International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

PO128

PREFERRED COLOUR TEMPERATURES OF AMBIENT LIGHT AT DIFFERENT LIGHT LEVEL SETTINGS

Tommy Goven et al.

DOI 10.25039/x46.2019.PO128

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

PREFERRED COLOUR TEMPERATURES OF AMBIENT LIGHT AT DIFFERENT LIGHT LEVEL SETTINGS

Tommy Govén[1], Thorbjörn Laike[2]
[1] Svensk Ljusfakta, Stockholm, SWEDEN, [2] Lund University, Lund, SWEDEN

tommy.goven@gmail.com, thorbjorn.laike@arkitektur.lth.se

DOI 10.25039/x46.2019.PO128

Abstract

Ambient light is taken more into account in today’s lighting design as it has a major impact on human well-being as well as reduction of glare. LED lighting provides new opportunities to design more efficient lighting systems in terms of improved color rendering and possibilities to vary the color temperature in order to mimic daylight.

Today there is a trend to use dynamic lighting in working environments to set the circadian rhythm by varying the CCT over the day by using higher colour temperatures and illuminance levels in the morning and lowering the values in the afternoon toward night.
This study investigated preferred color temperatures within an ordinary workplace area using various light levels and different ratios between task area and the ambient light in a laboratory environment. Furthermore we also compared different age groups and gender in order to examine if there were any such differences in preferences.

Keywords: Colour temperature, ambient light, room brightness, energy efficiency, light emitting diodes

1 Introduction

LED is today and will be our most common light source in future lighting systems both indoors and outdoors. It creates the greatest conditions for an energy-efficient lighting. At the same time, it provides the conditions for improved color rendering. In addition, the LED light source can vary the color temperature to mimic the variation of daylight over time in the range of 2700 K to 6500 K.

Risks with LED are increased risk of glare, of increased irradiance (increased spectral light intensity) in the range 460-480 nm as often contributes to increased light scattering in the eye lens. In addition, the light source is often dot-shaped which can cause glare due to high luminous fluxes within a limited luminous surface. We already know that the experience of glare can be reduced with an increased ambient light. In order to obtain a quick and positive implementation of LED lighting in our indoor lighting facilities, with this study, we want to investigate which correlated color temperatures are preferred for commonly recommended lighting conditions in indoor workplaces with respect to ambient illuminance/ luminance in working environments.

Lighting installations in the future will increasingly be varied both in terms of light level and color temperature in order to set humans daily circadian rhythm and by utilizing the presence frequency and daylight incidence for more efficient use of energy for lighting. We know that the preferred color temperature varies with the illuminance and with the amount of incident daylight over time. For these conditions, there is no international studies regarding LED as a light source.

In this study two age groups were examined. A younger group 20-40 years and an older 50-70 years since the vision abilities are different for different age groups. Since there currently is a discussion about increased retirement age for about 70 years, it is also of great importance to investigate the elderly's preferences for lighting in the work environment.

The relationship between illuminance and color temperature has been studied for a long time. Kruithof was already in 1941 [1] able to show that there was a connection between the lighting level and the color temperature when the light was generated with fluorescent lamps. To simplify, Kruithof showed that there was a preference for higher correlated colour temperatures when higher illuminance were used.

It must be emphasized, however, that this research was carried out with light sources that deviate greatly from the LED's spectral distribution.

In recent years Han and Boyce [2] examined which color temperatures were preferred for fluorescent lamps within the 3000 K to 6500 K range for a illuminance range of 300 to 900 lux and Vienot et. al [3] examined the perceived pleasantness within 2700 K to 6500 K vs. illuminance at 150 to 600 lux using LED lamps.

Boyce has also, together with Cuttle [4] looked at the importance of the room's color scheme for the preference of color temperature.

All these studies found no clear preference for higher CCT at higher illuminance levels as clear as Kruithof found in 1941 [1]. Other researchers also found the similar results that luminous colour is not dependent on illuminance [5].

The room's color scheme plays a major role in the preference. Access to daylight also plays a role. Thus, there are reasons to assume that several factors play a role in the choice of color temperature in relation to illuminance.

The European standard on lighting for indoor workplaces EN 12 464-1, 2011 [6] and other international requirements and guidelines has a clear focus on localized lighting systems in order to create conditions for more energy-efficient lighting systems. Localized lighting systems which are based on the fact that the lighting system is divided into three different zones: the working area, immediate surroundings and the outer envelope. Each zone receives different lighting requirements, which creates energy-efficient lighting facilities.

In this context, it is important to consider the importance of the ambient light and the increased requirements for higher room brightness of the work environment which have a major impact on the perceived the visual glare and non-visual effects such as alertness and well-being. For this reason it is of major interest to investigate in which way the preferred CCT is affected by different light distributions in the space e.g. ratios between the horizontal task area illuminance and the ambient vertical illuminance the interconnections there between. Today there is currently no recommendation on suitable correlated color temperatures for commonly used light distributions and illuminance levels for LED lighting.

