Applied Ergonomics 58 (2017) 446–453

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

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

ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form
4 August 2016
Accepted 5 August 2016
Available online 17 August 2016

Keywords:
Chronodisruption
Polychromatic light
Melatonin
Night work
Shift work
Phase shift
Melatonin suppression

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).

http://dx.doi.org/10.1016/j.apergo.2016.08.006
0003-6870/

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

Table 1
Technical data of the illuminations as used in experiments 1 and 2.

	Illuminations, technical data:						Used in:experiment			
	Trade name of lamp/device	Additional red filter	CCT	Melatonin-suppression factor	Ilumi-nance (lx)	Location of lamp	Experiment 1			Exper. 2
							Visual acuity	Contrast sensitivity	Color discri-imination	
L1	OSRAM T5 HO 39W/82	x	1600	0.092	200	Ceiling	X	X	X	X
L2	OSRAM T5 HO 39'W/840	x	1950	0.137	200	Ceiling	X	X	X	X
L3	OSRAM T5 HO 39W/827		2750	0.263	200	Ceiling	X	X	X	X
L4	OSRAM T5 HO 39W/840		3900	0.459	200	Ceiling	X	X	X	X
L5	NARVA T5 "HQ Bio vital", 39 W		6100	0.826	200	Ceiling	X	X	X	X
L6	OSRAM T5 HE 21W/880		7100	0.892	200	Ceiling	X	X	X	X
L7	NARVA T5 "Oceanic Blue", 39 W		14,000	1.265	200	Ceiling	X	X	X	X
L8	UnityColor Light2go, D65 (reference E1)		6500	–	2500	Table			X	
L0	Dimmed incandescent lamp (ref E2)		–	0	<0.1	Ceiling				X

CCT: Measured correlated color temperature (Kelvin); lx: unit of illuminance measured for a horizontal surface in 0.85 m height; Red Filter: Further reductions of the CCT of 2 lamps were achieved by application of color filters (LEE Filter 204 Full C.T. Orange); Melatonin suppression calculated according to the action spectrum of Gall and Lapuente (Gall and Lapuente, 2002; Kozakov et al., 2008).

ranging from 1600 K to 14,000 K (see Table 1). The fluorescent lamps inside the illuminants were powered by an electronic ballast delivering currents of sine-like waveforms typically with frequencies of around 50 kHz – so no flicker occurs. The change of illumination, i.e. from one type of fluorescent lamps to the other, was carried out slowly – within few seconds.

Color difference (DC) and general color rendering index for the applied illumination were verified to stay within the above given limits. Even for illuminations with CCTs below 2000 K the photometric properties were obtained according to CIE standards (CIE 15:2004. Colorimetry. CIE Technical Report, ISBN 3 901 906 33 9 (Commission Internationale de L'eclairage, 2004)) with Planckian radiators of CCT as reference illuminants.

Furthermore a table light illumination (UnityColor Light2go with standard light D65, a mobile fluorescent lamp for color matching, inspection and assessment) with 6500 K was used in experiment 1.

All CCTs of the polychromatic white light iluminations were measured on site (by means of a compact spectrometer from Avantes) with the fluorescent lamps installed in ceiling luminaires taking account of the transmission of opal glass pane (double-diffusion chamber optics) of the luminaire. The lower CCTs of illuminations L1 and L2 were achieved using the fluorescent lamps of illuminations L3 and L4 with additional color filters (LEE Filter 204 Full C.T. Orange) installed in the lamp device. This color filter has a high transmission in the red and the yellow spectral range and a much lower transmission for shorter wavelengths. This reduces the amount of light in the blue range that is known to be mainly responsible for the suppression of melatonin synthesis. For all illuminations the horizontal illuminance was set to 200 lx (measured at 0.85 m above ground level) with an average luminance in the field of view around 50 cd/m^2. It should be noted that the measured vertical illuminance at the position of cornea was also around 200 lx. The motivation for a horizontal illuminance of 200 lx is that an effect on melatonin expression is expected for any kind of polychromatic white light if the illuminance exceeds a certain limit. To study the effect of illuminations with different CCTs it is therefore reasonable to choose a rather low illuminance.

The table light illumination, which is used as reference for color discrimination only, had a non-adjustable luminance of 2500 lx.

2.1.5. Statistics

All statistical analyses (analysis of variance, ANOVA) were performed using SPSS (IBM SPSS Statistics, version 22). For the post-hoc testing the Bonferroni-Holm procedure (Holm, 1979) was used, a step-down method correcting for multiple comparisons, with the initial α-level set to 0.05.

2.2. Experiment 1, visual performance

Experiment 1 focused on the effects of 7 illuminations with different CCTs (see Section 2.2.2) on visual acuity (measured with Landolt charts), contrast sensitivity (measured with ETDR charts) and color discrimination (ascertained with the Farnsworth-Munsell test). It was expected that spectra with very low CCTs affect only color discrimination. As this experiment focused on visual performance only, the tests were performed during daytime. Melatonin concentrations were not measured as its synthesis is then rather negligible.

2.2.1. Participants

Nine healthy women and 8 healthy men (20–27 years of age) participated in experiment 1 (see also Section 2.1.3).

