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Perceived well-being and light-reactive hormones: An exploratory study

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Light can impact psychobiological processes in a healthy or harmful way, challenging designers to better understand the resources they are manipulating. The present exploratory study compared two forms of office lighting which differed in correlated colour temperatures and light level. A holistic approach, comprising visual, emotional and biological dimensions, was used to assess the lighting conditions that could favour productivity and well-being by means of the identification of congruent relationships between objective and subjective measurements in response to light stimuli. The former included analyses of melatonin and cortisol, and the latter were psychological instruments for measuring transitory mood, somnolence, and visual comfort. Controlled experiments were run in a laboratory with a repeated measures design, which yielded fifty-six evaluations. Although no extreme ranges of correlated colour temperatures were used in this study, the spectral blue component present in the correlated colour temperature of approximately 4000 K, and also provided by the light-emitting diodes system at a higher light level, could have contributed to render most of the strong effects on the inter and intra correlations among the psychobiological responses. The mediator role of the psychological profile of the individuals was demonstrated by the significant predictive value of the perceived stress measures.

1. Introduction

Life has always been dependent of natural light, its variation over 24 hours serving as a time-giver.[1] Artificial light adds its particular characteristics to provoke effects that could be hazardous. It can be said that humans react to environmental stimulation by means of psychobiological responses. To date, the most studied light-reactive hormones are melatonin and cortisol, whose patterns of secretion behave in a complementary way, being high levels of melatonin and low levels of cortisol secreted during night-time,

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and high levels of cortisol and low levels of melatonin secreted during daytime. Environmental light, by means of its intensity and spectral composition, has an acute suppressive effect on melatonin secretion.[2] As to psychology itself, seasonal affective disorder (SAD) probably constitutes the best example of light's effect on mood and behaviour, and the abnormal pattern of melatonin secretion in SAD sufferers is still the main hypothesis as to the genesis of this disorder.[3]

This study explored certain non-visual responses to different lighting conditions in office settings, whilst also taking into account the visual aspects involved.

1.1. Background

A review by Stephenson *et al.*[4] argued that bright light is an effective adjuvant treatment for depression and that four parameters of light have to be taken into account as affecting mood: the intensity, timing, duration and spectrum of the light. Exposure to natural light was also considered since the effect of light patterning over 24 hours is physiologically explained by the light sensitivity of the circadian system. Since bright light increases alertness during the day, when melatonin secretion is low, they concluded that via melanopsin[5] light may exert its antidepressant effect through a modulation of the homeostatic process of sleep. The participation of the amygdala in the limbic system to send signals to the cerebral cortex has also been proposed for light provoking and modulating the emotions that induce alerting responses.[6] Graw *et al.*[7] suggested that the susceptibility to winter depression in patients with SAD may arise not from behaviourally related lack of sufficient light exposure, but an increased vulnerability to the amount of light received, suggesting that this group will require a higher light exposure in summer and light therapy in winter. Hubalek *et al.*[8] have found that the effect of light exposure during the day on sleep quality was stronger than the effect on pleasure or arousal, the former being positively associated with total luminous exposure, the spectrum and the duration of exposure over thresholds of 1000 lx and 2500 lx. The investigation of the carryover effects of daylight on performance and self-reports of sleepiness showed that night-time performance on a 54-minute tracking task, but not subjective sleepiness, was significantly better following exposure to daylight, while there was no differential effect on performance or sleepiness from exposure to the blue or red lights.[9] In industrialized countries, 75% of the total workforce is estimated to have been involved in shift work and night work, this involving exposure to artificial light at night which can be deleterious to health. Research studies[10,11] have found that the potential and multifactorial mechanisms of the effects include the suppression of melatonin secretion, sleep deprivation, and circadian disruption, which in turn may elevate rates of cancer, diabetes, cardiovascular risks, obesity, mood disorders and age-related macular degeneration. Besides, inadequate photoreception of intrinsically photosensitive retinal ganglion cells (ipRGC) may aggravate many common age-associated problems including insomnia, depression and impaired cognition.

As to visual effects, in general, lighting conditions that improve visibility also improve task performance. Veitch *et al.*[12] have found that people who perceived their office lighting as being of higher quality rated the space as more attractive, reported a more pleasant mood and showed greater well-being at the end of the day. According to these authors, good lighting quality could support organizational productivity by means of the illuminance provided, the control of glare and the appearance of the space.

The visual effects of lighting are mostly related to visual performance, while its non-visual or psychobiological effects involve health and well-being. The action spectrum curves are also different; the visual peak efficiency lies in the yellow–green wavelength region, while the maximum biological sensitivity lies in the blue region of the electromagnetic spectrum.[13] The cool white light-emitting diode (LED) produces significant light output at this visible short-wavelength making it likely to elicit alertness since melatonin is more susceptible to suppression in this region.[14] Another study concluded that the cool white light with a correlated colour temperature (CCT) of 4000 K and artificial daylight of 6500 K were more beneficial for alertness and academic work for both computer-based and paper-based activities.[15] As to preference judgments, no differences were found between a fluorescent lamp spectrum of 3750 K and the LED spectrum with the closest (matched) CCT.[16] In 1941, Kruithof[17] stated that high colour temperatures are more acceptable when they occur together with high illuminance levels. Twenty-nine studies, in which a Kruithof type relationship was investigated, revealed that the one condition to avoid is low illuminance (these data refer to interior contexts only) and that variation in CCT (within the range of approximately 2500 K to 6500 K) does not affect pleasantness.[18] A Japanese study[19] tested the effects of 2700 K, 3000 K, 3500 K, 4200 K and 5000 K fluorescent lighting on subjective evaluations of brightness, comfort and glare sensation and electrocardiogram (ECG) and electroencephalogram (EEG) monitoring throughout exposure. The results showed that the boundary illuminances estimated from psychological responses were not significantly different from those estimated from these physiological responses. Dab and Lian[20] examined three physiological factors: melatonin levels, tear mucus ferning quality and degree of asthenopia, in relation to visual comfort by adjusting the illuminance, illuminance uniformity and CCT. Their results showed that as illuminance increased, the melatonin level decreased significantly and the tear mucus ferning quality was improved. The only differential effects among the three levels were found for illuminance uniformity and CCT. Much effort is being invested to improve the current methods of light measurement toward more inclusive ones, from CCT and spectral power distribution (SPD) metrics to methods that quantify effective irradiance for each of the photoreceptive inputs independently.[21] This would make it possible to tune the spectral irradiance distribution of the lighting system to the spectral sensitivity of the neural channel that provides the desired benefits, in order to maximize the benefits of lighting.[22] Records of the spectral irradiance at the eye level have identified the circadian stimulus (CS) value which corresponds to when the light does not cause suppression of melatonin secretion in the blood as 0, and as 0.7 when the maximal level of melatonin suppression is reached causing saturation of the system.[23] Nevertheless, these authors recognize that the CS metric is incomplete (timing, duration, distribution and photic history were not considered, neither are the spectral and the absolute sensitivity of the non-visual alerting effects of light exposure), but they still propose the adoption of CS as a new metric for quantifying light in architectural spaces,[24] where the spectral reflectances of architectural materials must be included in the CS calculations.