2 Aim of the study

The aim of the present study was to investigate the preferred color temperature at different illuminance levels, both horizontally and vertically, for workplaces equipped with LED lighting in order to obtain energy efficiency and good light quality. In order to obtain reliable values, the impact of glare and flicker were kept low and constant over for all different light scenes during the test.

3 Method

Initially, a literature review of available research was conducted. In the review the following sources were use; Web of Science, Scopus and CIE Proceedings.

The keywords used are shown in Table 1. The result of the literature review was used as a basis for selecting color temperatures for the study.

Table 1 - Keywords used for literature review

Lighting parameter's	Human evaluation	Context	Population
Colour temperature Correlated colour temperature, CCT Luminance Illuminance Vertical illumination Horizontal illumination Ambient illuminance Glare Flicker Brightness Light source Illuminant Light emitting diode, LED	Preference Preferred	Age Office Work Indoor Laboratory	Age Adult Older Younger

3.1 Sample

Experimental group and implementation.

A total of 47 subjects participated in the study, of which 27 were women and 19 were men. The average age was 43, 4 years (20-70 years). 31 of the subjects used glasses. All had adequate vision with correction and normal color vision.

The subjects were asked to choose the color temperature they preferred among five different possibilities. 2700K - 3000K - 3500K - 4000K and 6500K at different lighting levels from 50 to 1000 lux, a total of 7 levels. For each setting the subjects was adapted at 3500K for 10 minutes and then 5 min to test the different CCT (freely), select the preferred, leave and come back to the room for the next setting.

Three different illumination conditions were investigated based on the ratio of the mean horizontal illuminance / luminance measured on the work surface to the mean vertical illuminance / luminance on the room walls within the normal field of view (1: 1, 2: 1 and 5: 1). All started with the ratio 2: 1. Then half of the group was randomly given either their 1: 1 or 5: 1 preference judgments. All groups were evenly distributed concerning age. The different lighting conditions were based on the relationship between a reference point on the wall and a reference point on the work surface (Table 2).

The two groups also had different presentation arrangements to avoid the effects of the presentation scheme. One group began their low-light assessments and the other group began with high levels of illumination. 21 preset scenarios for different light distributions were used in the study (Table 3). In totals 105 different light preset scenarios for simple selection by the subjects between the five CCTs by pressing a neutral button labeled 1-5 on a tablet screen at all ratios. Each color temperature could be tried as many times as desired within a ten minute period before finally choosing the preferred color temperature. All selections were stored digitally for each subject. In total, the experiment lasted four hours. Before the experiment began, the subjects were asked to think that they were in a working environment and to choose the preferred color temperature in relation to this.

Table 2 - Overview of subjects and the different lighting conditions

Number of subjects	Gender	Age	Lighting conditions (N=3)			Order of presentation	Selection of CCT all settings (N=5)
			task area /walls	vertical walls	horizontal task area		
N=47	Female, N=27 Male, N=19	m=43,4 spread =20-70	**1:1**	**50 %**	**50 %**	Low vs. high 50-1000 lux High vs. Low 1000-50 lux	2700K - 3000K - 3500K - 4000K - 6500K
			2:1	**25 %**	**75 %**		
			5:1	**10 %**	**90 %**		

Table 3 - Compilation of the various lighting scenes used in the study

Light scene	Horizontal illuminance task area (lux)	Light Distribution Ratio task area vs. vertical, walls	Selection of CCT all settings (N=5)
1	50	1:1	1 = 2700 K 2 = 3000 K 3 = 3500 K 4 = 4000 K 5 = 6500 K
2	50	2:1	
3	50	5:1	
4	100	1:1	
5	100	2:1	
6	100	5:1	
7	200	1:1	
8	200	2:1	
9	200	5:1	
10	300	1:1	
11	300	2:1	
12	300	5:1	
13	500	1:1	
14	500	2:1	
15	500	5:1	
16	750	1:1	
17	750	2:1	
18	750	5:1	
19	1000	1:1	
20	1000	2:1	
21	1000	5:1	

3.2 The conditions of the lab environment

The test situation

The study was conducted in a lighting laboratory at the Department of Architecture at Lund University. The test room, which was windowless, had the dimensions 6.0m x 4.0m with a height of 3m. The walls were white with a gravy tone (NCS N1500).

The gloss steel in ceiling ≤ 3 and on walls ≤ 5. The reflectance of the wall surfaces was measured to about 82 % for the floor surface 35 % and roof surfaces approximately 90 %. The furniture consisted of a table and a chair where the subject sat during the experiment.

The light sources consisted of four different types of LED luminaires with different light distributions to uniformly illuminate the room surfaces. 36 luminaires of type Pleiad G3 from Fagerhult were installed named L1, L2, L3 and L4. Luminaire types L1 - L3 were installed in the test room and type L4 was located in the corridor directly outside the test room.

In the waiting room where the subjects waited before the test began, had a neutral colouring and the lighting was designed for a horizontal illuminance of about 200 lux and a colour temperature of 3000K. An overview is given in Table 4.