2.2.2. Illuminations

Therefore we applied the 7 polychromatic white light illuminations specified in Table 1 (L1-L7) at a fixed illuminance level of 200 lx. The table light illumination (UnityColor Light2go with standard light D65, Ill. 8, see Table 1) served as reference for color discrimination.

2.2.3. Experimental procedure and data analysis

The experiments started at either 10 a.m. or 2 p.m. and lasted approximately 2.5 h. Each experiment consisted of 8 trials of 15 min each, followed by breaks of 5 min i.e. enough time for rest and adaptation to the new illumination. The 7 polychromatic white light illuminations and the reference light condition (L1-L8) were in a pseudo-randomized order assigned to the 8 trials. The sequences used were constructed according to a Latin Square design, resulting in 8 sequences (8 illuminations). Each sequence was used twice except for one being used 3 times (17 subjects). In the reference condition with a table light of 6500 K and 2500 lx (L8) the subjects absolved only the Farnsworth-Munsell 100 Hue test for color discrimination. In each of the other 7 trials visual acuity, contrast sensitivity and color discrimination were tested using the same tests as described for screening (Section 2.1.3).

Color discrimination for the experimental illuminations was regarded as suitable for the workplace if it did not differ

significantly from the reference situation and was not worse than average color discrimination according to the norm of the Farnsworth-Munsell 100 Hue test.

2.3. Experiment 2, melatonin suppression and subjective assessment

Experiment 2 was designed to investigate the effect of illuminations with different CCT on melatonin suppression and subjective assessment. These measurements were performed during habitual bed time, when melatonin levels usually rise and compared with a dim light control condition. We applied the same 7 polychromatic white light illuminations used in Experiment 1 at a fixed illuminance level of 200 lx to identify the sole effect of CCT. It was expected that spectra with very low CCT scarcely affect nocturnal melatonin suppression.

2.3.1. Participants

Nine healthy young men and 7 healthy young women (19–28 years of age) completed the 8 trials (see also Section 2.1.3).

2.3.2. Illuminations

The same 7 polychromatic white light illuminations were used as in experiment 1 (see Table 1), likewise with a fixed horizontal illuminance of 200 lx. The control condition was a dim light condition provided by several dimmed incandescent lamps regulated down to <0.1 lx.

2.3.3. Experimental procedure and data analysis

Each subject completed with weekly intervals 8 sessions with different illuminations. The subjects came to the lab in the evening and were seated into comfortable recliner seats. They were instructed to leave their eyes open all the time. They remained in the lab from 8 p.m. until 2 a.m. The illumination in the first 2 h was always a dim light situation with <0.1 lx provided by incandescent lamps. At 10 p.m. the illumination was set to one of the illuminations L1-L7 or remained at < 0.1 lx in the control condition, the order was pseudo-randomized. Saliva samples were collected half-hourly. A cotton wool swab Salivette™ (Sarstedt) was moved within the mouth until soaked with saliva and centrifuged immediately thereafter. Saliva was then stored at −20 °C until assayed. Melatonin concentrations were determined using an enzyme-linked immunosorbent assay (ELISA, IBL). The detection limit was 0.3 pg/ml.

After the initial 2 h in dim light and only in the 7 trials with test illuminations the subjects filled in – just after the half-hourly saliva collection – the following questionnaires: Momentary felt alertness was ascertained with the German version of the Stanford Sleepiness Scale (SSS) (Hoddes et al., 1973). Pleasantness of the present illumination was rated using a 10 point likert scale (1 = very pleasant to 10 = very unpleasant). To measure the momentary felt energetic arousal and tenseness the subjects filled in the German version of the Activation-Deactivation Adjective Check List (AD-ACL) (Thayer, 1967).

3. Results

3.1. Experiment 1, visual performance

3.1.1. Visual acuity and contrast sensitivity

To analyze if there are differences between the light conditions the total error score of the Landolt test (for visual acuity) and the ETDRS test (for contrast sensitivity) were entered in a repeated measures ANOVA, respectively, with within-subject factor illumination (7 levels: illumination L1-L7). There was no significant result neither for the error score of the Landolt chart test nor for the error score of ETDRS test indicating that color temperature did not influence the visus value or the contrast perception.

3.1.2. Color discrimination

To analyze the deviation from the reference illumination the error score of the color discrimination test was entered in a repeated measures ANOVA with within-subject factor illumination [8 levels: L1-L7, L8 as reference]. There was a significant main effect [$F(2.887, 46.192) = 22.001$, $p < 0.001$, Greenhouse-Geisser adjusted]. Post-hoc Bonferroni-Holm pairwise comparison revealed larger error scores for the two illuminations with CCT <2000 K as compared to the reference illumination L8 (6500 K) (see Table 2).

The ability to discriminate colors correctly under the 7 illuminations was compared to the reference illumination. The results are depicted in Fig. 1. The average discrimination was under illuminations L1 and L2 (both < 2000 K) no longer within the norm range of the Farnsworth-Munsell 100 Hue test (Farnsworth, 1957). Instead, the error scores of these illuminations L1 (L1: 138.59, SD = 16.539; L2: 104.94, SD = 43.67) indicated insufficient color discrimination.

