

A Study about Colour-Difference Thresholds

Bieske, Karin; Vandahl, Cornelia (Ilmenau, D)

1 Introduction

Dynamic lighting systems contain light sources with different luminous colours like fluorescent lamps or LEDs or a combination of different types of light sources. By separate control of each component, the temporal variation of the illuminance level and the spectral and spatial distribution of light are applicable. Because of these variations, there may be effects not only on visual perception, but also on photo-biological and emotional processes of humans.

Today there are technical possibilities to realise dynamic lighting systems. Light sources, control units and detectors for feedback control are available. New lighting solutions are available on the market. However, what we need is a new knowledge of control strategies. Condition for such control strategies is the consideration of quantitative and qualitative light effects both in visual perception and in emotional and biological processes.

The focus of our investigations was the visual perception of colour differences for variable chromaticity coordinates. The main topics are the correlation between preferred luminous colour and illuminance, thresholds and tolerance limits of colour differences caused by the variation of chromaticity coordinates as well as colour differences on light emitting surfaces, between luminaries and shadows of luminaries.

2 Experimental Set-up and Methodology

Our investigations have been done under laboratory conditions. This has the advantage that most of the parameters are definable and stable. In some experiments light simulators have been used. The base area of a simulator was 1.3 m by 0.8 m. Red, green, blue and white fluorescent lamps have been applied for the illumination (Figure 1). We used a DALI-protocol, a digital addressable lighting interface, to tune the single lamps constituting given light scenarios. So it was possible to establish the planned illuminance levels, chromaticity coordinates and

colour temperatures for each situation. The same procedure has been used in our experimental laboratory shown in Figure 2.



Figure 1: Design and application of the light simulator

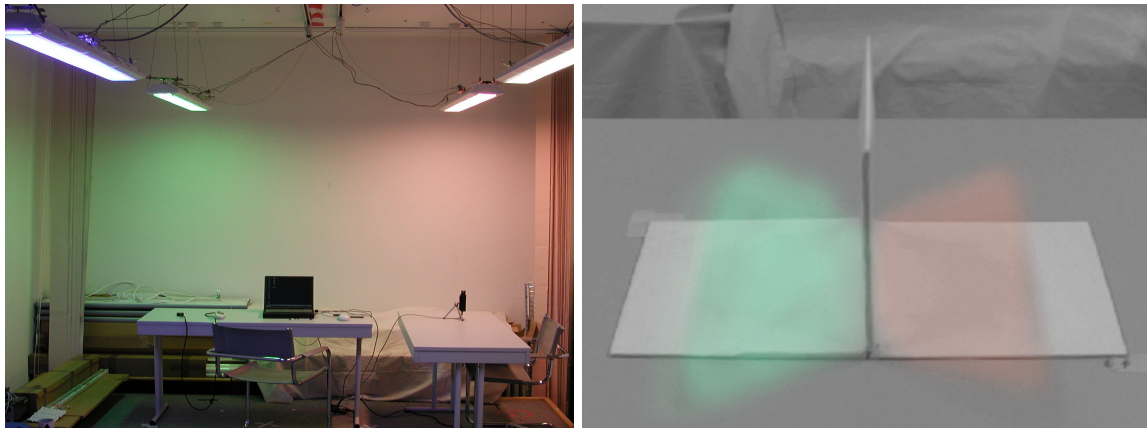


Figure 2: Experimental laboratory for the investigation of colour differences between luminaries (left) and between shadows of luminaries situated side by side on a shadow object (right)

3 Investigations

3.1 Correlation between preferred colour temperature and illuminance

Preferred colour temperatures for various illuminances have been investigated. The initial colour temperatures were between 3000 K and 8100 K. The luminous colour has been varied in steps of 300 K along the Planckian Locus (Figure 3). In further experiments, initial colour temperatures of 2800 K, 4900 K and 6500 K have been used.