Table 4 - The table shows the specification for the different luminaires and the measured light output fluxes of the LED modules.

Luminaire types	L1	L2	L3	L4
Mfr; Fagerhult	77 975 + 4201	77 974 + 42 031	77 974 + 420 31	77 951 + 42 031
Type; Pleiad G3, Recessed LED - downlight	Downlight 2700 - 6500 K 1296 lm	Wall washer 2700 - 6500 K 1345 lm	Wall washer 2700 - 6500 K 598 lm	Downlight 3000 K 830 lm

NOTE Other equipment used in the installation; LED module: Mfr. Osram, type Stark, Driver: Mfr. Tridonic, type DALI and Control equipment: Mfr. Helvar, Router 910.

The ambient light of the test room was provided indirectly by wall washers except for the luminaires providing direct light positioned above the workplace and located outside of the subject’s normal field of view. In this way no light was perceived directly from luminaires and glare was minimized.

The flicker situation was also the same for all conditions in order to avoid the effects of this. Figure 1 shows the design of the room and the location of the luminaires in the test room.

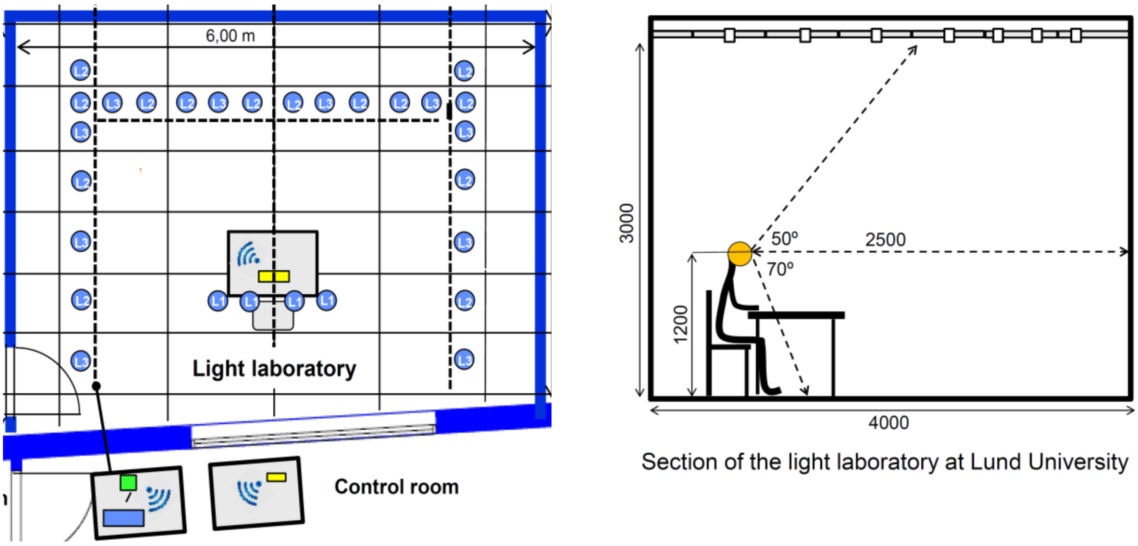

Figure 1 - Drawing of the light laboratory and control room where the experiments were carried out showing the location of the luminaires used in the test room

Measurements of the lighting conditions with respect to illuminance, correlated color temperature and color reproduction were performed prior to the start of the experiment and after the end of the experiment to control the stability of the light sources during the experiment.

It turned out that the deviation from the determined value was small both before and after the experiment (Figure 2a and 2b).

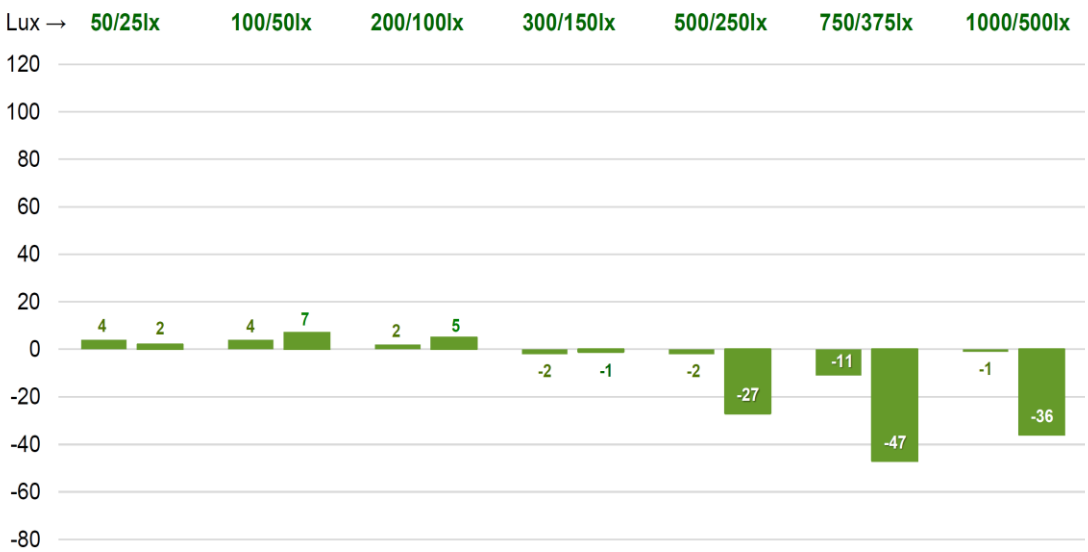

Figure 2a - Deviations in illuminance (lux) from measured and established illuminance levels before the experiment at ratio 2:1 between task area and ambient illuminance