By considering the background described above, the present study aimed to identify the lighting conditions of office workplaces that might boost users' well-being without negative interference with productivity. The influence of two CCTs and two light levels from compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) on transitory mood, somnolence, visual perception and comfort, as well as on melatonin and cortisol secretion, was investigated.

The spectral characteristics and spatial distribution of the lighting were also included in the analysis.

1.2. Problem and hypotheses

New and efficient lighting technologies are exhibited mainly in public offices, having a massive impact, and indeed acting as a kind of model. Working environments require a type of lighting being good enough for task achievement but also not risky to health and well-being. Suitable lighting designs, which encompass lamps and luminaires, light level and light spatial distribution, as well as the colour appearance of the space, need to be identified and disclosed, based on rigorous experimental procedures by selecting the relevant variables related to performance and well-being.

The main aim of this paper is to identify the lighting conditions of office workplaces that favour productivity but also well-being by means of the finding of congruent relationships between objective and subjective measurements in response to light stimuli. The former included the analysis of the more light-reactive hormones such as melatonin and cortisol, and the latter deal with psychological processes such as transitory mood, somnolence and visual comfort.

In formulating the operational hypotheses, it was assumed that lighting variations in terms of spectra and level during exposures of moderate duration will affect relevant psychobiological correlates. A secondary aim was to test the importance of co-variables such as the individuals' previous exposure to daylight (photic history), and their psychological profile in terms of personality type, perceived stress and emotional state.

Secretion patterns of melatonin and cortisol behave in a complementary manner, being high levels of melatonin secreted during the night and low levels during the day. Since the experiments were carried out during the morning, cortisol was considered a more reliable indicator than melatonin to test the hypotheses, which predicted:

H1: It is expected that the indicators of perceived quality will be better under the lighting with the CCT of approximately 3000 K, which will also favour a better mood. No changes as to hormonal secretions are expected in response to a light spectrum with less radiation in the visible short wavelength range.

H2: It is expected that the lighting with a CCT of approximately 4000 K will be experienced as less comfortable. Since shorter wavelength radiation can promote ipRGC photoreception, it is also expected that this lighting will provoke an increase in cortisol concentration that will be reflected in less somnolence.

H3: It is expected that the light level will reinforce these outcomes: the higher the light level the larger the predicted effects.

H4. It is expected that the psychological profile of the individuals will mediate the relation between the independent and the dependent variables.

2. Material and method

2.1. The laboratory set up

The laboratory consisted of one experimental space ($d = 578$ cm, $w = 400$ cm, $h = 280$ cm), of which $366 \times 200 \times 280$ cm were covered by two sets separated by a wood panel, simulating two office workplaces (Figure 1). The remaining space was used as a reception area. The sets were identically furnished with a desk made of light wood, and a black metal chair with a cushioned seat. Each of the desks contained similar laptop computers equated in terms of screen luminance and character format. The ceiling and walls were white and the floor was grey (sets were closed at the back by a thick black curtain). The decoration was a small plant in the left corner of the floor and a white curtain with colourful flowers placed on one of the lateral walls but not included in the visual

Figure 1 The experimental sets (warm and cool) at the higher level, with the wall lighting on (available in colour in online version)

field. The total laboratory space was soundproof and temperature controlled at 24°C.

The sets lacked windows, and the lighting system consisted of two luminaires for each set: one located over the desk and the other was directed to the front wall. The first luminaire, with aluminium reflectors and open louvres, provided the general lighting by means of three compact fluorescent lamps (CFL) of 36 W covered by a plastic diffuser. The other was a wall-washing luminaire with three tubes containing LEDs of 20 W, 21 W and 24 W aimed at the wall in front of the subject. The distance from the desk to the front wall was two metres. Both types of lighting, compact fluorescent lamps and LEDs, have CCTs of either 3000 K or 4000 K. They were selected because of their common use in office lighting in the place where the study was carried out.

2.2. Objective measures

2.2.1. Photometrics

The four experimental conditions involved two CCTs at two illuminances. The lower level employed only the general lighting provided by the compact fluorescent lamps with a horizontal illuminance on the desktop of around 450 lx. The higher level comprised a combination of this CFL lighting plus the illumination of the front wall by means of LED systems, delivering a horizontal illuminance on the desktop of around 800 lx. Table 1 shows the illuminances on the desk and walls as well as the luminances of those surfaces and the paper and screen.

The SPD and colour rendering index (CRI) of the compact fluorescent lamps used were obtained from a catalogue, and the SPDs of the LEDs used were measured in the laboratory with a calibrated spectroradiometer PhotoResearch PR 715 and JAZ Ocean Optics (Figures 2 and 3).

The SPD received at the cornea of the participants was also recorded so as to calculate the melanopic illuminance according to the Lucas *et al.*[21] methodology (Table 1). These measurements were carried out by means of a calibrated JAZ Ocean Optics spectroradiometer.

The exterior illuminance was also measured in an unobstructed place, at the same horizontal point every day of November and July (corresponding to the times of the data collection) between 12:00 and 13:00 by means of a luxmeter (Minolta T-1 M). The prevailing

Table 1 Average illuminances (E) and luminances (L) on desk and walls in the two sets with different CCTs[a]

Light levels	Surfaces	3000 K			4000 K		
		L (cd/m^2)	E (lx)	Melanopic illuminance (melanopic-lux)	L (cd/m^2)	E (lx)	Melanopic illuminance (melanopic-lux)
Front wall ON (higher level)	Front wall	271	923	7.12	270	900	8.86
	Right wall	172	560		183	588	
	Left wall	177	600		178	585	
	Desktop	146	796		155	800	
	Paper	170			170		
	Screen	117			117		
Front wall OFF (lower level)	Front wall	70	176	1.78	73	196	2.36
	Right wall	80	300		85	305	
	Left wall	65	297		74	300	
	Desktop	68	440		67	460	
	Paper	90			90		

CCT: correlated colour temperature.
[a]Illuminances were measured with a Minolta T-1 M. Luminances were measured with a Minolta LS-110. Melanopic illuminance was calculated from measurements taken with a JAZ Ocean Optic spectroradiometer.

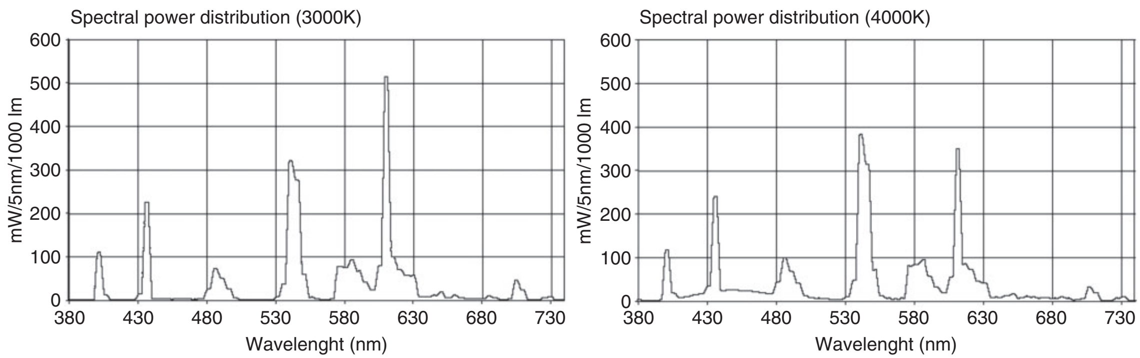

Figure 2 Spectral power distribution of compact fluorescent lamps (36 W) for the two CCTs (Source: http://www.gelighting.com/).CRI = 82 for both SPDs
SPD: spectral power distribution.

mean illuminance for July was 57,000 lx, and for November was 70,000 lx. Length of day was estimated from sunrise to sunset at these times of the year and varied between 10.5 hours in winter and almost 14 hours in summer. The outdoor temperatures were obtained from data for the same periods recorded by the national meteorological services as 15°C in winter and 30°C in summer.