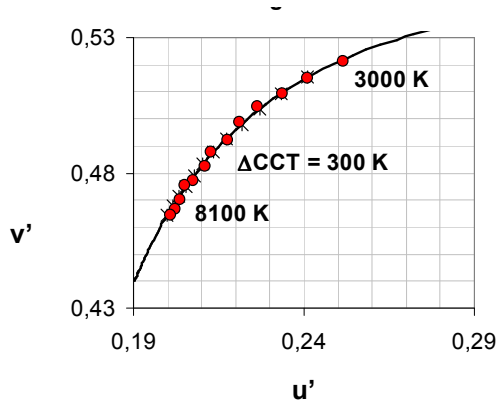


Figure 3: Colour coordinates of the used luminous colours in the UCS diagram

Illuminances of 300 lx, 500 lx and 1000 lx have been investigated. The parameters have been set according to the range of colour temperatures of typically used lamps and of typical illuminance levels at work places.

21 subjects took part in this experiment and adjusted their most pleasant colour temperature for each illuminance level. Every situation has been shown to the subject three times. Figure 4 shows the results.

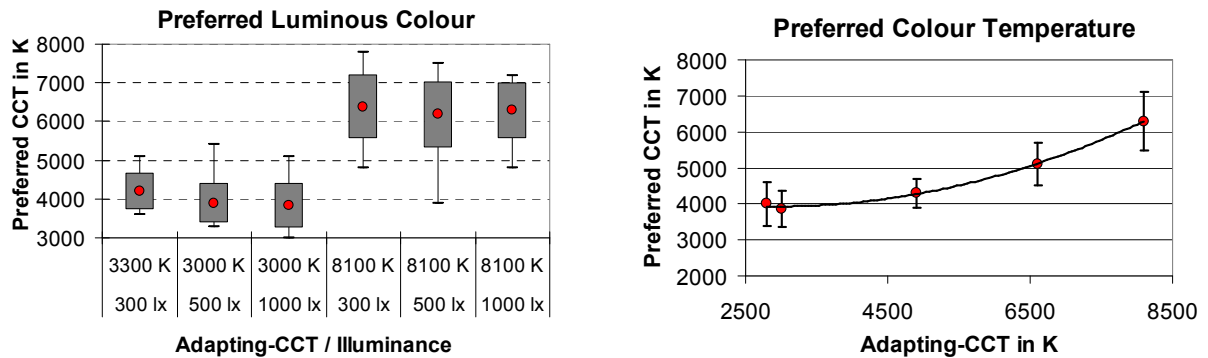


Figure 4: Preferred colour temperatures dependent on initial adapting conditions, 21 subjects

No correlation between preferred colour temperature and illuminance could be found. However the preferred colour temperature correlates with the initial colour the subjects were adapted to. The preferred colour temperatures range from 3800 K to 6500 K, but also 3000 K and 7800 K are acceptable. In the range between 3000 K and 8000 K, the connection between preferred colour temperature (CCT_{pref}) and initial adapting colour temperature (CCT_{adapt}) can be described by a second-degree polynomial:

$$CCT_{pref} \approx 9 \cdot 10^{-5} \cdot CCT_{adapt}^2 - 0,5239 \cdot CCT_{adapt} + 4700 \text{ K} \quad (1)$$

The results of the test series are in accordance with those of Han and Boyce [Han03]. They investigated the perception of office lighting at different illuminances, colour temperatures and room decors. All parameters interact to affect the perception of office lighting. The range of acceptable illuminances is stable at about 300 lx to 900 lx, over a range of CCTs from 3000 K to 6500 K. There is a contradiction to the result of Kruithof [Kruithof41], whereby, at low illuminance, low colour temperatures are preferred, and, at high illuminance, high colour temperatures are more pleasant. Similar disagreement was found by Polle [Poll05]. The preferred colour temperature had not a fixed value. It was better to implement a range of colour temperatures.

The recommendation for colour temperatures used in dynamic lighting systems ranges from 3000 K to 8000 K at least, independent of the available illuminance.