3.2. Experiment 2, melatonin suppression and subjective assessment

3.2.1. Hormonal data

Fig. 2a shows half-hourly measured mean salivary melatonin concentrations from 8 p.m. to 2 a.m. for each of the 8 light conditions. The ascents of the increase of melatonin levels within the first 2 h under dim light seem to flatten after the onset of test illuminations. To illustrate the increase of melatonin levels under the influence of light melatonin levels at 10 p.m. (onset of light exposure) were set to 0 in Fig. 2b. This reveals the steepest increase for the control condition, followed by conditions with polychromatic light with CCT <2000 K. The flattest increase was measured for illuminations with CCT >7000 K.

Fig. 3 presents melatonin production as indicated by the Area under Curve (AUC) calculated for the 8 successive time points after 10 p.m. (onsets of test illuminations L1-L7 or continuation of control illumination) until 2 a.m. for each condition. It reveals highest values in the dim light situation, an only small melatonin suppression under illuminations with CCT <2000 K and strong melatonin suppressions under illuminations with CCT of 3900 K and more.

The AUC values were entered in a repeated measures ANOVA with within-subject factor illumination [8 levels: test illuminations L1-L7, control illumination L0]. There was a significant main effect for illumination [$F(7, 105) = 10.3$, $p < 0.001$]. Post-hoc Bonferroni-Holm pairwise comparison revealed smaller AUC values compared to the control illumination (L0, <0.1 lx) for illuminations L4-L7 (see Table 3). Furthermore, the AUC values under L4-L7 were significantly lower than under L1 and AUCs under L3-L7 were significantly smaller than under L2 (see Table 3).

Table 2
Statistical parameters of the color discrimination analysis (error score of the Farnsworth-Munsell 100 Hue Test) of all subjects under illuminations L1-L7 compared to the reference condition (L8) (only significant comparisons (Bonferroni-Holm procedure) with $p \leq 0.05$ are listed).

Experiment 1 – Statistical Parameters for the Color discrimination analysis			
Comparison	Mean difference	Standard error	p-value
L8 vs. L1	−67.765	16.097	0.001
L8 vs. L2	−101.412	21.579	<0.001

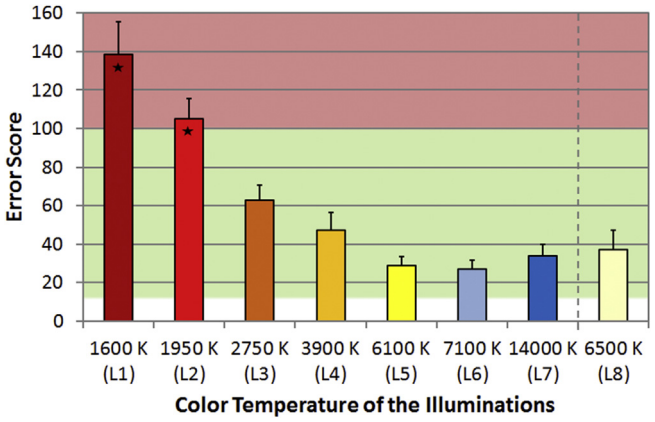

Fig. 1. Bar chart of mean error scores for color discrimination (Farnsworth-Munsell 100 Hue test error score on y axis) of all subjects under illuminations L1-L8 (on x axis). The error bars indicate standard errors, the asterisks significant differences compared to the reference illumination (L8). The white background at the bottom indicates superior (<16 errors), the green background sufficient (16–100 errors) and the red background insufficient discrimination (>100 errors). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

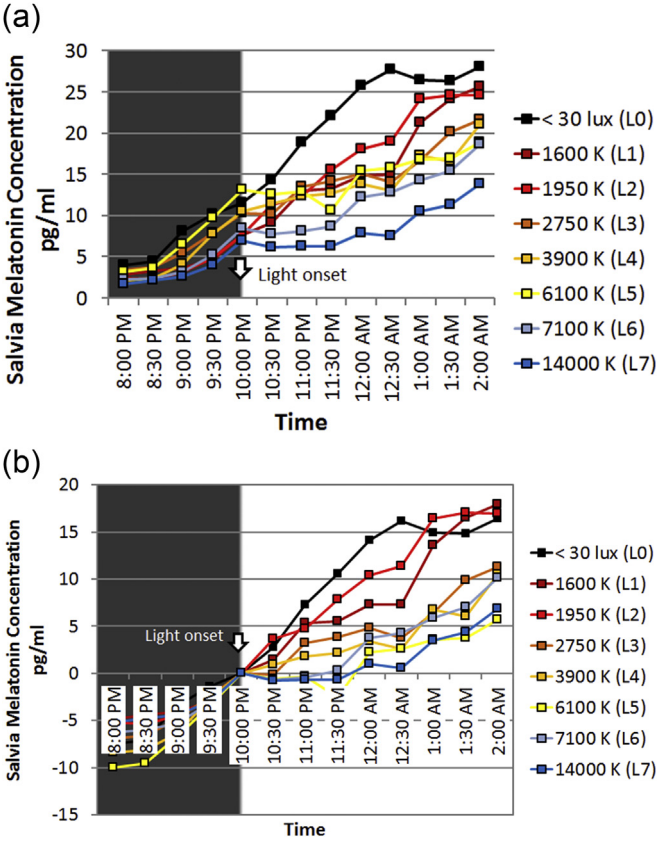

Fig. 2. a: Mean salivary melatonin concentrations of all subjects over time (8 p.m.–2 a.m.) under illuminations L1-L7 and the control condition (L0). The arrow at 10 p.m. indicates light onset in the illumination conditions L1-L7. b: Mean salivary melatonin concentrations of all subjects over time (8 p.m.–2 a.m.) under illuminations L1-L7 and the control condition (L0) with concentrations at 10 p.m. set as zero point. The arrow at 10 p.m. indicates light onset in the illumination conditions L1-L7.

