This modification may help to sustain the body's circadian rhythms while in space and reduce insomnia, which can trigger deleterious effects.

Sleeping in space has long been a concern for NASA. A study showed that 50 percent of a Space Shuttle crews relied on medication to help sleep in orbit and nearly half of all medication used while in space was used to improve sleep. Unfortunately, the problem remains unsolved, since astronauts still lose their feeling about day and night on board of the ISS (private discussion with Andreas Mogensen and Jean-François Clervoy). Thus, the aim of this project is to look closer at biological adaptations to light, and based on this to propose and characterize generic tools for future lighting design.

4 Biological Requirements for Time Architecture

"Light impacts on our circadian rhythms more powerfully than any drug." Charles Czeisler, Nature 2013 [21]

Lighting needs for human health have to be recharacterized and reevaluated, since the discovery of a novel non-rod, non-cone photoreceptor in the mammalian eye that mediates a range of 'non-visual' responses to light. Existing literature provides useful information about how to quantify non-visual spectral sensitivities to light but the optimal approach is far from decided. A flexible framework to describe the non-visual spectral effectiveness of light using a common language with a unified description of quantities and units is actually developed [33].

Dissecting specific light wavelengths and intensities corresponding to circadian proteins is the key to finding requirements for future designs of the optimal human health lighting conditions [10]. Light strongly affects brain areas such as the cortex, hypothalamus and emotion centers. The circadian and neurobehavioral effects of light are primarily mediated by photosensitive melanopsins and cryptochromes in retinal cells of the eye. A clear influence-response relationship between the visible short-wavelength 420 nm light and melatonin suppression with a half-saturation constant of 2.74 × 1011 photons/cm2/sec was shown. Another study revealed, that 460 nm light is significantly stronger than 420 nm light for melatonin suppression. Interestingly, 419 nm was the most efficient wavelength to induce melatonin suppression and inhibitory gamma-aminobutyric acid (GABA) neurons. Also monochromatic light 460 nm or blue light enriched 6500K lamps were sufficient [17]. UV light can alter cutaneous serotonergic system with subsequent effects on the central nervous system affecting the mood [23]. Solar energy absorbed by skin results in the transformation of a chromophore-like trans-urocanic acid to its cis-isomer form revealing agonistic activity on serotonin receptor 2A [31]. UV radiation increases the synthesis of vitamin D, beta-endorphines [22] and proteins involved in the DNA repairing processes. UV exposure can suppress the clinical symptoms of multiple sclerosis independently of vitamin D synthesis. Furthermore, UV generates nitric oxide (NO), which may reduce blood pressure and generally improve cardiovascular health. UVA-induced NO may also have antimicrobial effects and act as a neurotransmitter [27]. Research suggests that visible blue light in 450-480 nm range provides an altering function to the brain [16] and may aid in stabilizing circadian cycles. Table 1 represents spectral dependence of light to synthesis or suppression of specific proteins. Since certain amounts of blue LED light exposure may induce retinal damage (blue light exposure

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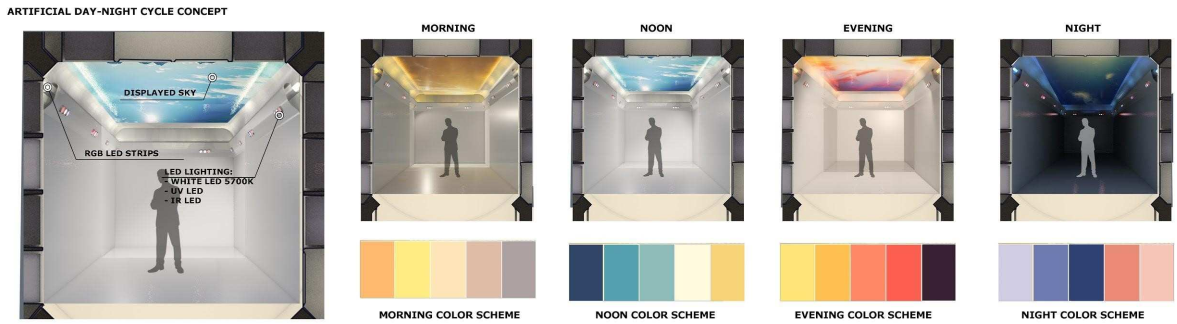

FIGURE 3. *Color palette used to simulate day, dawn and dusk lightning. RGB LED strips together with spotlights will simulate various times of a day.*

may cumulatively induce photoreceptor loss), the exact risks considering blue-light hazards for the pigmented human retina require further investigation [32, 8, 20].