2.2.2. Melatonin and cortisol sampling

Most of the circulating melatonin is metabolized in the liver to 6-hydroxymelatonin and subsequently to 6-sulfatoxymelatonin which is excreted into the urine and correlates highly with the 02:00 hour peak value of serum melatonin. In this study, for melatonin detection, the collection included two samples of urine. In order to identify the nocturnal pattern of secretion, a urine sample was collected at home in a plastic bottle, over 12 hours, between 20:00 and 08:00 hours. Thus, each subject arrived at the laboratory with their nocturnal urine bottle, where later, aliquots of the total urine of each subject were extracted, frozen and stored at −20°C

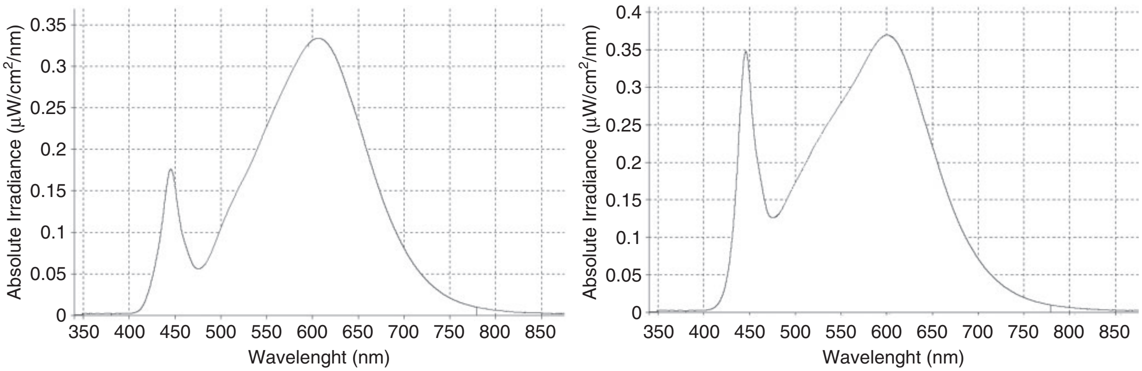

Figure 3 Spectral power distribution of LEDs (20 W, 21 W, 24 W) for the two CCTs
CCT: correlated colour temperature; LED: light-emitting diode.

until assayed. A second sample of urine was collected at the laboratory, during the experiment, using the same procedure. The test used was the enzyme immunoassay for the quantitative determination of melatonin sulphate in human urine (IBL International). Melatonin values are expressed as secretion in μg.

Since there is also a high correlation between serum and saliva cortisol levels, in this study, cortisol was collected six times, in saliva, at 23:00 hours the night before the experiment, at 07:00 hours the morning of the experiment, two samples during the experiment in response to changes in light level, and two samples after the experiment (at 17:00 and 23:00 hours) (see Table 2). Samples were analysed through immunoassay test for the quantitative determination *in vitro* of free cortisol in human saliva (IBL International). Cortisol values were expressed as concentration in μg/dL saliva.

Participants were screened in order to rule out severe vision disabilities, infections, extreme chronotypes and endocrinology disturbances. In addition to the signature of the consent form, subjects were invited for an introduction at the laboratory to be informed about the aims and procedure of the experiment (Table 2). On this occasion, they obtained the test materials and instructions for collecting the urine and saliva samples which were to be taken in their homes the previous night to the experiment, during the experiment and after the experiment in order to complete the 24 circadian periods.

On the day preceding, the experiment participants were instructed to avoid: Staying up later than 23:00 hours, consumption of alcohol, corticoids (oral, injection, or topical use), hormones, psychotropic drugs (included herbal teas), and antihistamines. Due to possible interference in plasma levels of cortisol and melatonin, participants were also told to avoid eating nuts such as almonds, hazelnuts, peanuts, etc. tomatoes, cereals (rice, barley, etc.), strawberries, olives, olive oil, wine, beer, milk or vitamin supplements, for 48 hours before and during the day of the experiment. All these recommendations as well as the specific conditions for the saliva and urine collection were given in both verbal and written formats.

2.3. Subjective measures

Subjective evaluations comprised two psychological tests: the Scale for Mood Assessment[25] and the Epworth Sleepiness Scale.[26] The former was designed for

Table 2 Schedule of the experiment carried out on eight occasions by each of the seven participants

At home
Previous day:
Melatonin 1: urine collection from 8 pm until 8 am the next day.
Cortisol 1: saliva collection at 11 pm.
Cortisol 2: saliva collection at 7 am.
At the laboratory
08:45 Welcome and brief instructions
09:00 Photic history (as adaptation time)/lighting assessment 1.
Start of urine collection for melatonin 2.
09:15 Somnolence test 1/task 1.
10:00 Transitory mood test 1.
10:15 Type A/B test.
10:30 Perceived stress test.
10:45 Discomfort symptoms report 1/Cortisol 3.
11:00 Pause
11:20 Chronotype test (as adaptation time).
11:30 Emotional state test.
11:40 Lighting assessment 2.
12:00 Somnolence test 2/Task 2.
12:45 Transitory mood test 2.
13:00 Discomfort symptoms report 2/ cortisol 4.
Post-laboratory sampling: saliva cortisol sample 5 (at 17:00) and 6 (at 23:00).

measuring transitory mood in the context of experimental studies using mood induction procedures and it exhibits sensitivity to detect momentary mood changes (how the participant feels right now). Some examples of the 16 rating scales are nervous, angry, cheerful, melancholic, tense, optimistic, on a 10-graded scale from 0 = nothing to 10 = a lot.

In contrast to feeling just tired, the Epworth Sleepiness Scale estimates the chance of dozing in eight different situations: sitting and reading, watching television, sitting inactive in a public place (e.g. a theatre or meeting), as a passenger in a car for an hour without a break, lying down to rest in the afternoon when circumstances permit, sitting and talking to someone, sitting quietly after a lunch without alcohol, in a car while stopped for a few minutes in the traffic. The scale ranges from 0 = would never doze to 3 = high chance of dozing. The above items identify the tendency of the individual to doze, so that a final item about the chance of dozing *now,* during the experiment, was added to the original items of this test. To ensure that somnolence was only caused by the experimental situation, the number of nocturnal sleep hours during the working week and at weekends were also asked for.

