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Effect of color temperature on melatonin production for illumination of working environments

Anja Kraneburg [a,*], Steffen Franke [b], Ralf Methling [b], Barbara Griefahn [a]

[a] Leibniz Research Centre for Working Environment and Human Factors, University of Dortmund, Dortmund, Germany
[b] Leibniz Institute for Plasma Science and Technology, Greifswald, Germany

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ABSTRACT

We studied the influence of correlated color temperature (CCT) of 7 polychromatic white light illuminations (1600 K–14,000 K, 200 lx) in two experiments.

Visual performance was tested in 17 students (8 men) during daytime. Visual acuity, contrast sensitivity and sleepiness did not vary with illuminations but polychromatic white light of <2000 K impaired color discrimination.

Melatonin synthesis was tested with weekly intervals in 8 trials from 10pm to 2am (7 polychromatic illuminations and a dim light reference (<0.1 lx)) in 16 students (9 men, semi-recumbent position). Melatonin suppression was almost negligible for CCT <2000 K but increased with increasing CCT.

Conclusions: CCTs <2000 K are not suitable for work places. Polychromatic white light with higher CCTs and significant melatonin suppression is expected to shift the circadian rhythm and to accelerate the adaptation to night work. This effect should be enhanced with elevation of luminance.

1. Introduction

Night work is an essential prerequisite for the functioning of human societies, e.g. in health care, provision of energy and water, communication services, traffic control and security maintenance, restaurant services and entertainment. However, light at night leads to chronodisruption (Erren and Reiter, 2008). Here the suppression of the hormone melatonin plays a major role. Melatonin transfers the environmental light situation into the organism and thus mediates the synchronization of the physiological rhythms with the natural light-dark schedule. Melatonin is therefore the best marker for the actual phase position and for chronodisruption (Arendt, 2010, 2006). Chronodisruption is associated with dissociations between various physiological rhythms (Goichot et al., 1998; Weibel et al., 1996). Thus night work is a mismatch between the timing of work demands and people's chronobiologically determined capacity to cope adequately and can have serious health effects. Acute effects are insomnia with sleepiness and fatigue during work shifts along with impaired performance (Dinges, 1995; Lockley et al., 2006) and an increased risk of accidents and associated injuries (Smith et al., 1994). In the long run, shift work contributes to the genesis of cardiovascular (Bøggild and Knutsson, 1999) and gastrointestinal diseases (Knutsson, 2003) and even to cancer (Megdal et al., 2005) as well as to decrements in psychological well-being (Bara and Arber, 2009; Øyane et al., 2013).

Adverse effects of night work might be reduced when the individual circadian rhythm is shifted accordingly (Crowley et al., 2003). Spontaneous shifts of the circadian system were observed in experimental night work studies but were usually less than 1 h per day (Horowitz and Cade, 2001; James et al., 2004; Weibel and Brandenberger, 1998). In the real life situation light scenarios at night compete with the natural light-dark cycle thus preventing considerable shifts. Accordingly, a metaanalysis performed by Folkard has shown that only a few permanent night workers (<3%) adapt completely to night work (Folkard, 2008) as indicated with the melatonin profile.

Adaptation to night work, i.e. the synchronization of the circadian rhythm with the (inverted) sleep-activity rhythm can be accelerated with accordingly designed light scenarios at the workplace. Artificial light can have the same chronobiological properties as natural light. It can suppress melatonin production and delay or advance the circadian rhythm when applied in the early or in the late night respectively (Czeisler et al., 1986;

* Corresponding author.
E-mail address: kraneburg@ifado.de (A. Kraneburg).

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Shanahan et al., 1997; Zeitzer et al., 2000). Thus numerous studies performed in the lab and in the field as well focused successfully on the development of light scenarios that enforce the circadian shift, usually the delay of the circadian system (Czeisler et al., 1986; Eastman and Martin, 1999; James et al., 2004; Shanahan et al., 1997). Most studies have been done with polychromatic white light where clear dose-response relations were established. Both the degree of melatonin suppression and the extent of the phase shifts increase with light intensity (Boivin et al., 1996; Zeitzer et al., 2000).

A major impact on the extent of the chronobiological effects of light is related to the wavelengths of light (Brainard et al., 2001; Thapan et al., 2001). Extended experiments with monochromatic light revealed action spectra where the degree of melatonin suppression and of the shift of the circadian system decrease with increasing wavelengths, i.e, blue light has stronger effects than red light (Brainard et al., 1984; Morita and Tokura, 1998; Revell et al., 2005; Thapan et al., 2001).