5 Simulation of Day/Night Cycle by a Smart Lighting System

Our lighting system will mimic day and night cycles by creating an illusion of time passing. The sun's progression through the sky, along with sunrises and sunsets, is projected onto the ceiling using dedicated color pallets. Programmed RGB LED strips will simulate dawn, noon and dusk cycles by using morning, noon and evening color schemes. (Fig. 3) pursuing integrated design solutions.

In order to provide metabolic and homeostatic health of astronauts and reduce their problems with the melatonin cycle, the synthesis or suppression of specific proteins has to be induced by strengthening the light signals at specific wavelengths at specific times. Since the majority of clock proteins are activated by UV light, this high-energy radiation has to be used at low intensities to prevent DNA damage. The day/night cycle has to be framed within 24 h mode depending on the mission needs, which usually means 8h of night and 16h of day. The same lighting tools could simulate random weather systems, moon phases or seasons of the terrestrial year. The function of the system is not only to illuminate the base, but mostly to simulate day-night cycles by inducing clock protein cycles.

6 Experimental Design

An astronaut's circadian rhythm will be experimentally tested in the upcoming lunar analogue simulation campaign in August 2016 at the Polish Modular Analog Research Station (M.A.R.S.) (Fig. 4, up). Eight programmed types of LED lights (white LED 5700 K, UV 300 nm, violet 420 nm, blue 460 nm, green 500 nm, yellow 560 nm, red 700 nm and IR), and spectral spotlights will be installed in the facets just below the habitat's ceiling and evenly distributed on the contour of the room. A simulation of the sun's trajectory through the sky will be additionally assembled on the habitat's dome ceiling using high intensity bright light LED lamp combined with 8% of blue light (Fig. 4. bottom left). The simulation of solar movement will be provided by controlled mirror system located only in the central dome, while LED RGB strips with morning, noon and evening color schemes will be applied in all compartments of the habitat. Herewith, the possibility will be opened up to program different lengths of a day as well as various heights of simulated sun's trajectory. Directional heat, which will be used as an integral part of the habitat's thermal control system, will follow the artificial sun's movement, which might additionally contribute to the simulation of the solar effects. LED lights will be assembled in diverse modes depending on the number of specific LED lamps used (Fig. 4, bottom right): (A, B) spectral lamps with equal proportion of LED lights (14% of each sort of the wavelength type), (C, D) circadian lamps affecting clock protein synthesis by three or four reactive wavelengths (either 30% of 420 nm + 70% 460 nm and 500 nm, or 11% of 300 nm and 19% of 420 nm + 70% green).