3.2 Thresholds and tolerance limits

During a further investigation, the chromaticity coordinates have been varied in steps of several ranges along the Planckian Locus and the iso-temperature lines while the illuminance has been kept constant. Starting from a reference situation (initial basic value that the subjects have been adapted to) the colour difference increased continuously (Figure 5). The subjects had to rate the perceived steps as follows: “*just noticeable*”, “*distinctively perceptible*” and “*disturbing*”.

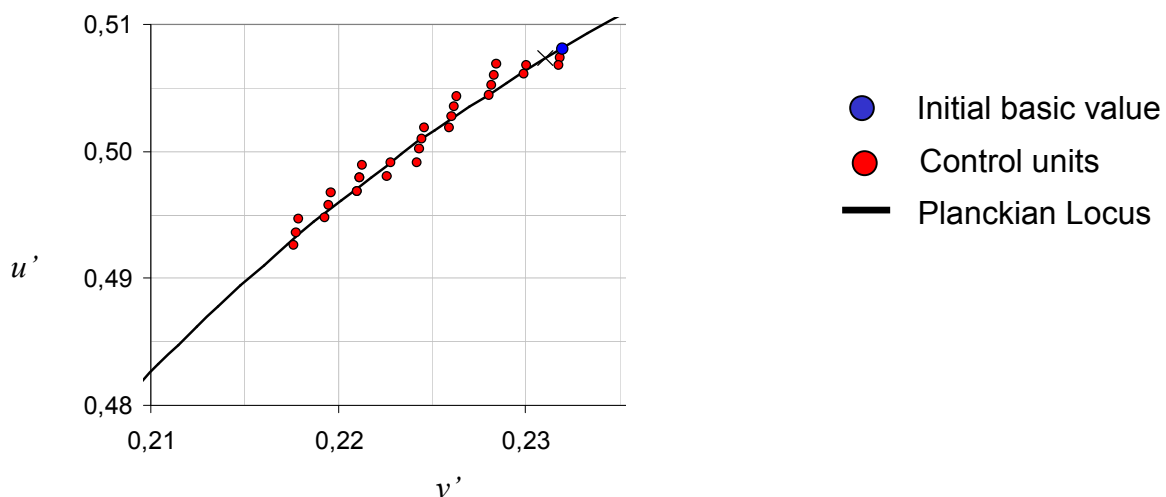


Figure 5: Control values 3700 K (initial basic value) variation along the Planckian Locus

The investigated situations consisted of different colour temperatures and illuminances. 21 subjects took part in this investigation. There are no significant differences in the ratings of the subjects between illuminances of 300 lx and 1000 lx.

For the analysis, the UCS-difference and the CIELAB colour difference have been used (Equations 2 and 3).

UCS-Difference:

$$\Delta u'v' = \sqrt{(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2} \quad \begin{array}{ll} u'_1, v'_1 & \text{Reference} \\ u'_2, v'_2 & \text{Test} \end{array} \quad (2)$$

CIE-Lab-Colour Difference [CIE04]:

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2} \quad \begin{array}{ll} a^*_1, b^*_1, L^*_1 & \text{Reference} \\ a^*_2, b^*_2, L^*_2 & \text{Test} \end{array} \quad (3)$$

with $L^*_1 = L^*_2$

3.2.1 Variation along the Planckian Locus

These results are shown in Figure 6.