The interior lighting quality was assessed by means of a questionnaire containing five-grade rating scales[27] in order to estimate the impact of lighting on the appearance of the space in terms of unpleasant–pleasant, weak–strong, cold–warm, natural–unnatural, glaring–no glaring and soft–hard. The visibility condition (readability) was also measured ranging from very poor to very well. These aspects were computed as indices which revealed Cronbach's reliability to be between moderate and high: transitory mood ($\alpha = 0.94$), somnolence as a trend ($\alpha = 0.97$), somnolence now ($\alpha = 0.53$) and visibility ($\alpha = 0.61$).

Visual discomfort had to be reported as experienced at the end of the experiment by means of a list of three-grade symptoms related to tears, visual fatigue, dryness, blurred vision and headache.[28,29]

Photic history, or the individuals' previous exposure to daylight, was investigated by means of two categorized questions referred to 'How much time do you usually spend under natural light during a normal day this week?', and 'How much time did you spend under natural light yesterday?'. These questions were answered in minutes as time spent in two separate periods of the morning and the afternoon. Since no differences were found between both periods in the four occasions, it was decided to take the 'yesterday exposure' as a reference.

2.4. Complementary measures as co-variables

Since it has been proven that the interaction between the environment and the individual is mediated through emotional processes,[30] complementary evaluations were also carried out in order to investigate to what extent the impact of workplace lighting on the selected psychobiological outcomes would be mediated by the psychological profile of the participants. This construct was composed of tests of personality type, emotional state and perceived stress. Personality tests describe characteristics of individuals in term of permanent reactions. For this purpose, the type A/B personality test was selected, where type A is characterized by signs of personal tension, type B with few signs of tension, and there is an intermediate group C.[31] The emotional state was analysed in terms of four basic emotional qualities: activation (rested/tired, alert/drowsy, awake/sleepy), orientation (interested/bored, efficient/inefficient, devoted/indifferent), evaluation (secure/anxious, friendly/angry, happy/sad) and control (confident/hesitating, independent/dependent, strong/weak).[30] Each of the 12 four-grade rating scales were to be answered in terms of 'How did you feel most of the time during the last few days?' The stress proneness was approached by means of the Perceived Stress Scale (PSS),[32] which measures the degree to which situations in one's life are appraised as stressful. Items were designed to tap how unpredictable, uncontrollable and overloaded respondents found their lives during the last month, on a scale from 0 = never to 4 = very often.

Thus, the subjective measurements covered different periods of time: right now (transitory mood test, the item added to somnolence test, questionnaire of visual perception and discomfort symptoms), last few days (emotional state scales), last month (perceived stress test), and as a behavioural pattern (tests of somnolence and personality).

The photic history of the participants and their sleep hours during the working week and at weekends were also included as co-variables.

2.5. Experimental design, sample and procedure

This pilot study was a controlled experiment with a repeated measures design. Each participant was randomly exposed to the four experimental conditions (two light levels and two CCTs), during a period of two consecutive weeks in November (summer) and July (winter). In all, each participant attended eight sessions, at the same time of the day, from 09:00 to 13:00 hours. Each session lasted 1.5 hours and covered the exposure to one CCT and one light level (Table 2). Between the two levels, there was a pause of 20 minutes inside another section of the room, which was lit with light of the same CCT but at a much lower level than the experimental sets. The adaptation time consisted of 10 minutes for each lighting condition. The same procedure was followed the next week but under another CCT.

A total of 56 evaluations were performed by seven participants, four males and three females (mean age = 31 years, standard deviation = 8.7 years). They were asked to eat a light dinner and breakfast before they come to the laboratory, to wear clothes of neutral colours and to bring glasses if they used them.

Computers were used to fill in the psychological tests and the various questionnaires. For the performance task itself, both computer and paper were used since the task consisted of comparisons and error corrections between lists of numbers (product prices) and letters (directory) into which errors had been randomly entered. No errors were detected during the trials since the participants did not have time restrictions.

2.6. Statistics

Data were treated mainly by means of non-parametric statistics such as Spearman's rho correlation test. Other types of statistical treatment included graphs of frequency analysis, Wilcoxon range test, analysis of variance, and regression analysis. The internal reliability of the computed indices was checked by Cronbach's alpha. The level of significance was set at $p = 0.05$. The analyses were carried out in SPSS 15.0.

3. Results

3.1. Visual perception: assessment of workplace appearance

To get an overall impression of the lighting quality, the appearance of the experimental sets was rated by means of six differential scales and a visibility question. Putting together the two occasions of summer and winter, the CCTs of 3000 K as well as 4000 K were perceived as warm and cool, respectively, these features being accentuated by the light level (Table 3). At the higher light level (with the front wall light ON), the warm lighting was rated as pleasant and natural, while the cool lighting was rated as strong. The results show significant differences for the pair cool–warm ($p < 0.01$) and soft–hard ($p = 0.025$). None of the lighting modes were perceived as glaring (Figure 4).

Visibility was estimated as 'How well can you see under these lighting conditions', from 1 = very poorly to 5 = very well. Mean values show that 4000 K at the lower light level (front wall lighting OFF) was best rated for this purpose (M = 2.86), as well as 3000 K at the higher level (front wall lighting ON), (M = 2.64).

3.2. Light-reactive hormones

3.2.1. *Melatonin secretion, photic history and sleep hours*

Melatonin was measured twice, its nightly production from 20:00 to 08:00 hours, and during the experiment from 09:00 to 13:00 hours, thus covering the total exposure to one CCT irrespective of the light level. Participants of the present study secreted less melatonin (mean value) than expected for apparently healthy subjects aged 20–35 years: 36.8 µg for 24 hour and 2.8 µg/h for 12 hours (nocturnal)(IBL International – Melatonin-Sulfate Urine ELISA – RE54031, 2014-05). Even so, they are inside the 90% nocturnal fraction percentile.

In line with the evidence, the studied group ($N = 7 \times 4$ occasions, 2 weeks in summer and 2 weeks in winter) secreted more melatonin

Table 3 Mean values – and standard deviations – for items included in the perceptual assessment of the experimental office spaces under the two CCTs and light levels – on the two occasions of summer and winter

Rating scales (1–5)	4000 K Off	4000 K On	3000 K Off	3000 K On
Unpleasant–pleasant	2.50 (0.86)	2.50 (0.94)	2.36 (0.74)	2.79 (0.98)
Weak–strong	1.79 (0.98)	2.43 (0.76)	1.57 (0.94)	1.79 (0.89)
Cool–warm	1.71 (1.07)	1.36 (1.01)	2.43 (0.94)	2.64 (1.01)
Natural–artificial	2.64 (0.84)	2.57 (1.34)	2.64 (1.01)	2.14 (1.10)
Glaring–no glaring	2.57 (1.16)	2.43 (1.09)	2.14 (1.46)	2.71 (1.14)
Soft–hard	1.21 (0.80)	2.07 (0.83)	1.07 (0.92)	1.14 (0.77)

CCT: correlated colour temperature.

