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Solid-state lighting for the International Space Station: Tests of visual performance and melatonin regulation

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ABSTRACT

The International Space Station (ISS) uses General Luminaire Assemblies (GLAs) that house fluorescent lamps for illuminating the astronauts' working and living environments. Solid-state light emitting diodes (LEDs) are attractive candidates for replacing the GLAs on the ISS. The advantages of LEDs over conventional fluorescent light sources include lower up-mass, power consumption and heat generation, as well as fewer toxic materials, greater resistance to damage and long lamp life. A prototype Solid-State Lighting Assembly (SSLA) was developed and successfully installed on the ISS. The broad aim of the ongoing work is to test light emitted by prototype SSLAs for supporting astronaut vision and assessing neuroendocrine, circadian, neurobehavioral and sleep effects. Three completed ground-based studies are presented here including experiments on visual performance, color discrimination, and acute plasma melatonin suppression in cohorts of healthy, human subjects under different SSLA light exposure conditions within a high-fidelity replica of the ISS Crew Quarters (CQ). All visual tests were done under indirect daylight at 201 lx, fluorescent room light at 531 lx and 4870 K SSLA light in the CQ at 1266 lx. Visual performance was assessed with numerical verification tests (NVT). NVT data show that there are no significant differences in score ($F=0.73$, $p=0.48$) or time ($F=0.14$, $p=0.87$) for subjects performing five contrast tests (10%–100%). Color discrimination was assessed with Farnsworth-Munsell 100 Hue tests (FM-100). The FM-100 data showed no significant differences ($F=0.01$, $p=0.99$) in color discrimination for indirect daylight, fluorescent room light and 4870 K SSLA light in the CQ. Plasma melatonin suppression data show that there are significant differences ($F=29.61$, $p<0.0001$) across the percent change scores of plasma melatonin for five corneal irradiances, ranging from 0 to 405 $\mu W/cm^2$ of 4870 K SSLA light in the CQ (0–1270 lx). Risk factors for the health and safety of astronauts include disturbed circadian rhythms and altered sleep–wake patterns. These studies will help determine if SSLA lighting can be used both to support astronaut vision and serve as an in-flight countermeasure for circadian desynchrony, sleep disruption and cognitive performance deficits on the ISS.

1. Introduction

Known risk factors for the health and safety of astronauts and ground control workers include disturbed circadian rhythms and sleep loss [1,2]. Sleep and circadian

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problems have been documented in space flight missions as short as 10 days [3]. An analysis of pharmaceutical use during 79 space flight missions showed that sleeping pills or hypnotic compounds accounted for 45% of all medications taken by 219 astronauts [4]. Despite the use of these drugs, studies of more than 60 astronauts on space shuttle (Space Shuttle Transport System or STS) missions showed that approximately half of them slept 6 h or less per 24-hour mission day, even though they are scheduled to sleep for 8 h [5]. Chronic partial sleep loss can pose a considerable threat to the success of a mission by diminishing alertness, cognitive ability and psychomotor performance [3,6–10].

The International Space Station (ISS) uses General Luminaire Assemblies (GLAs) that house fluorescent lamps for illuminating the astronauts' working and living environments [11]. Solid-state light emitting diodes (LEDs) are attractive candidates for replacing the fluorescent lighting system on the ISS. The advantages of LEDs over conventional fluorescent light sources include lower up mass, power consumption and heat generation, as well as fewer toxic materials, greater resistance to damage and long lamp life [12]. A prototype Solid-State Lighting Assembly (SSLA) was developed at Kennedy Space Center and successfully installed on the ISS during Expedition 18. Since then, NASA has developed a set of specifications for the solid-state lighting system that will replace the existing fluorescent lighting system onboard ISS [13]. This new lighting system will provide multiple settings that can support astronaut vision and potentially serve as a lighting countermeasure for performance decrements due to sleep and circadian disruption aboard the ISS.