1.1. Aims of this study, hypotheses

Monochromatic light impairs visual performance, in particular color discrimination and is therefore inconvenient at the worksite. Unimpaired vision requires polychromatic white light. The relevance of the spectral composition of polychromatic light (i.e. the amount of short wavelengths) for the extent of chronobiological effects was tested in a few studies. They compared not more than 2 or 3 polychromatic light sources, where illuminance levels were not always comparable (Kozaki et al., 2008; Kozakov and Schoepp, 2011; Morita and Tokura, 1996; Van de Werken et al., 2013; Wahnschaffe et al., 2013). None of them tested visual performance. Therefore, we studied the effects of 7 polychromatic white light illuminations covering a wide range of correlated color temperatures (CCT) from 1600 K to 14,000 K at a fixed illuminance level of 200 lx on visual performance in experiment 1and on melatonin synthesis in experiment 2.

We adopted the following hypotheses.

- Polychromatic white light with a reduced amount of short wave lengths (blue light, low CCT) affects color discrimination but not visual acuity and contrast sensitivity for which the green-yellow part of the spectrum is more important.
- Melatonin suppression increases with the amount of short wavelengths within polychromatic light spectra. However, for light sources that fulfill the requirements for undisturbed visual performance, i.e. a limited range of polychromatic white light, the differences are rather moderate. (Major differences would allow the selection of suitable light sources for the prevention and the enhancement of phase shifts, i.e. illumination with strong and weak melatonin suppression, respectively.)

2. Materials and methods

2.1. General overview

2.1.1. Ethics

Both experiments were conducted according to the Declaration of Helsinki and approved by the Local Ethics Committee.

2.1.2. Location

The experiments were conducted at the Leibniz Research Centre for Working Environment and Human Factors at TU Dortmund, Germany. We used 3 identical rooms of 2.40 × 5.60 square meters and an overall height of 3.90 m. Each of these windowless rooms was equipped with 2 ceiling luminaires of 0.90 × 0.90 square meters positioned 3 m above the ground level. Due to the design of the luminaires including a double-diffusion chamber optics and the white colored side walls an approximately evenly distributed illumination throughout the rooms was achieved. The ceiling luminaires could be simultaneously equipped with three different light sources for a smooth change of the color temperature of the illumination. Further equipment is specified in Section 2.1.1.

2.1.3. Screening procedure and participants

Screening. The participants were students recruited at the Universities of Dortmund and Bochum. All applicants filled in a short questionnaire on health to exclude those younger than 18 or older than 30 years, those with chronic diseases or color blindness. Those who applied for participation in Experiment 2 were further asked about their usual bedtimes, whether they had done night work or changed between time zones within the last six months. Those who passed these questionnaires were invited for a screening procedure that focused on visual acuity, contrast sensitivity, color blindness and color discriminability.

Visual acuity was assessed at standard room light (4200 K, 300 lx) with Landolt charts while the subjects stood at 5 m distance. According to the Guideline 37 of the German Social Accident Insurance (DGUV) for work at monitors we regarded a visus of at least 0.8 as sufficient (Grundsatz für arbeitsmedizinische Vorsorgeuntersuchungen “Bildschirmarbeitsplätze” G 37, BGG 904–937 (BGG, 2010)).

Contrast sensitivity, an important parameter for visual performance (Darius et al., 2010) was assessed with ETDRS charts (Sloan letters, 4 m distance).

After screening for color blindness (Ishihara Tables), color discrimination was tested with the Farnsworth-Munsell 100 Hue test (Farnsworth, 1957), using a table light illumination (see illumination L8 in Table 1 below) of 6500 K and 2500 lx, as recommended for this test.

Due to the results of these tests, the visus of our subjects varied between 1.00 and 1.25, contrast sensitivity was at least 2.5 and color discrimination was “average” or “superior” according to the norm determined for the Farnsworth-Munsell 100 Hue test (Farnsworth, 1957).

Participants. Nine healthy women and 8 healthy men (20–27 years of age) participated in experiment 1. Eighteen healthy subjects took part in experiment 2. None of them had ever done night work or traveled across time zones within the previous 6 months and all of them went to bed habitually before 12 p.m. One subject retreated due to personal reasons, another one was suspended due to undisciplined behavior. The analysis bases therefore on the data of 7 women and 9 men (19–28 years of age).

2.1.4. Illuminations

From the photometric point of view, illumination can be characterized by properties like the luminance (given in cd/m^2), the illuminance (given in lx), the general color rendering index (CRI), the correlated color temperature (CCT, given in K) and the color difference (DC) to the Planckian locus. A color difference less than 5E-2 was required to ensure white light illumination without color fault and the CRI should reach at least a value of 80 – as usual for general lighting applications. Finally, different spectra with a wide range of CCTs were applied to investigate the effects on melatonin synthesis.

In both experiments, 5 types of commercially available fluorescent lamps (16 mm diameter, 849 mm length) with different CCTs were used. CCT was slightly reduced by the double-diffusion chamber optics of the luminaire. A further reduction of CCT is achieved by the application of color filters. The resulting polychromatic white light illuminations are characterized by CCTs