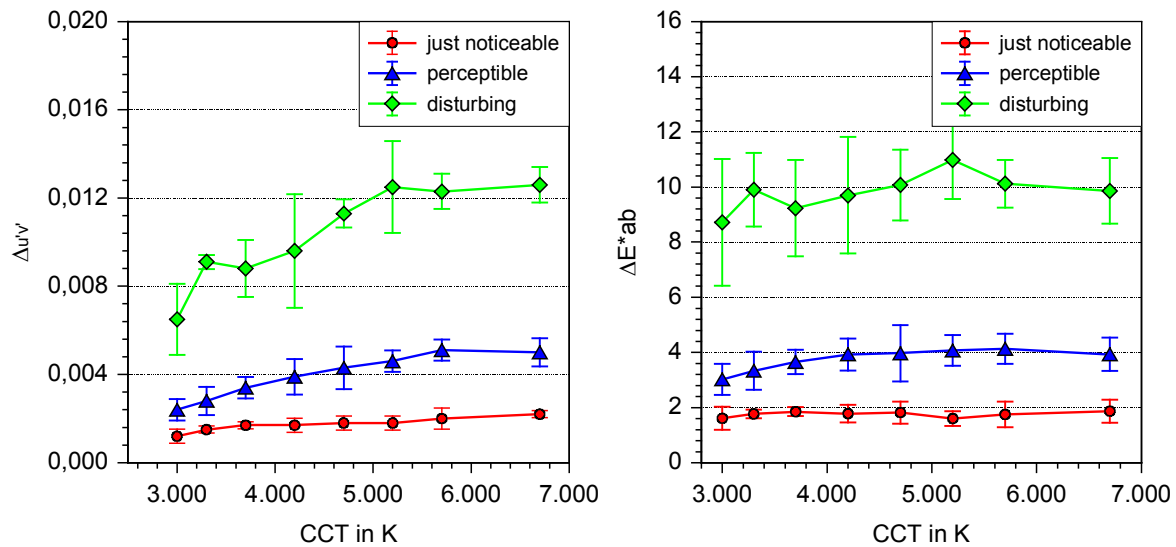


Figure 6: Variation along the Planckian Locus – summarized data for all illuminances and variation directions for the criteria “just noticeable”, “distinctively perceptible” and “disturbing” – in dependence of the Correlated Colour Temperature (CCT)

For the UCS-Differences given by the rating criteria there was a dependence on CCT but there is virtually no such dependence in the CIELAB system. Therefore it was possible to calculate a mean value for each criterion in the CIELAB system, shown in Table 1.

Table 1: Mean values of CIELAB Colour Difference for the variation along the Planckian Locus in steps

Criteria	<i>just noticeable</i>	<i>distinctively perceptible</i>	<i>disturbing</i>
ΔE^*_{ab}	1,8	3,8	9,8

Based on these values it was possible to calculate the functional dependence of CCT on UCS-Difference and the criterion determined dependence of CCT on deviation of the colour temperature. These results are shown in Figure 7. There are no large deviations between the fit function and the experimental data (Figure 7 left).