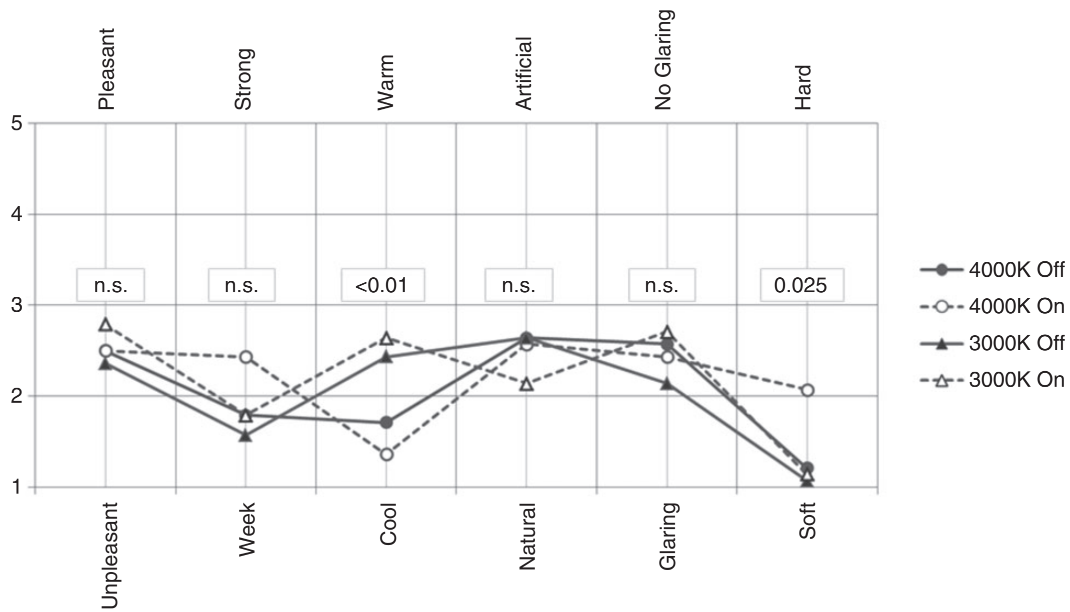

Figure 4 The perceptual assessment of the experimental office spaces under the two CCTs and light levels – mean ratings averaged over summer and winter

Table 4 Descriptive statistics of nocturnal and diurnal melatonin secretion (μg) for the two consecutive weeks, in summer and winter ($N = 7 \times 4$)

Occasion	Minimum melatonin (μg)	Maximum melatonin (μg)	Mean melatonin (μg)	Standard deviation melatonin (μg)
Night summer 1	6.21	31.59	15.9	8.44
Night summer 2	4.62	26.00	13.0	8.76
Day summer 1	0.92	8.69	4.8	2.91
Day summer 2	1.10	14.61	6.1	4.86
Night winter 1	7.98	26.66	15.3	6.94
Night winter 2	5.13	36.44	17.8	12.39
Day winter 1	1.22	17.50	6.4	5.69
Day winter 2	0.22	14.82	5.1	5.21

during winter than during summer, and more melatonin during night-time than during the day (Table 4 and Figure 5). The nocturnal values correspond to the urine collection of the twelve night hours, while the diurnal values correspond to the urine collection during the experiment.

As can be seen in Figure 5, the secretion pattern of melatonin of each of the participants is lower during the day than in the night for the two seasons, except for subject 5. On the average, all participants show higher melatonin in winter than in summer. Besides, participant 7 always (in the four conditions) shows lower values than the rest of the subjects.

The nocturnal values were correlated with the photic history of the subjects during the week and the day before the experiment, as well as with the reported sleep hours during the working week and at weekends (participants slept almost one hour more in winter than in summer during the working week and 1.5 hours more during the weekends).

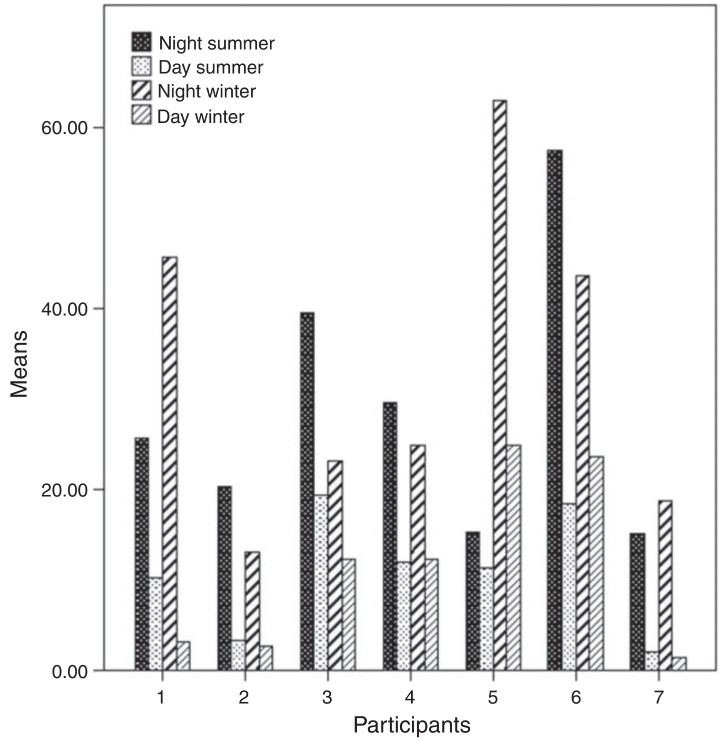

Figure 5 Mean melatonin secretion (μg) of individual participants at night-time and in daytime in summer and winter

Significant and positive correlations emerged in summer between the photic history and the nocturnal secretion of melatonin and in winter between nocturnal melatonin and sleep hours during the week (Table 5).

It should be remembered that the diurnal melatonin values respond to the experimental artificial lighting only, since the test room lacked windows. Higher values of melatonin can be observed under the warm lighting (3000 K) in summer and under the cool lighting (4000 K) in winter. The difference between the two CCTs was statistically significant for the first week ($p = 0.04$, Wilcoxon range test), and not statistically significant for the second ($p = 0.06$). See Table 6.

Figure 6 shows that melatonin secretion of the individuals was affected by the different lighting conditions of the experiment, except for subjects 2 and 7. These two participants have lower values than the others in all conditions.

From the comparison between seasonal and experimental melatonin responses (Figures 5 and 6), it is evident that those individuals who are more sensitive to seasonal variation also showed greater sensitivity to the different experimental lighting conditions. On the contrary, subjects who did not show the expected seasonal variation, such as participants 2 and 7, showed less variability to the experimental stimulus.