3.2.2. Subjective assessment

As some subjects missed to fill in their questionnaires at some time points, their data were excluded from further analysis

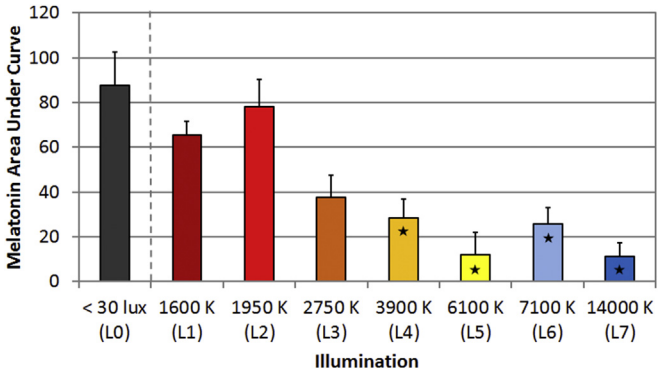

Fig. 3. Bar chart of mean melatonin production indicated by integrated Area under Curve (10:30 p.m. – 2 a.m.) of all subjects under illuminations L1-L7 and the control condition (L0) with concentrations at 10 p.m. set as zero point. Error bars indicate standard errors and asterisks significant differences compared to the control illumination (L0).

Table 3
Statistical parameters of melatonin production. Mean integrated area under curve (10:30 p.m. – 2 a.m.) of salivary melatonin concentrations of all subjects under illumination L1-L7 compared to the control condition (L0) with 10 p.m. set as zero point (only significant comparisons (Bonferroni-Holm procedure) with $p \leq 0.05$ are listed).

Experiment 2 – Statistical Parameters for the hormonal analysis (melatonin)			
Comparison	Mean difference	Standard error	p-value
L0 vs. L4	59.116	15.520	0.002
L0 vs. L5	75.628	16.854	<0.001
L0 vs. L6	62.015	20.405	0.008
L0 vs. L7	76.395	14.308	<0.001
L1 vs. L4	36.835	10.588	0.003
L1 vs. L5	53.347	11.461	<0.001
L1 vs. L6	39.734	8.511	<0.001
L1 vs. L7	54.114	7.162	<0.001
L2 vs. L3	40.737	12.325	0.005
L2 vs. L4	49.720	9.994	<0.001
L2 vs. L5	66.232	17.792	0.002
L2 vs. L6	52.620	11.397	<0.001
L2 vs. L7	67.000	12.621	<0.001

resulting in a sample size of n = 11 for the SSS values, n = 13 for the AD-ACL values and n = 11 for the pleasantness ratings of the illuminations. The statistical procedure was the same for all subjective variables: The values were entered in a repeated measures ANOVA with within-subject factor time (8 levels: time points every half hour, starting from 10:30 p.m. – half an hour after light onset – until 2 a.m.) and illumination [7 levels: test illuminations L1-L7].

Stanford Sleepiness scale (SSS). The ANOVA revealed a significant main effect for time [$F(2.808, 30.888) = 73.218$, $p < 0.001$, Greenhouse-Geisser adjusted] but not for illumination and no significant interaction effect. As the development over time was not in the focus of our interest this aspect was not elaborated any further.

Pleasantness ratings. The results of the ANOVA showed a main effect for illumination [$F(6, 60) = 3.407$, $p = 0.006$] and time [$F(1.882, 18.818) = 4.004$, $p = 0.038$, Greenhouse-Geisser adjusted] but no interaction effect. As indicated by the means, illumination L4 was rated highest (mean = 6.000), signifying least pleasant and illumination L1 was rated lowest (mean = 3.841), signifying most pleasant. As no illumination was rated as unpleasant [range means: 6.000 (illumination L4) to 3.841 (illumination L1)] all illuminations were judged as suitable for night work.

Activation – Deactivation. Separately calculated ANOVAs for the

2 dimensions of the AD-ACL, revealed no main effect of illumination for dimension A (energetic arousal). The dimension B (tenseness) had a possible main effect for illumination [$F(6, 72) = 2.287$, $p = 0.045$] but the post-hoc Bonferroni-Holm pairwise comparison did not support these findings (no significant pairwise comparison), therefore it was not considered any further.

4. Discussion

We tested 7 polychromatic illuminations with correlated color temperatures (CCT) from 1600 K to 14,000 K and expected that melatonin suppression increases with the amount of blue light, i.e. with increasing CCT. This should allow the identification of light that more or less preserves or suppresses melatonin synthesis. Zeitzer et al. (2000) have shown that both, the extent of melatonin suppression and the extent of the shift of the circadian system, increase with increasing illuminance level. An analog association is expected for increasing CCT, meaning that the extent of melatonin suppression might hint to the potential phase shifting power of CCT. As we focused on the suitability of polychromatic white light at the work place we also tested visual performance in terms of visual acuity, contrast sensitivity and color discrimination. As another criterion we ascertained subjective assessment of the 7 light conditions in terms of sleepiness, pleasantness and activation.