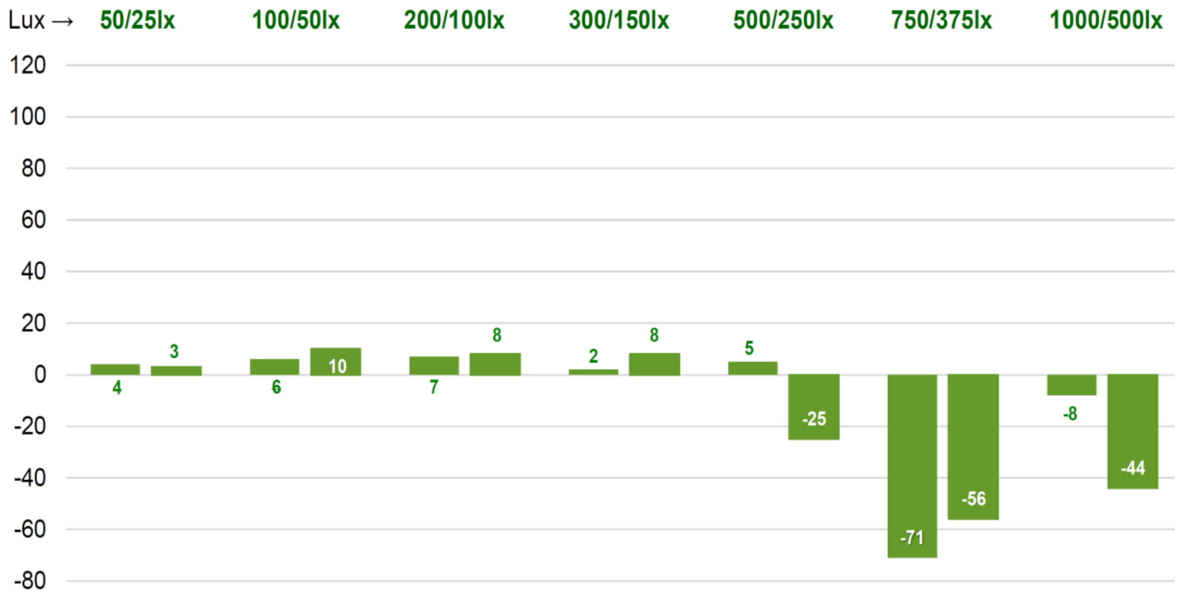

Figure 2b - Deviations in illuminance (lux) from measured and established illuminance levels after the experiment at ratio 2:1 between task area and ambient illuminance

Similarly, the color temperature, the deviation from the determined value and the stability of the color temperature are reported by showing the deviation before and after the experiment.

We have chosen to present only results from the four illuminance levels that are the most commonly used in working environments (Figure 3a and 3b).