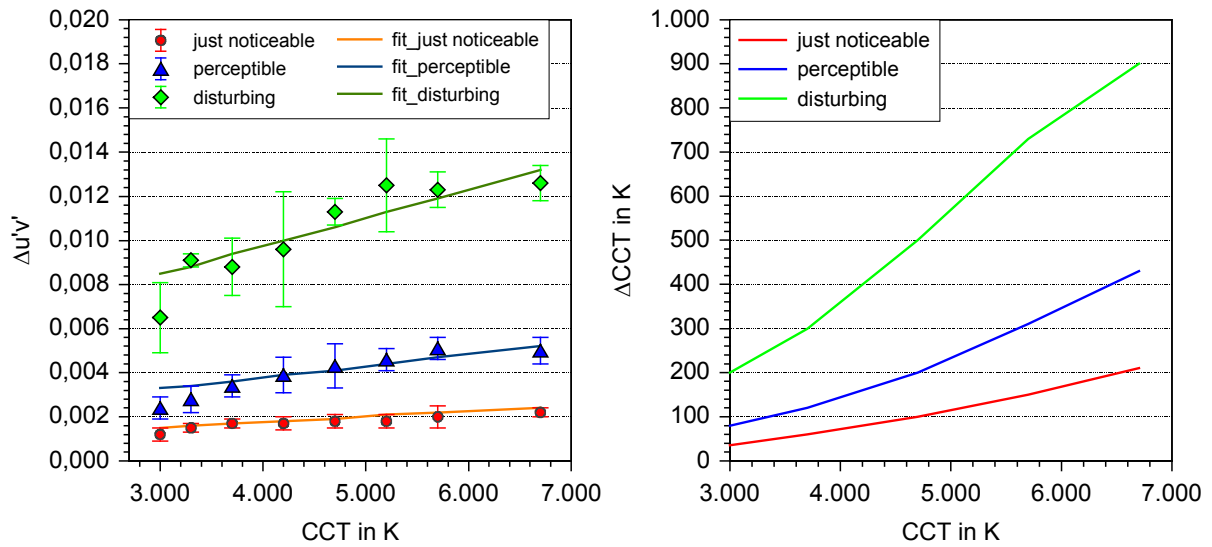


Figure 7: Thresholds and tolerance limits for the perception of colour differences during the variation along the Planckian Locus as a function of the CCT for constant ΔE^*_{ab} values, calculation by the fit-functions and experimental data (left)

The calculation is possible with the help of the following equations:

For UCS-Differences:

$$\text{Just noticeable:} \quad \Delta u'v' = 0,0008 + CCT \cdot 2,44 \cdot 10^{-7} \quad (4)$$

$$\text{Distinctively perceptible:} \quad \Delta u'v' = 0,0017 + CCT \cdot 5,20 \cdot 10^{-7} \quad (5)$$

$$\text{Disturbing:} \quad \Delta u'v' = 0,0046 + CCT \cdot 1,28 \cdot 10^{-6} \quad (6)$$

For colour temperature deviations:

$$\text{Just noticeable:} \quad \Delta CCT = CCT \cdot 0,047 - 113 \quad (7)$$

$$\text{Distinctively perceptible:} \quad \Delta CCT = CCT \cdot 0,0953 - 226 \quad (8)$$

$$\text{Disturbing:} \quad \Delta CCT = CCT \cdot 0,1952 - 403 \quad (9)$$

Table 2: Permitted CCT deviations for several CCTs

CCT in K	<i>just noticeable</i>	<i>distinctively perceptible</i>	<i>disturbing</i>
3000	+/- 28 K	+/- 60 K	+/- 182 K
4000	+/- 75 K	+/- 155 K	+/- 377 K
5000	+/- 122 K	+/- 250 K	+/- 572 K
6500	+/- 192 K	+/- 393 K	+/- 865 K

Based on these functional dependences, Table 2 shows some examples of permitted CCT deviations for some selected colour temperatures. For instance, at a colour temperature of 4000 K up to a colour temperature of 4075 K, a change of the luminous colour in one step is possible without most subjects noticing this change. Up to 4155 K, the subject can see the change but are not disturbed. Changes of larger differences in one step can produce disturbances. Thus it is possible to extract specifications for colour-dynamic lighting systems.

3.2.2 Variation along the iso-temperature lines

Because the illuminance had no influence on thresholds and limits, the investigation along the Iso-temperature lines took part only at an illuminance of 500 lx. We used colour temperatures of 3000 K, 3700 K, 4700 K and 6700 K. 21 subjects (22 to 59 years) took part in this investigation and rated the presented luminous colours changes three times. Colour differences in dependence of the rating criterion and of the colour temperature in the CIEu'v'-system and the CIELAB system are shown in Figure 8.

We used the same procedure for the analysis of the experimental data from the investigation along the iso-temperature lines as well as the investigation along the Planckian Locus. The mean values used for the calculation are summarized in Table 3.

If there is no dependence of the CIELAB values on colour temperature then it is possible to calculate single UCS-Differences. There is a good correlation between the calculated values and the experimental data (Figure 9).