3.2.2. *Cortisol secretion*

Cortisol measurements covered the 24-hour cycle by means of six measurements: at 23:00 the night before and the night after the experiment, at 07:00, at the end of the two

Table 5 Correlations (Spearman's rho) between photic history, sleep hours and nocturnal melatonin ($N = 7 \times 4$)[a]

	Sleep hours		Week 1			Week 2		
	Week	Weekend	Week sleep hours	Weekend sleep hours	Nocturnal melatonin	Week sleep hours	Weekend sleep hours	Nocturnal melatonin
Summer								
Photic history	–0.255	–0.673			0.550			**0.775**[b]
Nocturnal melatonin			0.524	–0.491		0.094	–0.436	
Winter								
Photic history	–0.111	–0.611			–0.357			–0.036
Nocturnal melatonin			0.518	0.075		**0.926**[c]	0.315	

[a]Statistically significant correlations in bold.
[b]Correlation is significant at the 0.05 level (two-tailed).
[c]Correlation is significant at the 0.01 level (two-tailed).

Table 6 Descriptive statistics of melatonin secretion (μg) at the end of the experiment in the four occasions, for two consecutive weeks in summer and winter ($N = 7 \times 4$)

CCT and occasions	Minimum melatonin (μg)	Maximum melatonin (μg)	Mean melatonin (μg)	Standard deviation melatonin (μg)
4000 K summer	0.92	8.69	4.3	2.62
3000 K summer	1.10	14.61	6.7	4.78
4000 K winter	0.22	17.50	7.2	6.72
3000 K winter	0.54	8.80	4.3	3.24

CCT: correlated colour temperature.

sessions of the daily experiment, and at 17:00. The statistical analyses were performed with mean values but for the sake of comparison with expected values for apparently healthy subjects, the median was also considered (Table 7(a) and (b)). Except for the 23:00 measures in summer, participants' cortisol values are inside the range limits (IBL International – Cortisol ELISA – RE52611). Nevertheless, the expected values established by each laboratory must be taken as initial guideline ranges.

A statistically significant difference was found in winter between the 23:00 before (23 previous) and after (23 post) the experiment, when participants were exposed to the CCT of 4000 K ($p = 0.018$, Wilcoxon range test). (Figure 7). In response to the experimental conditions, cortisol values were higher under 4000 K during summer, while in winter values were higher under 3000 K, which is consistent with the melatonin output, both hormonal patterns being significantly different during the summertime ($p = 0.018$, Wilcoxon range test).

Correlations for paired samples showed that the relation between cortisol secretion and the light's spectrum became significant and positive only during winter (rho = 0.95, $p = 0.001$ for 4000 K; rho = 0.91, $p = 0.004$ for 3000 K), while the light levels manipulated in the experiment had no effect.

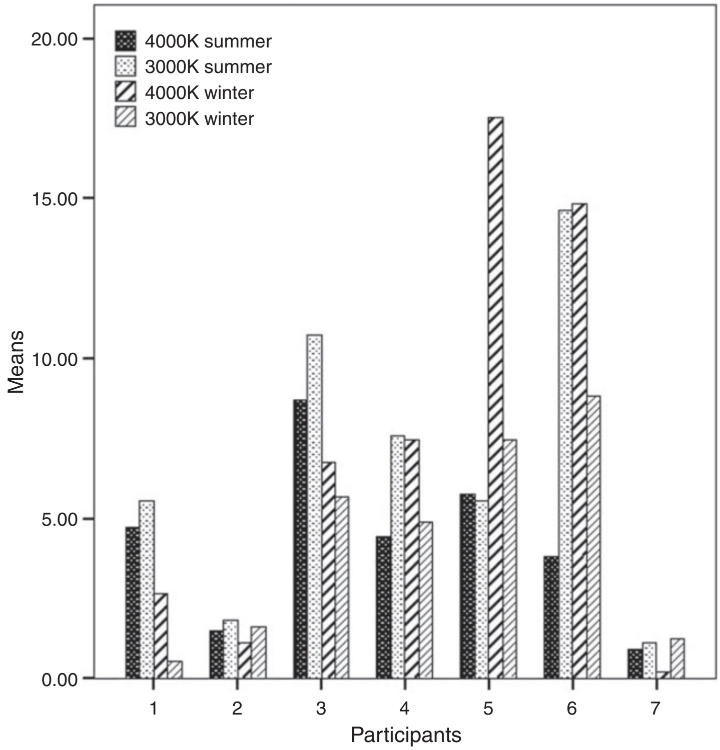

Figure 6 Mean melatonin secretion (μg) of individual participants in response to the experimental lighting conditions in summer and winter

3.3. Subjective indices

By putting all the lighting conditions together, significant correlations can be observed among the subjective indices (transitory mood, somnolence now and visibility), so that, a better mood was accompanied by less somnolence and more visibility, and a high somnolence could have caused less visibility. An analysis by lighting conditions showed that the above relationships took place under the CCT of 4000 K, in the two consecutive weeks of summer and winter (Table 8).

The index of transitory mood remained positive across the entire experiment, being significantly predicted by cortisol ($p = 0.03$), so that a high value of cortisol explained a better mood.

On the other hand, the index of visibility showed a significant association (rho = –0.77, $p = 0.04$) with the melatonin secreted during the experiment under the CCT of 4000 K in winter, then, the higher the melatonin level, the lower the visibility to perform the task.

Although the relationship between cortisol and the index of somnolence now (during the experiment) did not reach statistical significance, a consistent and inverse relationship during the winter was observed in terms of the higher the somnolence the less the cortisol value.

3.4. Relations between co-variables: personality type, perceived stress and emotional state

Table 9 shows three participants with proneness to stress associated with negative affects (lower scores on the test). On the other hand, the remaining four participants with no

Table 7 (a) Median cortisol concentrations (μg/dL) at six different times in summer and winter ($N = 7 \times 8$)

Occasion	Median cortisol at 23:00 (previous)	Median Cortisol at 07:00	CCT	Front wall light	Median cortisol at end of session	Median Cortisol at 17:00	Median Cortisol at 23:00
Summer	0.021	0.188	4000 K	On	0.092	0.075	0.014
				Off	0.085		
			3000 K	On	0.072		
				Off	0.078		
Winter	0.064	0.219	4000 K	On	0.11	0.070	0.046
				Off	0.123		
			3000 K	On	0.160		
				Off	0.115		

(b) Expected median and range of cortisol concentrations for apparently healthy people at different times relative to awakening – IBL International– Cortisol saliva ELISA–RE52611, 2015-08.

Time after awakening (h)	Median (μg/dL)	Range (μg/dL)	
		5%	95%
Awakening	0.343	0.113	0.803
0.5	0.478	0.200	1.076
1	0.384	0.101	0.936
2	0.234	0.083	0.574
5	0.150	0.074	0.355
8	0.116	0.055	0.314
12	0.082	0.032	0.322

CCT: correlated colour temperature.