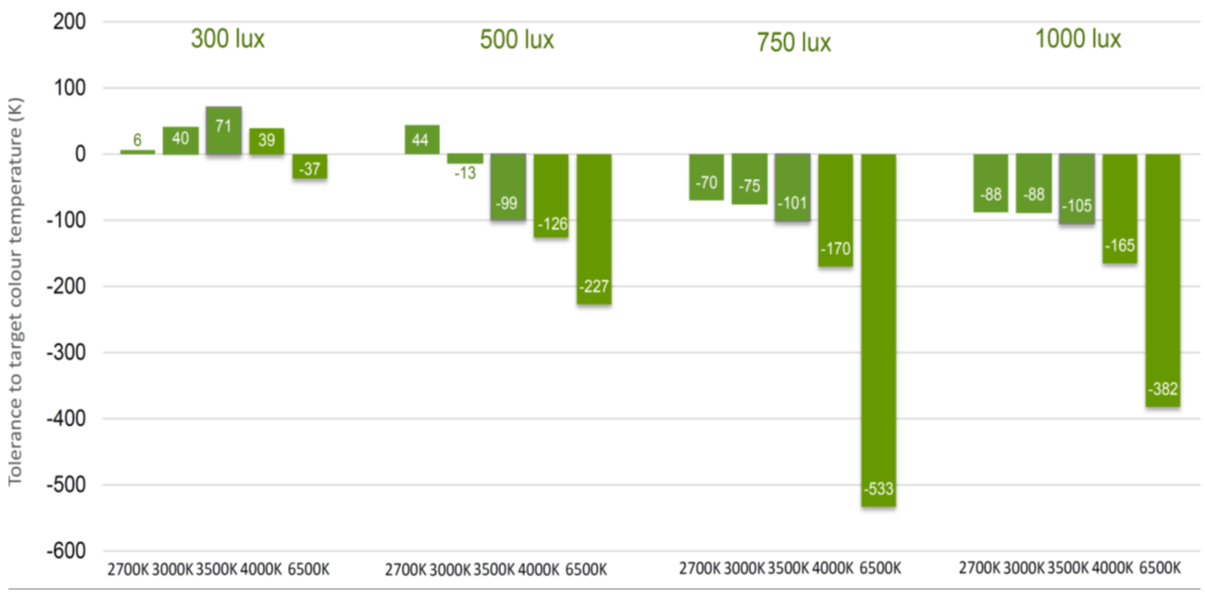

Figure 3a - Deviation from established correlated color temperatures, CCT in Kelvin before the experiment for four illumination levels

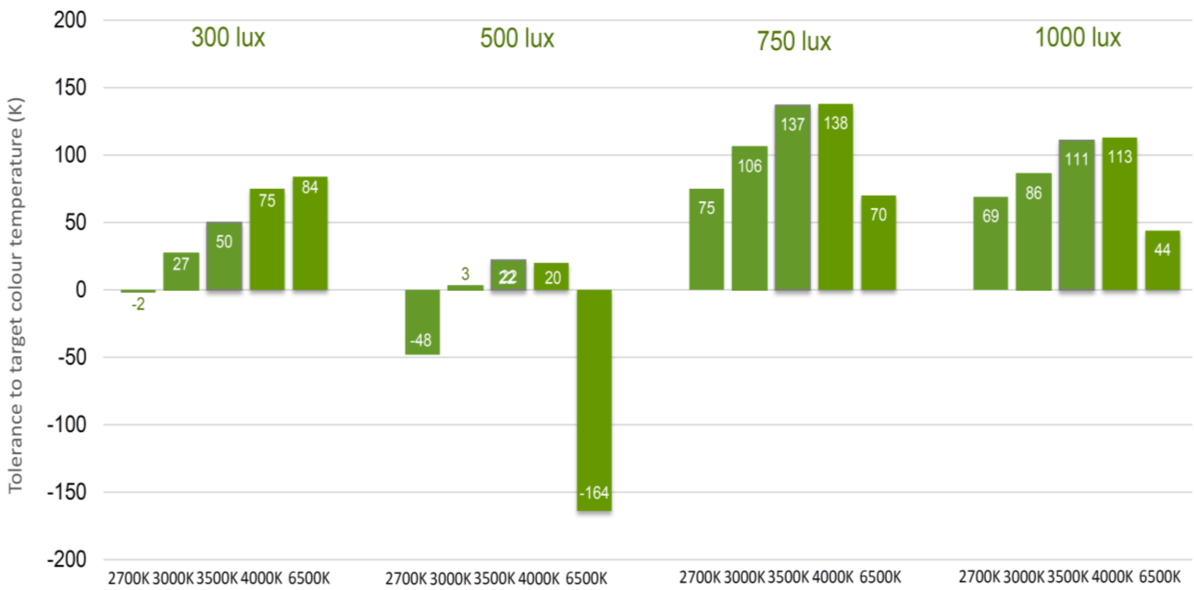

Figure 3b - Deviation from established correlated color temperatures, CCT in Kelvin after the experiment for four illumination levels

The measurements show that the deviation is relatively small and below normal tolerances of ± 200K and that the color temperature was stable over time. This means that the subjects have been exposed to similar conditions throughout the test period.

The spectral distribution of the light under different conditions was also measured with a spectrometer. Figure 4 shows the spectral composition of the 2:1 ratio at 500 lux horizontal illuminance at the task area. The spectral distribution of the light was measured 1.2 meter above the floor towards the eye in the direction of the front wall.