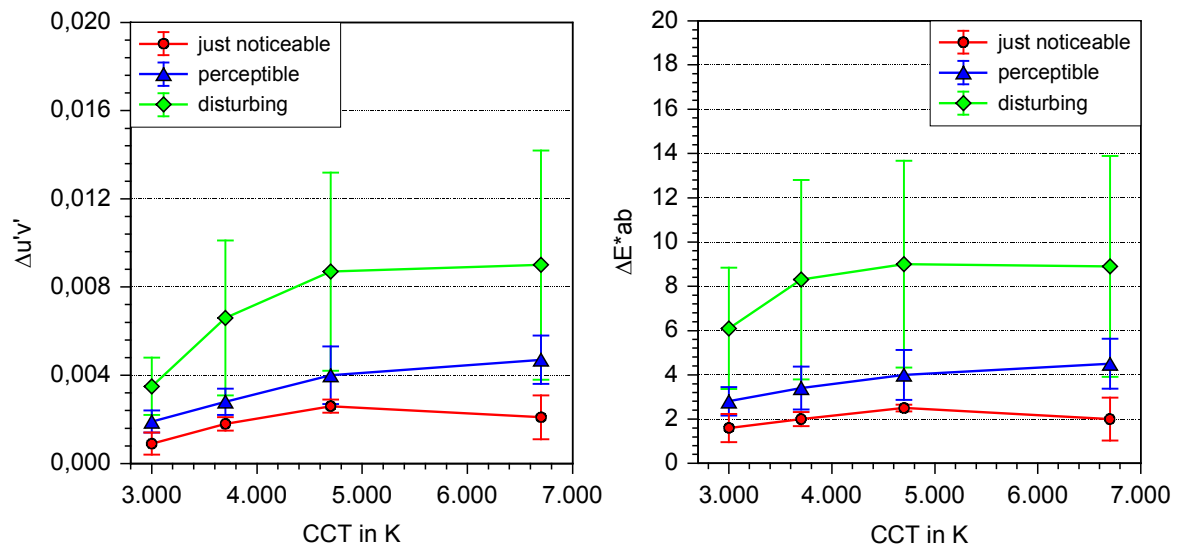


Figure 8: Thresholds and tolerance limits for the perception of colour differences during the variation along the iso-temperature lines for the criteria “just noticeable”, “distinctively perceptible” and “disturbing” – in dependence of the Correlated Colour Temperature (CCT)

Table 3: Mean values of CIE-Lab-Colour Difference for the variation along the Iso-temperature lines in steps

Criteria	<i>just noticeable</i>	<i>distinctively perceptible</i>	<i>disturbing</i>
ΔE^*ab	1,8	3,5	7,8

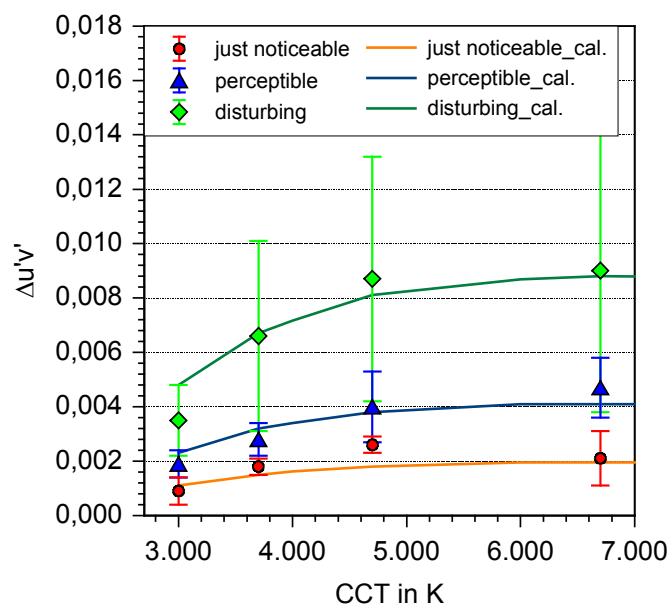


Figure 9: Comparison between the calculation and the experimental data variation along the Iso-temperature lines

Based on this dataset, it is possible to conclude that a variation of the luminous colour is possible in a range around the Planckian locus.