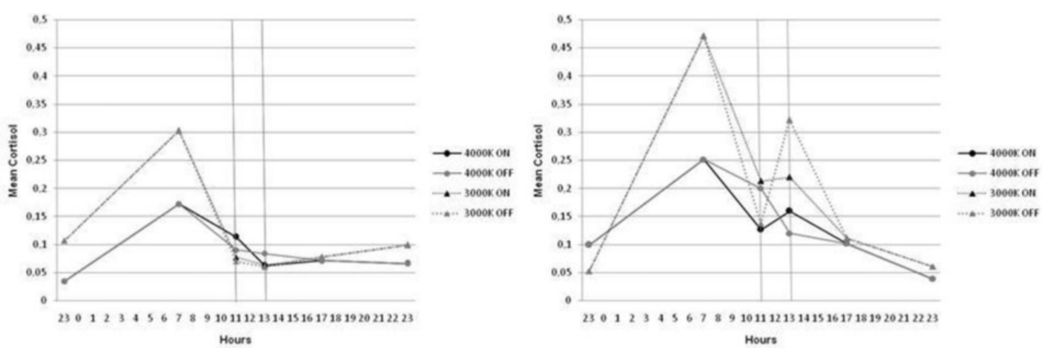

Figure 7 Mean cortisol concentration (μg/dL) at six times, the experimental lighting conditions occurred between the lines (Left: summer, Right: winter).

stress proneness show positive affects (higher scores on the test). The intermediate type C of the personality test type A/B shows more individuals without a proneness to stress.

Among the tests selected to characterize the psychological profile of the individuals, perceived stress was the most reliable feature to be related with the index of transitory mood, which showed high and significant correlations in summer under the CCT of 4000 K at the higher light level (rho = –0.821, $p = 0.023$).

Table 8 Correlations between the subjective indices under the different lighting conditions (Spearman's rho, $N = 7 \times 8$)

	Mood vs somnolence		Mood vs visibility		Somnolence vs visibility	
	Correlation	Significance	Correlation	Significance	Correlation	Significance
Week 1						
4000 K Off	–0.837[a]	0.019	0.849[a]	0.016	–0.904[b]	0.005
4000 K On	–0.926[b]	0.003	0.449	0.312	–0.606	0.149
3000 K Off	–0.725	0.065	0.304	0.507	–0.617	0.140
3000 K On	–0.144	0.758	0.512	0.240	–0.319	0.486
Week 2						
4000 K Off	0.000	1.000	0.000	1.000	–0.382	0.398
4000 K On	–0.896[b]	0.006	0.037	0.937	–0.031	0.947
3000 K Off	0.433	0.332	–0.134	0.775	0.000	1.000
3000 K On	–0.722	0.067	0.144	0.758	0.167	0.721

[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).

Table 9 Relationships between categorized variables of emotional state and perceived stress ($N = 7$)

	Emotional state		Personality type A/B	
Perceived stress	Negative affects	Positive affects	Type C	Type B
No stress	0	4	3	1
Stress	3	0	1	2

3.5. Visual discomfort

Symptoms of visual discomfort relating to tears, ocular fatigue, eye dryness, blurred vision and headache were analysed by lamp spectrum and light level (Table 10). In general, the most frequent symptom was ocular fatigue, followed by blurred vision. However, they were distributed almost evenly across the lighting conditions. Only headache occurs mostly under 4000 K. The mean value of visual symptoms was higher under this CCT (1.36 vs. 0.93), irrespective of the light level, hence correlations with hormonal outputs were carried out by CCT (Table 11).

Correlations between number of symptoms and melatonin were significant and negative at both CCTs, being higher at 3000 K, by increasing the number of symptoms in response to less melatonin. Cortisol coefficients show the same tendency but not statistically significantly.

In order to probe further into the relationships, a multiple regression analysis was performed under the CCT of 4000 K by including the two occasions of summer and winter, with number of visual symptoms as the dependent variable on light level, melatonin, cortisol, type A/B personality and perceived stress. Due to colineality issues, perceived stress was chosen instead of emotional state because it fits better into the model (Table 12). The results show that the perception of being a stressful person had a significant effect on the production of symptoms.

4. Discussion

The non-visual effects of light have become an additional dimension in the traditional objectives of architectural lighting, which

Table 10 Frequency of various symptoms by CCT and light level ($N = 7 \times 8$)

		Light level	Tears	Ocular fatigue	Dry eyes	Blurred vision	Headache
CCT	4000 K	Lower	2	7	2	5	3
		Higher	2	6	2	7	2
		Total	**4**	**13**	**4**	**12**	**5**
	3000 K	Lower	1	7	2	3	1
		Higher	2	6	1	4	0
		Total	**3**	**13**	**3**	**7**	**1**
	Combined	Lower	3	14	4	8	4
		Higher	4	12	3	11	2
		Total	**7**	**26**	**7**	**19**	**6**

CCT: correlated colour temperature.

Table 11 Correlations (Spearman rho) between number of symptoms, melatonin and cortisol averaged over the different lighting conditions ($N = 7 \times 8$)

CCT	Melatonin	Cortisol
4000 K	–0.433[a]	–0.183
3000 K	–0.535[b]	–0.329

CCT: correlated colour temperature.
[a]Correlation is significant at the 0.05 level (two-tailed).
[b]Correlation is significant at the 0.01 level (two-tailed).

Table 12 Regression for number of symptoms as dependent on light level, melatonin, cortisol, personality type and perceived stress

Variables entered	B	SEB	Beta	Significance
(Constant)	0.225	0.694		0.749
Light level	–0.301	0.385	–0.127	0.443
Melatonin	–0.045	0.057	–0.188	0.440
Cortisol	–1.131	2.655	–0.096	0.674
PersAB	–0.375	0.442	–0.156	0.405
Stress[a]	0.832	0.294	0.564	0.010

$R^2 = 0.42$, R^2adj $= 0.29$, $F(5,22) = 3.25$ $p = 0.024$.
[a]$p < .01$.
SEB: standard error for the unstandardized Beta.

should provide the optimal light for visual performance, for visual comfort, for the aesthetic appreciation of the space and for energy conservation.[33] Thus, in working environments, light must serve not only to meet task demands but also for comfort and health, which make up the state of well-being. Specifically, in the context of office spaces, this exploratory study aimed to determine whether lighting variations in terms of colour temperatures, light spectra and light levels, during exposures of moderate duration, would have any systematic impact on psychobiological correlates of well-being, by means of an holistic approach comprising visual, emotional and biological assessing methods. The literature[21] suggested that CCT and illuminance are the proper metrics for characterizing the visual system responses. For the non-visual system responses, melanopic illuminance at the eye was proposed. Nevertheless, there are emerging data that suggest an interaction at various levels between these two systems.[5] In this study, both metrics were recorded, as well as the CS calculation.

A secondary aim was to test the possible mediating role of the participants' psychological profiles composed of personality type, perceived stress and emotional state. The previous exposure to daylight (photic history) was also included for this purpose.

Although the present study has the limitations of a pilot study, certain trends were identified so they could be analysed in depth in further research.

The experiments comprised a repeated measure design with four conditions: low CCT low light level, low CCT high light level, high CCT low light level and high CCT high light level. The higher light level involved the illumination of the front wall (light ON), which was added to the horizontal light over the task. Alone this lighting formed the lower level (front wall lighting OFF). These conditions were assessed by seven participants on eight occasions yielding a total of 56 psychological responses in terms of transitory mood, somnolence, visual perception and comfort, which were further analysed in relation to melatonin and cortisol secretion.

Our hypotheses stated that better indicators of perceived quality will emerge in the set lit by the CCT of 3000 K, which will favour a better mood, while the set lit with 4000 K will be experienced as less comfortable but will provoke less somnolence. As to hormonal responses, it was hypothesized that a light spectrum with more radiation in the blue region will increase cortisol values. It was also stipulated that the light level will reinforce these outcomes.