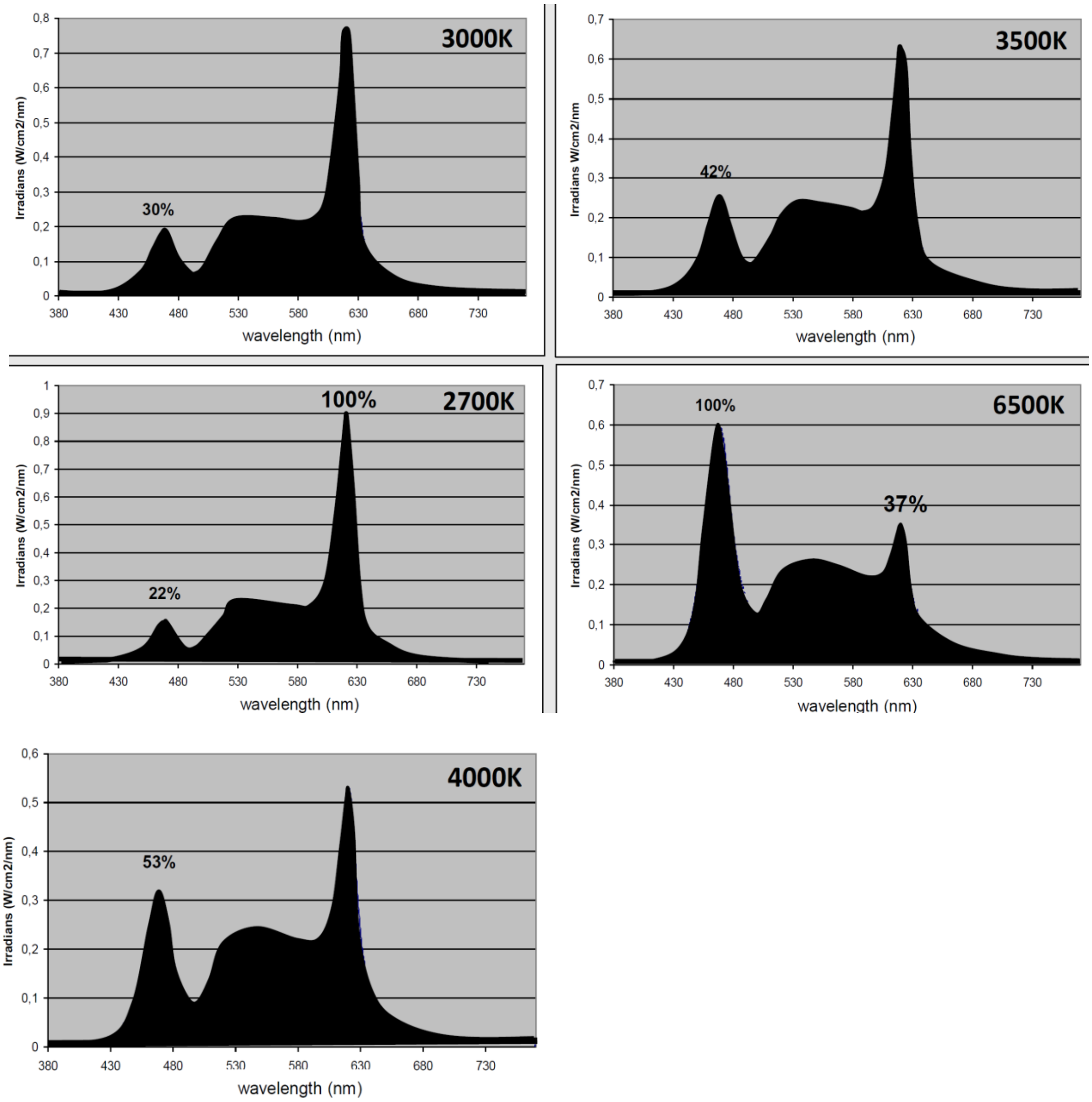

Figure 4 - Spectral distribution of the light at 500 lux horizontal illumination and 250 lux vertical illumination for the five color temperatures.

4 Results

4.1 Subjective experience of the lighting conditions

Generally, there are small systematic differences for preference of color temperature relative to illumination levels. In this study we cannot verify Kruithof's model where LED lighting is used. However, we can see systematic differences between the preferred color temperature and the relationship between horizontal illuminance at the task area and ambient vertical illuminance on the walls.

A significant difference is found for the ratio 2: 1 when all lighting situations were compared ($F(6; 276) = 2{,}048$, $p < .05$). For the ratio 5: 1, this appears as a tendency $F(6; 132) = 1{,}450$, $p = .06$.

For the ratio 1: 1 there were no differences at all. This means that the distribution of light in the room is important for the choice of color temperature. These differences were general and not dependent on age, gender or presentation scheme.

For a practitioner, however, it is also interesting to look at different illuminance levels and ratios and preferences for these and, in particular, the illuminance levels recommended in the European standard EN 12 464-1, Lighting of indoor workplaces [6] and in other international requirements and guidelines which can be considered as fairly normal conditions at a workplace. We have therefore chosen to report results for task area illuminance of 300 and 500 lux and ratio between task area and the ambient illuminance in the field of view of 2:1.

There were no significant differences for the individual color temperatures, but we can observe that very few subjects prefer the lowest color temperature (2700 K) and the highest (6500 K).