4.1. Methodological considerations and limitations

Due to the applicability at work places we did not dilate the pupils of the participants, a procedure that is most valuable for basic research as e.g. performed by Brainard et al. (2001) and by Thapan et al. (2001) (Brainard et al., 2001; Thapan et al., 2001). This contributes most likely to the relative small differences between the effects of polychromatic illuminations with CCTs >2000 K in our study.

The experiments were conducted in an artificial situation of an especially prepared laboratory and only with young and healthy persons. Thus our findings might deviate quantitatively from effects that might be observed in real life working situations, in older and in unhealthy persons. The results of this study are nevertheless a suitable basis for both directed experiments and field studies.

4.2. Visual performance

None of the 7 polychromatic illuminations affected visual acuity and contrast sensitivity. Color discrimination worsened, however, significantly under both illuminations with CCTs <2000 K (L1 and L2, see Fig. 1) (Strasser, 1993; Wyszecki and Stiles, 1982). Although the spectral remission coefficients of the test colors used in the Farnsworth-Munsell 100 Hue test are not available it is reasonable to attribute the poor color recognition to the reduced amount of short wavelengths (blue light) in the spectra at CCTs < 2000 K. A sufficient color rendition cannot be expected, if significant parts of the visible spectrum are missing. It should be noted that the German standard DIN 06169–2:1976 for determination of color rendering properties requires a minimum CCT for reference illuminants of 2300 K.

4.3. Subjective assessment

Cajochen et al. exposed their subjects to white light with intensities from 3 to 9000 lx and found a dose dependent increase of alertness (assessed by EEG activity) and a reduction in self-reported sleepiness (Cajochen et al., 2000). The latter correlated with the degree of melatonin suppression. We therefore expected for our study with a fixed illuminance of 200 lx but varying CCT, that sleepiness as ascertained with the Stanford Sleepiness Scale decreases with decreasing melatonin levels, due to increasing CCT. This assumption was, however, not verified. Our results are, on the other hand, in line with other studies in which color temperature of polychromatic light was manipulated by filtering out lower wavelengths (Kayumov et al., 2005; Rahman et al., 2011; Van de Werken et al., 2013).

We also could not find a significant influence of CCT on activation (energetic arousal or tenseness), as indicated by the dimension 1 and 2 of the AD-ACL. This contradicts the results of van de Werken et al., who applied the same test but found a negative influence of short-wavelength attenuated light using the same test (Van de Werken et al., 2013). This might, however, be explained by the fact that light intensity of the attenuated light was lower (193 lx) than that of the full spectrum light (256 lx). Pleasantness did as well not vary with the 7 polychromatic white light Illuminations tested here. Thus the illuminations are rather equal with respect to subjective assessment.

4.4. Melatonin production

Experiment 2 consisted of 8 trials that were performed at weekly intervals. In each trial salivary melatonin concentrations were measured half-hourly, first for 2 h under dim light (<0.1 lx) and then for 4 h again under dim light in the control condition or under one of the 7 polychromatic white light illuminations with CCTs between 1600 and 14,000 K and a fixed illuminance of 200 lx. The experiments revealed that melatonin production under illuminations of up to 2750 K (L1- L3) did not differ significantly from the dim light situation (L0). Illuminations with higher CCTs (L4-L7) were, however, associated with significantly lower melatonin levels (see Figs. 2 and 3.). Rea et al. developed a complex model that describes the dependency of melatonin suppression on spectra with different CCTs (Rea et al., 2012). A less complex model of circadian action was suggested by Kozakov et al. who used the action function suggested by Gall and Lapuente to obtain melatonin suppression factors (Gall and Lapuente, 2002; Kozakov et al., 2008). These melatonin suppression factors are given in Table 1 for the illuminations used in this study. The actual melatonin levels observed in our experiments are as indicated by the Area under Curve related to these suppression factors in Fig. 4. This figure suggests a decay of melatonin concentration with increasing melatonin suppression factor and hence with increasing CCT.

These results are supported by other studies where the effects of 2 or 3 different polychromatic illuminations were applied. Van de

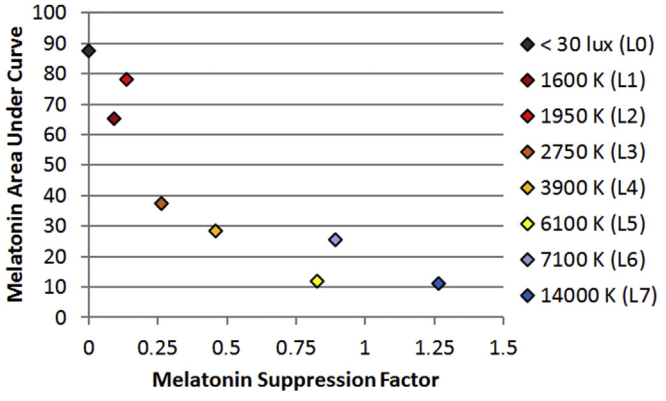

Fig. 4. Mean integrated Area under Curve (10:30 p.m. – 2 a.m.) of salivary melatonin concentrations of all subjects under illuminations L1-L7 and the control condition (L0) with concentrations at 10 p.m. set as zero point in relation to the melatonin suppression factor.