It is crucial to characterize the new solid-state lighting units for their circadian, neuroendocrine and neurobehavioral efficacy as well as their capacity to support astronaut vision. Non-visual information about light is detected by the eyes and transmitted by the retinohypothalamic tract, a neural pathway which projects to both visual and non-visual regions of the human brain [14,15]. These neural centers receive environmental photic input from a specialized subset of photoreceptive retinal ganglion cells containing the photopigment melanopsin [14,16–18]. It has been demonstrated that more light is required for circadian, neuroendocrine and neurobehavioral regulation than is needed for vision [19–21]. Further, a different wavelength sensitivity has been identified for the non-visual regulation of physiology and behavior compared to stimulating visual responses [22]. For example, studies have shown that exposing humans to light of sufficient intensity and duration at night suppresses the pineal gland hormone melatonin, with the strongest response occurring between 446 and 477 nm, the portion of the spectrum that has a blue appearance [23,24]. Further research has shown that blue monochromatic light at 460 nm is more effective than longer wavelength light at 550–555 nm for phase-shifting circadian rhythms and enhancing alertness levels [25–27]. In contrast, daytime vision has a peak sensitivity to light at 555 nm [28].

The broad aim of the ongoing work is to test light emitted by prototype SSLAs for supporting astronaut vision and assessing neuroendocrine, circadian, neurobehavioral and sleep effects. Three initial ground-based studies were conducted inside of a high-fidelity replica of the ISS Crew Quarters (CQ). The four CQs onboard ISS are acoustically quiet, visually isolated areas for crewmember sleep, relaxation and private retreat [29,30]. The studies presented here include experiments on visual performance, color discrimination, and acute plasma melatonin suppression in cohorts of healthy, human subjects under different SSLA light exposure conditions.

2. Materials and methods

2.1. Light production

The experimental light exposure system used in this study, the Solid-State Lighting Module-Research (SSLM-R), was based on the SSLA prototype installed on ISS in terms of mechanical and electronic connectivity. The SSLM-R, however, was developed as a research tool with significantly expanded capacity for variable light outputs. The SSLM-R was developed at Kennedy Space Center (Bionetics Corporation, Cape Canaveral, FL) and contained LED arrays of 294 white LEDs and 254 RGB LEDs behind a lens diffuser. Although the SSLM-R has a broad capacity for emitting different blends of polychromatic illumination, the experiments reported here only utilized light emitted by the white LEDs that have a spectral power distribution as shown in Fig. 1. Light intensity emitted by the SSLM-R was adjusted by a built-in current-controller. For the visual tests, comparisons were made with (1) indirect daylight from a window on a laboratory counter top that averaged 7042 K CCT and 221 lx (163 μW/cm^2) at the middle of the test site; and (2) overhead fluorescent room light at an average of 3531 K CCT and 531 lx (168 μW/cm^2) at the middle of the test site.

2.2. Light measurement

The spectral power distribution measurement, shown in Fig. 1, was taken using a Model FSHH 325-1075P FieldSpec handheld spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO). Routine light measures were taken using an ILT-1400BL radiometer/photometer (International Light Technologies, Inc., Peabody, MA). For irradiance measures the meter had a Model SEL033 detector with a silicon photodiode (#8376) with wide-eye diffuser input optic W#11990 and a flat response filter F#28875. Illuminance

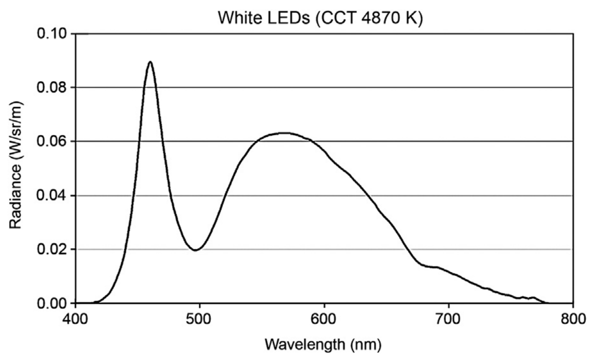

Fig. 1. Graph shows the spectral power distribution corresponding to the 4870 K polychromatic white light emitted by the SSLM-R.