For both conditions 300/150 lux and 500/250 lux, 3500 K or 4000 K seems to be the most preferred color temperatures. There is also a tendency for female in both conditions to prefer a slightly lower color temperature than male. At the same time, the male group shows a greater spread. No female preferred 2700 K at illuminance ratio of 500/250 lux, while 10% of men did. (Figure 5a and 5b)

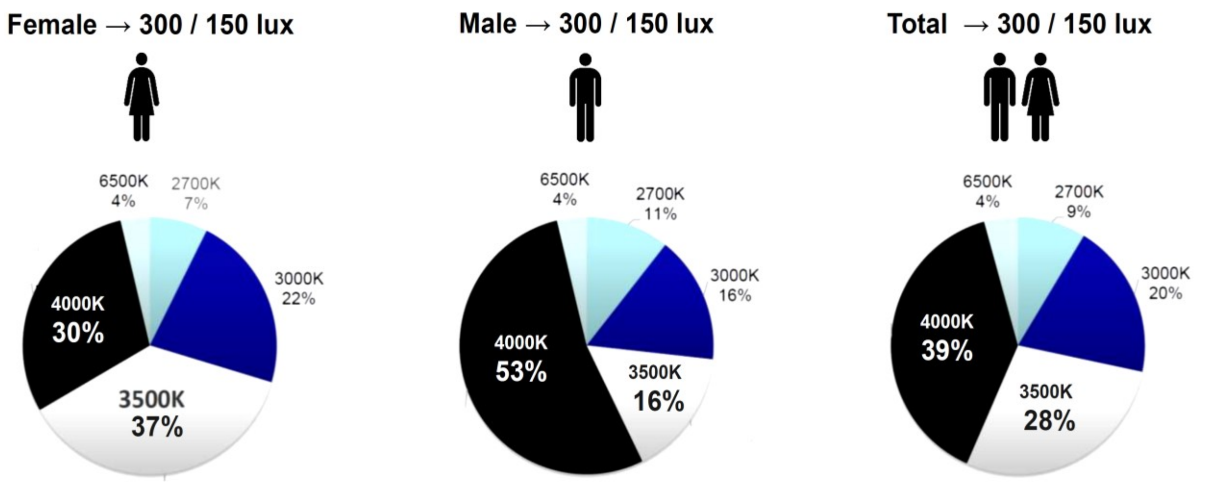

Figure 5a - Preferred color temperatures at an illuminance ratio of 2:1 between task area / ambient illuminance (300/150 lux) for male and female - 20-70 yrs. (N = 46)

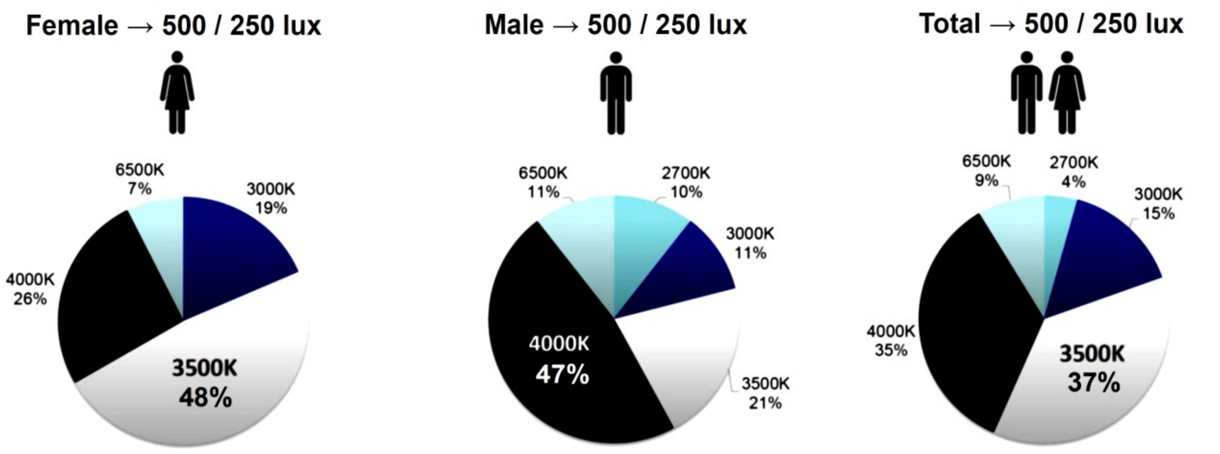

Figure 5b - Preferred correlated color temperatures at an illuminance ratio of 2:1 between task area / ambient illuminance (500/250 lux) for male and female - 20-70 yrs. (N = 46)

There were no differences regarding age for general preference at any illuminance level. We may thus conclude that with good lighting conditions, i.e. low flicker level and low glare, the subjects seem to prefer 3500 - 4000 K.

The preference for color temperature is dependent on many factors, but this study shows that higher color temperatures can be achieved at least in neutral office environments without negative reactions occurring.

Are there any differences at all? Yes, when we reach extreme levels, there are differences and these do not go in the expected direction. In the light situation 2:1, we received significant differences in color temperature preference for the following lighting levels:

- 50 lux (CCT mean = 4004; SD = 1127.1) and 1000 lux (CCT mean = 3636; SD = 864.8), $F(1, 46) = 5.879$, $p <.05$, $ɯ2 = .11$.
- 50 lux (CCT mean = 4004; SD = 1127.1) and 750 lux (CCT mean = 3717; SD = 948.9), $F(1, 46) = 4.282$, $p <.05$, $ɯ2 = .09$.
- 50 lux (CCT mean = 4004; SD = 1127.1) and 300 lux (CCT mean = 3665; SD = 755.6), $F(1, 46) = 5.156$, $p <.05$, $ɯ2 = .10$.
- 50 lux (CCT mean = 4004; SD = 1127.1) and 100 lux (CCT mean = 3674; SD = 717.9), $F(1, 46) = 6.602$, $p <.05$, $ɯ2 = .13$.