Werken and colleagues compared the effects of a full spectrum light with a short-wavelength attenuated polychromatic white light of about 3000 K and found that the latter caused a rather negligible melatonin suppression (Van de Werken et al., 2013), Kayumov et al. blocked low-wavelengths of less than 530 nm and observed then smaller chronobiological effects in terms of melatonin suppression and circadian delays (Kayumov et al., 2005). Rahman et al. supplied 14 nurses with spectacles that filtered wavelengths of less than 480 nm and found then higher melatonin levels (Rahman et al., 2011).

Based on the significances of the pairwise comparisons of melatonin production and visual performance determined under different light conditions, the 7 polychromatic illuminations (L1-L7) administered in our experiments could be divided into 2 groups: The first group consists of 2 rather 'red' illuminations with CCTs < 2000 K (L1, L2). These illuminations are associated with negligible melatonin suppression but are not suitable for workplaces due to impaired color discrimination. The second group (L4-L7) consists of rather 'blue' illuminations with CCTs of 3900 K and higher. These illuminations provide unimpaired visual performance (visual acuity, contrast sensitivity, color discrimination) but cause significant melatonin suppression as compared to the dim light control situation and to illuminations of CCTs < 2000 K (L1, L2). The differences between L4 to L7 are despite the large range of CCTs (3900–14,000 K) statistically negligible with respect to melatonin suppression. This weak resolving power might partly be related to the fact that we did not dilate the pupils of our participants. The remaining illumination (L3) with a CCT of 2750 K does again not impair color discrimination but causes a rather moderate melatonin suppression that is neither significantly different from the control condition (dim light, L0) nor from the illumination of 1600 K (L1) or from illuminations with higher CCTs L4-L7, 3900–14,000 K) (see Table 3).

4.5. Applicability of the results

The proper selection and application of light has become more and more important during the last years for clinical applications, e.g. for the treatment of Seasonal Affective Disorder (Terman, 2007) as well as in various settings of daily life, where the alerting effects of light and the regulative influence on the sleep-wake-cycle are used (Cajochen, 2007).

Concerning work at night light may be used to enforce or to prevent shifts of the circadian system. Due to Zeitzer et al. (2000) the extent of melatonin suppression is expected to predict the phase shifting power of light. Based on our results and important studies performed by Brainard et al. and Thapan et al. we expect that higher CCTs are associated with larger phase shifts (Brainard et al., 2001; Thapan et al., 2001).

Due to the results of our experiments illuminations with CCTs <2000 K are not suitable for workplaces as they impair color discrimination though they prevent a major suppression of melatonin synthesis. Illuminations of about 3000 K might be useful for situations with short night shift periods where melatonin suppression and thereby the disruption and a shift of the circadian rhythm should be avoided. In case of longer night shift periods it is, however, useful to accelerate the process of adaptation, i.e, the synchronization with the (inverted) sleep-activity rhythm of night workers. For this purpose polychromatic white light with CCTs of 4000 K and more would be more appropriate. However, due to the limited effect of CCTs of polychromatic white light on melatonin suppression that was also demonstrated by Smith and Eastman (2009) and Smith et al. (2009), it might be reasonable to combine different CCTs with increased illuminance levels in order to obtain an optimized chronobiological action. Further studies on experimental shift work should verify these conclusions.

5. Conclusions

Based on our results on melatonin suppression and visual performance we conclude that polychromatic white light illuminations.

- with CCTs <2000 K that impair color discrimination are not suitable for workplaces,
- with CCTs of about 3000 K might be useful for situations where melatonin suppression and shifts of the circadian rhythm should be avoided,
- with CCTs of at least 4000 K could promote the adaptation to night work. This effect should be enhanced by variation of illuminance levels.

Acknowledgements

This study was funded by Deutsche Forschungsgemeinschaft (DFG) under grants GR 691/15-1 and FR 3270/2-1. We would like to thank our test subjects for their cooperation, our technician Petra Spielvogel for the hormone assay, our research assistant Katharina Wald for supporting the data acquisition and our statisticians Katrin Linβen and Peter Bröde for their statistical support.