Our results showed that the colour temperature of approximately 4000 K rendered most of the strong effects as to inter and intra correlations among psychobiological responses. The visual metrics in terms of illuminance and luminance were kept constant across the different experimental conditions while the non-visual metrics in terms of CS and melanopic illuminance were higher at each light level for 4000 K. This CCT has promoted less somnolence and more visibility, and therefore a better mood.

The lighting quality differentials used to rate the appearance of the experimental spaces have clearly discriminated the selected CCTs of 3000 K and 4000 K as warm and cool, respectively. The warm lighting was rated as pleasant and natural, while the cool lighting was rated as strong, and neither of them was rated as glaring. In this regard, the influence of the light level was important for various purposes, by accentuating the warmness and coolness properties, and also for visibility, which improved at the lower light level under the cool lighting and at the higher light level under the warm lighting. This last finding may be explained by the spectral irradiance measurements that characterized the total light spectrum where the observer was immersed. That is, the LED system used at the higher light level expanded the blue component from 415 nm up to 480 nm even in the CCT of 3000 K. Melanopsin, the photopigment of the ipRGCs, is particularly sensitive to blue light (i.e. wavelengths of 460–480 nm), and in addition to being involved in non-image-forming processes, it also plays a role in visual functions.[10,21]

Since the experiments were carried out during the morning, melatonin was taken as a positive control and cortisol became a more reliable indicator to test the hypotheses. In this study, the expected complementary behaviour of melatonin and cortisol was confirmed. In line with scientific evidence,[7,8,11] significant and positive correlations emerged in summer between the previous exposure to daylight and the nocturnal secretion of melatonin, and in winter between nocturnal melatonin and sleep hours during the working week. In summer, people spent more hours outdoors and secreted more melatonin at night. In winter, the secretion of melatonin was higher and provoked more sleep hours. In response to the artificial lighting manipulated in the experiment, more melatonin was produced under 3000 K in summer and 4000 K in winter, these seasonal variations being statistically significant. Complementary higher values of cortisol were exhibited under 4000 K during summer, while in winter, values were higher under 3000 K. These hormonal reactions to the experimental lighting conditions might be explained by the seasonally related photic history of the participants. Indeed, a significant difference was found in cortisol secretion between the 23:00 before and after the experiment for the 4000 K exposure during winter, a season in which artificial light becomes more important to people.

The comparison between seasonal and experimental melatonin responses showed that those individuals more sensitive to seasonal variation showed greater sensitivity to the different experimental lighting conditions as well. Thus, those subjects who did not display the expected seasonal variation showed less variability to the experimental stimulus. On the other hand, and in spite of the small sample, the results also suggest that low melatonin secretors might be less sensitive to the experimental lighting stimulus.

The psychological profile of the individuals was a construct developed to better understand the dynamic of the assessment since their reaction tendencies might act as mediators. Vulnerability and resilience became key concepts in environmental stress research, once it had been demonstrated that cognitive processes such as perceived control do mediate the impact of chronic environmental demands.[34]. Among the tests selected to characterize the psychological profile of the individuals, perceived stress was the most reliable feature to be related with the index of transitory mood, which showed high and significant correlations in summer under the CCT of 4000 K at the higher light level. Not significantly but as a consistent tendency, the higher light level improved mood, which was mediated by a relaxed personality such as type B.

According to Stephenson *et al.*,[4] quality of mood tends to reflect the level of alertness: as sleepiness increases, quality of mood declines and sleepiness impairs concentration and memory, which further negatively impacts performance and well-being. Participants of this study showed a positive mood throughout the experiment, nevertheless, mood was affected significantly by cortisol and perceived stress: an increased cortisol concentration improved mood while the increased perception of stress worsened mood. Cortisol was a strong predictor of transitory mood, and low values of cortisol were somewhat associated with more somnolence. Conversely, an increase in melatonin affected mood negatively, and correlations showed that, under the 4000 K CCT, the higher the melatonin level, the lower the visibility to perform the task. Thus, it can be inferred that the transitory mood of persons prone to stress might be affected by the exposure to a lighting of 4000 K and a level of 800 lx (horizontally) and 900 lx (vertically) with a melanopic illuminance of 8.86 lx.

In spite of the differences between the two sets in terms of CS and melanopic illuminance, none of the tested lighting conditions have affected hormonal secretion in acute suppressive ways, maybe due to the limited exposure time and the range of CCTs used. Colour temperatures of 3000 K and 4000 K were chosen due to their common use in workplaces where this study was carried out. The exposure to each CCT lasted almost four hours while the combination CCT plus light level lasted for 1.5 hours. Since one of the aims was to investigate transitory mood, the stay at each office set should have been moderate so that changes in mood are due to the experimental stimuli and not to feelings of confinement. Notwithstanding, statistically significant indirect effects were identified in the comparison of these apparently close CCTs.

Symptoms of visual discomfort that had to be reported at the end of each experimental session were few and distributed almost evenly among the lighting conditions, the most frequent being ocular fatigue and blurred vision. The mean values of visual symptoms and headaches were higher under 4000 K, and perceived stress significantly predicted the number of symptoms. So, the perception of being a stressful person could have facilitated the experience of visual discomfort.

In line with previous work,[15,17] this paper has identified that 4000 K lighting has the potential to provoke alertness or less somnolence, and therefore improved mood and visibility, but it was experienced as less comfortable. On the other hand, 3000 K lighting was better for the appraisal of the space, and its improvement on visibility seemed to be related to the higher light level, which was provided by the LED system. Lighting from LEDs can increase or decrease the CCT depending on the phosphors' properties. Both CCTs had a lot of spectral content in the blue area, this contribution being more noticeable in the set lit by 4000 K. Thus, this CCT should be able to modulate certain cognitive functions.

People respond to environmental exposure through a holistic process composed of psychobiological correlates. Our results bring empirical support to the existing and long studied evidence of the impact of light on mood.[35] The results showed that the reported experimental lighting design which comprised compact fluorescent lamps and LEDs with ranges of CCTs from 2877 K to 3856 K, horizontal illuminances from 450 lx to 800 lx, vertical luminances from 73 cd/m^2 to 270 cd/m^2, circadian stimulation from 0.27 to 0.46 and melanopic illuminance values from 1.78 lx to 8.86 lx have the potential to impact psychobiological parameters relevant to office workers well-being, mediated by their personal resources.

5. Conclusions

Although the findings presented in this paper are interim in nature, a contribution for lighting practice may be the consideration of the individuals' psychological profile, since it was suggested that this factor might explain the vulnerability to light found in many SAD studies.[3] The psychological tests selected to characterize the psychological profile worked well in relation to the mediator role predicted in the hypotheses, which certainly seems a large enough effect to deserve further study using a bigger sample size, longer exposures in larger spaces with the higher CCTs that are becoming common in other office workplaces. This exploratory study also contributes to research on the identification of the optimal lighting for visual comfort and the perception of the space and, at the same time, promotes the desired ipRGC photoreception.

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