Similar results were also obtained for the light situation 5: 1 when we compared the color temperature preference between 50 lux (CCT m = 4082; SD = 1214.9) and 1000 lux. (CCT m = 3573; SD = 746.6), $F(1, 22) = 4.512$, $p <.05$, $ɯ2 = .17$.

Overall, these results show that a high color temperature is preferred when having extremely low lighting levels (50 lux), while slightly warmer, but still relatively cold light is preferred at the highest lighting levels. When it comes to the general preference, the subjects preferred a color temperature between 3500 and 4000 K.

5 Discussion

The results of the present study show that the color temperature is dependent on several factors, not least the relationship between horizontal and vertical illumination. Furthermore, the study shows that the connections between preference and illuminance levels seem to be more complex than previously assumed.

In addition to the direction of light, the color scheme plays a role for the preference of color temperature. In the present study, the environment was very neutral in color, which plays a role in the results. This means that the choice of color temperature in an environment must take all these factors into account.

The study also shows that the tolerance for slightly higher color temperatures than 3000 K is general. 3500 K to 4000 K is the most preferred levels regardless of the lighting level that applies. There were relatively small differences between different groups regarding age and gender. This means that these correlated colour temperatures are recommended to be used for larger groups in working areas with LED lighting if the above mentioned factors are taken into account.

The activity within in the environment is another factor of importance. In this study, the subjects would imagine an office environment, i.e. a workplace, and it also seems to be important for the preference. We believe that this can explain the deviating results for the extremely low levels, where, contrary to previous research, we found that in the lowest light level a higher color temperature was preferred. A higher color temperature has an activating effect, something that is necessary in connection with work. However, these results must be interpreted with caution. There are reasons to assume that several of the factors mentioned above account for the preference.

We also want to emphasize that the present results have been obtained in a lighting environment completely without daylight which was in principle glare-free without any glare sources in the field of view and with very low levels of flicker level, i.e. high quality light sources positioned to avoid glare.

If we look at the light sources as such, they exhibit relatively good stability during the whole experiment, both in terms of illuminance levels and color temperatures. It should be noted that the measured color temperatures are correlated color temperatures, so the spectral composition and color reproduction may vary between different light sources of the same color temperature (Figure 4).

All light sources / LED modules within the experimental room exceeded the requirements set in the European standard EN 12464-1 (requirements for lighting of indoor workplaces) [6] for color reproduction on CRI, Ra 80 in at all lighting levels.

What can be taken out from the present results is that the mostly preferred color temperature in a working environment seems to be higher than the in Sweden commonly used 3000 K. An alternative would be to raise the level to 3500 K or 4000K.

This can contribute to improve energy efficiency as visibility increases with increased color temperature. However, more studies should be conducted as the present study also shows that the question is very complex and that there are no simple connections. As previously mentioned, the room's color scheme plays a role and also the access to daylight.

Difficulties in connection with the study have been that spectral light distribution and color reproduction can vary between different LED modules and control systems at the same stated or measured correlated color temperature. We have tried to meet this by carrying out accurate measurements for each situation studied, but when the results are translated into reality and no measurements are made, errors can occur. There is a need for a more developed standard for describing color temperature and color reproduction.

In order to better understand the connections between the external factors and the preference for color temperature, it would be beneficial to add daylight penetration to the test environment, i.e. to conduct the investigations in rooms when there is a normal daylight penetration. This, together with varied wall décor, would give us more knowledge about the complex relationships that exist between preference and environmental factors.

Acknowledgements

This work has been funded by the Swedish Energy Agency the Swedish Energy Agency and the EELYS project "The application of research and science within the standardization in the field of light and lighting for more efficient use of energy and good lighting quality".

References

1. KRUITHOF. A.A. 1941. *Tubular luminescence lamps for illumination*. Philips Technical Review, 3(6), 65-73.
2. HAN, S. & BOYCE, P. 2003. *Illuminance, CCT, decor and the Kruithof curve.* CIE 178:2007 Proc. of the 25th Session of the CIE, San Diego, D3-178ff.
3. VIENOT, F., DURAND, M-L. & MAHLER, E. 2009. *Kruithof's rule revisited using LED illumination.* Journal of Modern Optics, 56 (13), 1433-1446
4. BOYCE, P. & CUTTLE, C. 1990. *Effect of correlated col to or temperature on the perception of interiors and color discrimination performance*. Lighting Research and Technology, 22(1), 19-36
5. BIESKE, K., SCHIERZ, C., *Dynamic Lighting – Perception of luminous colour variation*. Proceedings of CIE 2010 "Lighting Quality and Energy Efficiency", 291-297.
6. CEN 2011. CEN/TC 169, EN 12 464-1, 2011. *Lighting of workplaces: Indoor workplaces*.