References

Arendt, J., 2010. Shift work: coping with the biological clock. Occup. Med. (Chic. Ill) 60, 10–20. http://dx.doi.org/10.1093/occmed/kqp162.
Arendt, J., 2006. Melatonin and human rhythms. Chronobiol. Int. 23, 21–37. http://dx.doi.org/10.1080/07420520500464361.
Bara, A., Arber, S., 2009. Working shifts and mental health–findings from the british household panel survey (1995-2005). Scand. J. Work. Environ. Health 35, 361–367.
BGG, 2010. DGUV Grundsatz für arbeitsmedizinische Vorsorgeuntersuchungen "Bildschirmarbeitsplätze" G 37.
Bøggild, H., Knutsson, A., 1999. Shift work, risk factors and cardiovascular disease. Scand. J. Work. Environ. Health 25, 85–99 doi:10.5271/sjweh.410.
Boivin, D.B., Duffy, J.F., Kronauer, R.E., Czeisler, C.A., 1996. Dose-response relationships for resetting of human circadian clock by light. Nature 379, 540–542. http://dx.doi.org/10.1038/379540a0.
Brainard, G.C., Hanifin, J.P., Greeson, J.M., Byrne, B., Glickman, G., Gerner, E., Rollag, M.D., 2001. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. J. Neurosci. 21, 6405–6412.
Brainard, G.C., Richardson, B.A, Hurlbut, E.C., Steinlechner, S., Matthews, S.A., Reiter, R.J., 1984. The influence of various irradiances of artificial light, twilight, and moonlight on the suppression of pineal melatonin content in the Syrian hamster. J. Pineal Res. 1, 105–119. http://dx.doi.org/10.1016/0006-8993(84)91045-X.
Cajochen, C., 2007. Alerting effects of light. Sleep. Med. Rev. 11, 453–464. http://dx.doi.org/10.1016/j.smrv.2007.07.009.
Cajochen, C., Zeitzer, J.M., Czeisler, C.A., Dijk, D.J., 2000. Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness. Behav. Brain Res. 115, 75–83. http://dx.doi.org/10.1016/S0166-4328(00)00236-9.
Commission Internationale de L'eclairage, 2004. Technical Report Colorimetry.
Crowley, S.J., Lee, C., Tseng, C.Y., Fogg, L.F., Eastman, C.I., 2003. Combinations of bright light, scheduled dark, sunglasses, and melatonin to facilitate circadian entrainment to night shift work. J. Biol. Rhythms 18, 513–523. http://dx.doi.org/10.1177/0748730403258422.
Czeisler, C.A., Allan, J.S., Strogatz, S.H., Ronda, J.M., Sánchez, R., Ríos, C.D., Freitag, W.O., Richardson, G.S., Kronauer, R.E., 1986. Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. Science 233 (80), 667–671. http://dx.doi.org/10.1126/science.3726555.
Darius, S., Rößler, T., Schenk, D., Böckelmann, I., 2010. Beurteilung der Kontrastempfindlichkeit – ein Methodenvergleich. Prakt. Arbeitsmedizin 21, 28–31.
Dinges, D., 1995. An overview of sleepiness and accidents. J. Sleep. Res. 4, 4–14.
Eastman, C.I., Martin, S.K., 1999. How to use light and dark to produce circadian adaptation to night shift work. Ann. Med. 31, 87–98 doi:10.3109/07853899908998783.
Erren, T.C., Reiter, R.J., 2008. A generalized theory of carcinogenesis due to chronodisruption. Neuro Endocrinol. Lett. 29, 815–821.
Farnsworth, D., 1957. The Farnsworth-munsell 100-Hue Test for the Examination of Color Discrimination – Manual.