3.2.3 Luminous colour tolerances between luminaries

In further experiments, the limits of luminous colour differences between luminaries have been investigated. Different components in the luminaries, different properties over time and influences of the surrounding temperature can cause differences in the colour appearance of the luminaires. 25 subjects rated the colour appearance of two luminaries situated side by side (Figure 2 left). Starting from a colour temperature of 4000 K, the luminous colour of one luminaire varied in the direction of red, green or blue with increasing colour differences (Figure 10). The rating scale was the same as in the other investigations and the luminance of the luminaires has been kept constant at $L = 9300 \text{ cd/m}^2$ during the experiments. The results are summarized in Table 4 for each rating criterion.

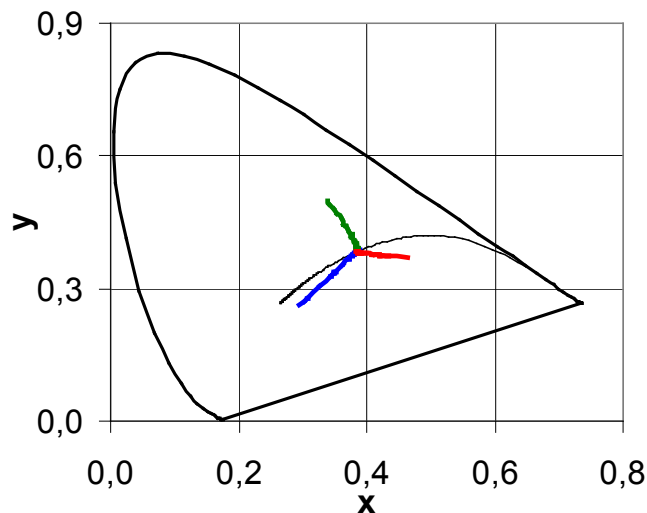


Figure 10: Range of the luminous colours starting at 4000 K

Table 4: Mean values of threshold and tolerance limit differences of luminous colours between luminaires in the CIELAB system

Kriterium	<i>just noticeable</i>	<i>distinctively perceptible</i>	<i>disturbing</i>
ΔE^*_{ab}	1,8	5,7	10,7

3.2.4 Investigation of luminous colour combinations

Within a workplace, similar luminous colours are preferred. The combination of different luminous colours in one workplace can cause coloured shadows. We used the same procedure as in the investigation of luminous colour differences between luminaries but subjects rated the shadows of two luminaries at a so called shadow-

object (Figure 2 right). The illuminance on the desk was 500 lx. The results are shown in Table 5.

Table 5: Mean values of threshold and tolerance limit of coloured shadows in the CIELAB system (distance between the luminaries: 1.6 m, height above the desk: 1.4 m, 25 subjects)

Criteria	<i>just noticeable</i>	<i>distinctively perceptible</i>	<i>disturbing</i>
ΔE^*_{ab}	1,6	2,4	8,5

Coloured shadows are more critical than the colour differences at different locations and at different times.

4 Summary

- The preferred luminous colour can be described as a function of the adapting colour temperature. A dependence on the illumination level could not be shown. So the control of the luminous colour of dynamic illumination systems can be planned independent of control of the illuminance level. Because of the biological effects of light, the illuminance level and luminous colour should be independently adjustable.
- The preferred luminous colours range at least 3000 K to 8000 K. Up to the determined thresholds, the change of luminous colours can be implemented in steps.
- Within one illumination area, similar luminous colours have to be used. In order to stabilize the colour coordinates, a feedback control in the luminaires is beneficial.

Dynamic lighting systems are often a combination of different types of light sources. The colour rendering properties are an additional problem, especially when LEDs are used. There are disagreements between the traditional calculation of the Colour Rendering Index (CRI) and the subjective colour perception for such light sources [Jung07].

Future projects should be directed to the daytime depended control and the speed of changes in luminous colour.

5 Literature

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Authors:

Dipl.-Ing. Karin Bieske/ Dr.-Ing. Cornelia Vandahl

Technische Universität Ilmenau

Tel +49 3677 846921

Fachgebiet Lichttechnik

karin.bieske@tu-ilmenau.de

Postfach 10 05 65

98684 Ilmenau