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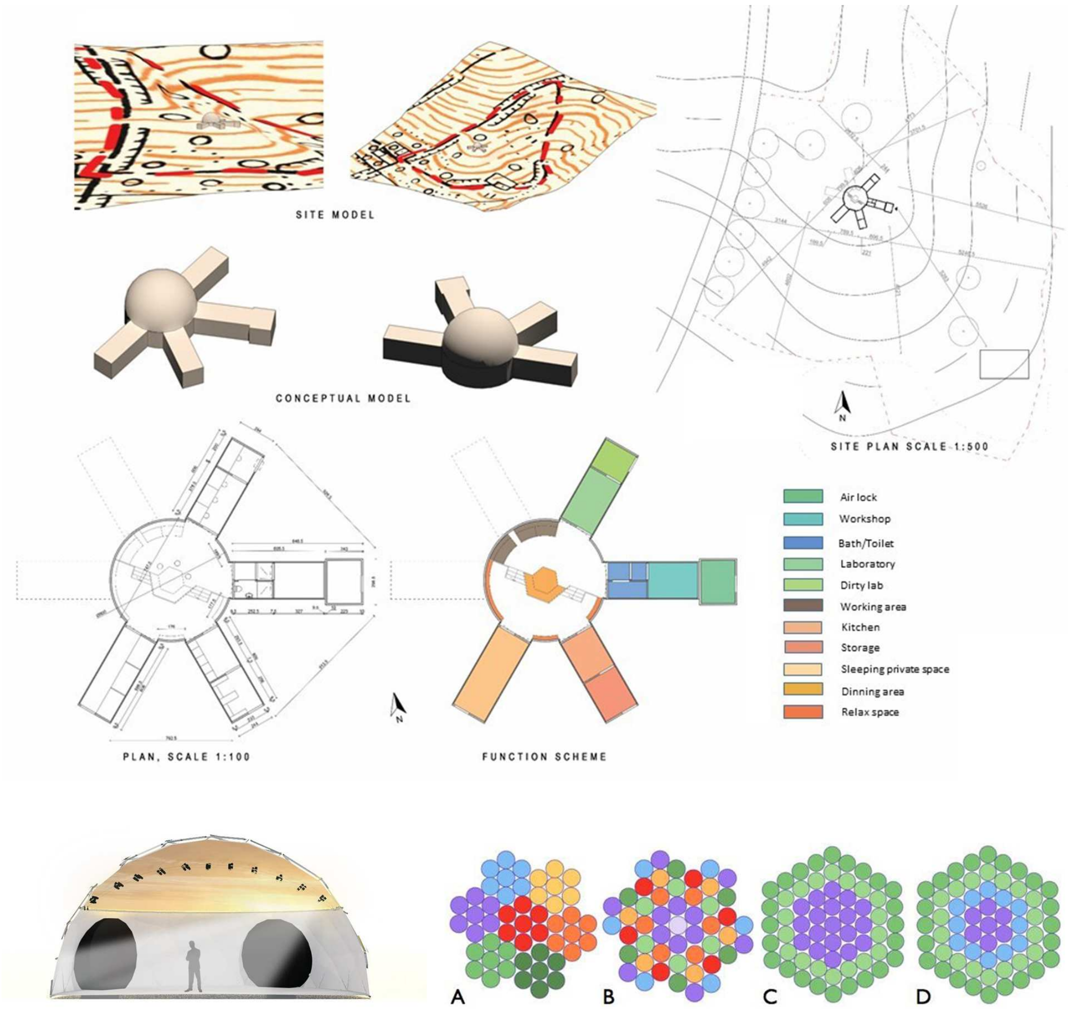

Figure 4. *The Modular Analog Research Station in Poland (ϕ=49°46'36".16 N, λ=21°05'22".27 E, h=351 m.n.p.m.). Conceptual model mounted in original site together with the plan and function scheme. Lighting setup in four elongated sections will be similar to the lighting in the dome using LED programmable lightning. Sun trajectory will be performed only in the central part of the base (up). Visualization of a sun trajectory across the sphere in the central part of the habitat using the mirror system (bottom, left). A various LED setups (bottom, right) will be tested to obtain different types of physiological lightning: spectral spotlights with seven various types of light wavelengths in clustered (A) and dispersed (B) configurations, circadian spotlights with UV, blue and green activation spectra (C, D).*

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7 Conclusion

Disruptive technologies in lighting and a better understanding of human physiology lead into a new era of healthy, smart, and economic way of building and living. The simulation of solar light in isolated spaces is a complex issue. The type of the light source, emission spectra and time duration have to be taken into account. LEDs are expected to become the primary light sources in the near future, including spacecrafts and space habitats. UV lighting is considered to be of a particular interest. UV light is also involved in the regulation of reproductive cycles in insects or in optimal plant and fish cultivation, which might be important in the future development of self-sustaining systems. It seems to be critical for activation and inhibition of specific photo-sensitive proteins, for example those, which synchronize the biological clocks of the astronaut crew and drives the physiological rhythms. In this paper we presented a concept design for a lighting system to improve metabolic and homeostatic health of astronauts and reduce their problems with the melatonin cycle. To achieve this, the synthesis or suppression of specific proteins has to be induced by strengthening the light signals at specific wavelengths at specific times. Since the majority of clock proteins are activated by UV light, the lighting system has an integrated UV lighting, which is used at low intensities to prevent DNA damage. In total our system has three components: a visualisation of a sky on the ceiling, spectral spotlights with seven various types of light wavelengths in clustered and dispersed configurations, and circadian spotlights with UV, blue and green activation spectra. The lighting system will be tested during the upcoming lunar analogue simulation campaign in August 2016 at the Polish Modular Analog Research Station (M.A.R.S.).

Author contributions

AK: concept proposal, writing manuscript, LO: lighting system design, graphic representations

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