Folkard, S., 2008. Do permanent night workers show circadian adjustment? A review based on the endogenous melatonin rhythm. Chronobiol. Int. 25, 215–224. http://dx.doi.org/10.1080/07420520802106835.
Gall, D., Lapuente, V., 2002. Beleuchtungsrelevanten Aspekte bei der Auswahl eines förderlichen Lampenspektrums. Aspects involving illumination in the selection of an effective lamp spectrum. LICHT 54, 860–871.
Goichot, B., Weibel, L., Chapotot, F., Gronfier, C., Piquard, F., Brandenberger, G., 1998. Effect of the shift of the sleep-wake cycle on three robust endocrine markers of the circadian clock. Am. J. Physiol. – Endocrinol. Metab. 275, E243–E248.
Hoddes, E., Zarcone, V., Smythe, H., 1973. Quantification of sleepiness: a new approach. Psychophysiology 10, 431–436.
Holm, S., 1979. A simple sequentially rejective multiple test procedure. Scand. J. Stat. 6, 65–70 doi:10.2307/4615733.
Horowitz, T., Cade, B., 2001. Efficacy of bright light and sleep/darkness scheduling in alleviating circadian maladaptation to night work. Am. J. Physiol. – Endocrinol. Metab. 281, 384–391.
James, F.O., Walker, C.D., Boivin, D.B., 2004. Controlled exposure to light and darkness realigns the salivary cortisol rhythm in night shift workers. Chronobiol. Int. 21, 961–972. http://dx.doi.org/10.1081/LCBI-200035944.
Kayumov, L., Casper, R.F., Hawa, R.J., Perelman, B., Chung, S.A., Sokalsky, S., Shapiro, C.M., 2005. Blocking low-wavelength light prevents nocturnal melatonin suppression with no adverse effect on performance during simulated shift work. J. Clin. Endocrinol. Metab. 90, 2755–2761. http://dx.doi.org/10.1210/jc.2004-2062.
Knutsson, A., 2003. Health disorders of shift workers. Occup. Med. (Chic. Ill) 53, 103–108. http://dx.doi.org/10.1093/occmed/kqg048.
Kozaki, T., Koga, S., Toda, N., Noguchi, H., Yasukouchi, A., 2008. Effects of short wavelength control in polychromatic light sources on nocturnal melatonin secretion. Neurosci. Lett. 439, 256–259. http://dx.doi.org/10.1016/j.neulet.2008.05.035.
Kozakov, R., Franke, S., Schöpp, H., 2008. Approach to an effective biological spectrum of a light source. LEUKOS 4, 255–263.
Kozakov, R., Schoepp, H., 2011. Proposal for the standard evaluation procedure for non-visual action of light. J. Light Vis. Environ. 35, 274–277 doi:10.2150/jlve.35.274.
Lockley, S.W., Landrigan, C.P., Barger, L.K., Czeisler, C.A., 2006. When policy meets physiology: the challenge of reducing resident work hours. Clin. Orthop. Relat. Res. 449, 116–127. http://dx.doi.org/10.1097/01.blo.0000224057.32367.84.
Megdal, S.P., Kroenke, C.H., Laden, F., Pukkala, E., Schernhammer, E.S., 2005. Night work and breast cancer risk: a systematic review and meta-analysis. Eur. J. Cancer 41, 2023–2032. http://dx.doi.org/10.1016/j.ejca.2005.05.010.
Morita, T., Tokura, H., 1998. The influence of different wavelengths of light on human biological rhythms. Appl. Hum. Sci. 17, 91–96 doi:doi.org/10.2114/jpa.17.91.
Morita, T., Tokura, H., 1996. Effects of lights of different color temperature on the nocturnal changes in core temperature and melatonin in humans. Appl. Hum. Sci. 15, 243–246.
Øyane, N.M.F., Pallesen, S., Moen, B.E., Akerstedt, T., Bjorvatn, B., 2013. Associations between night work and anxiety, depression, insomnia, sleepiness and fatigue in a sample of Norwegian nurses. PLoS One 8, e70228. http://dx.doi.org/10.1371/journal.pone.0070228.
Rahman, S.A., Marcu, S., Shapiro, C.M., Brown, T.J., Casper, R.F., 2011. Spectral modulation attenuates molecular, endocrine, and neurobehavioral disruption induced by nocturnal light exposure. Am. J. Physiol. Endocrinol. Metab. 300, E518–E527. http://dx.doi.org/10.1152/ajpendo.00597.2010.
Rea, M.S., Figueiro, M.G., Bierman, A., Hamner, R., 2012. Modeling the spectral sensitivity of the human circadian system. Light. Res. Technol. 44, 386–396. http://dx.doi.org/10.1177/1477153511430474.
Revell, V.L., Arendt, J., Terman, M., Skene, D.J., 2005. Short-wavelength sensitivity of the human circadian system to phase-advancing light. J. Biol. Rhythms 20, 270–272. http://dx.doi.org/10.1177/0748730405275655.
Shanahan, T.L., Zeitzer, J.M., Czeisler, C.A., 1997. Resetting the melatonin rhythm with light in humans. J. Biol. Rhythms 12, 556–567. http://dx.doi.org/10.1177/074873049701200610.
Smith, L., Folkard, S., Poole, C., 1994. Increased injuries on night shift. Lancet 344, 1137–1139.
Strasser, H., 1993. Ergonomie – umgebungseinflüsse. Beleuchtung. In: Hettinger, T., Wobbe, G. (Eds.), Kompendium Der Arbeitswissenschaft. Kiehl Verlag, Ludwigshafen, pp. 288–318.
Terman, M., 2007. Evolving applications of light therapy. Sleep. Med. Rev. 11, 497–507. http://dx.doi.org/10.1016/j.smrv.2007.06.003.
Thapan, K., Arendt, J., Skene, D.J., 2001. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. J. Physiol. 535, 261–267. http://dx.doi.org/10.1111/j.1469-7793.2001.t01-1-00261.x.
Thayer, R.E., 1967. Measurement of activation through self-report. Psychol. Rep. 20, 663–678. http://dx.doi.org/10.2466/pr0.1967.20.2.663.
Van de Werken, M., Giménez, M.C., de Vries, B., Beersma, D.G.M., Gordijn, M.C.M., 2013. Short-wavelength attenuated polychromatic white light during work at night: limited melatonin suppression without substantial decline of alertness. Chronobiol. Int. 30, 843–854 doi:10.3109/07420528.2013.773440.
Wahnschaffe, A., Haedel, S., Rodenbeck, A., Stoll, C., Rudolph, H., Kozakov, R., Schoepp, H., Kunz, D., 2013. Out of the lab and into the bathroom: evening short-term exposure to conventional light suppresses melatonin and increases alertness perception. Int. J. Mol. Sci. 14, 2573–2589 doi:10.3390/ijms14022573.
Weibel, L., Brandenberger, G., 1998. Disturbances in hormonal profiles of night workers during their usual sleep and work times. J. Biol. Rhythms 13, 202–208.
Weibel, L., Spiegel, K., Follenius, M., Ehrhart, J., Brandenberger, G., Spiegel, K., Ehrhart, J., 1996. Internal dissociation of the circadian markers of the cortisol rhythm in night workers. Am. J. Physiol. Metab. 33, E608–E613.
Wyszecki, G., Stiles, W.S., 1982. Color Science: Concepts and Methods, Quantitative Data and Formulae, Color Research & Application. John Wiley and Sons. http://dx.doi.org/10.1002/col.5080080421.
Zeitzer, J.M., Dijk, D.-J., Kronauer, R.E., Brown, E., Czeisler, C.A., 2000. Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression. J. Physiol. 526 Pt 3, 695–702.