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Research Article

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Methods for describing illumination colour uniformities

Abstract: Optimizing angular or spatial colour homogeneity has become an important task in many general lighting applications and first requires a valid description of illumination colour homogeneity. We analyse different frequently used methods to describe colour distributions in theory and with measurement data. It is described why information about chromaticity coordinates, correlated colour temperature and global chromaticity coordinate distances are not sufficient for describing colour homogeneity perception of light distributions. We present local chromaticity coordinate distances as expandable and easy implementable method for describing colour homogeneity distributions that is adaptable to the field of view by only one intuitive, physiological meaningful parameter.

Keywords: colour; colour uniformity; illumination and lighting technology; optical engineering; standards.

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1 Introduction

The manufacturing process of LEDs results in varying colours for the individual dies, which are then characterized via binning. However, although the spatial or angular colour homogeneity is as important as the integrated colour, it cannot be characterised in this way. The reasons for inhomogeneities, like the angular dependence of the conversion lengths of phosphor-based light sources are summed up in [1]. Methods to gain better homogeneity of LEDs or better colour mixing homogeneity in optical designs were reported in previous publications [2–6]. The methods used to describe or compare the colour homogeneity in those publications or data sheets vary mainly between correlated colour temperature (CCT) [3], chromaticity coordinates [4], chromaticity coordinates differences [7] and global chromaticity coordinate distances [5, 8, 9] as a function of angle or spatial directions. Today, a newly founded committee of VDI (Association of German Engineers) [10] aims to create a guideline for a more general and physiological meaningful homogeneity description or figure of merit for light sources and luminaires in a way you can use it in lighting applications or in data sheets.

The aim of this article is to analyse and improve different methods, which are currently used for describing spatial or angular colour distributions in the context of colour uniformity perception to ensure a qualitative interface between manufacturers of light sources, optical designers, light designers, architects and physiologists. Our analysis is done with artificial colour distributions as well as measurement data. We used the *u'v'* colour coordinates for the general description of different methods as this colorimetric representation is widely used in science and technology [1, 2, 5–14] and can be calculated without additional information.

2 Analysis of frequently used method

2.1 Correlated colour temperature (CCT)

For example, in [3], the colour homogeneity of a light source is presented as CCT as a function of angle. The CCT bases on the obsolete CIE 1960 uniform chromaticity scale diagram commonly referred to as *uv* and is defined

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as a point on defined straight lines (Judd) perpendicular to the Planckian locus. While the CCT is a well-known parameter, there are three disadvantages if it is used as a homogeneity criterion. First, absolute colour temperature changes are nonlinear in terms of perceived uniformity. Second, there is an implicit uncertainty as different chromaticity coordinates might correspond to the same CCT. This uncertainty is within disturbing chromaticity coordinate distances of light sources, which are below $\Delta u'v'=0.02$ according to [1, 11, 12]. The last, but not the least, the boundary condition for a maximum admissible distance from the Planckian locus ($\Delta uv=0.05$ [15]) cannot be used generally. Altogether, the compact chromaticity description CCT is not suitable as a homogeneity criterion and may actually lead to misinterpretation of colour homogeneity.

2.2 Chromaticity coordinates and chromaticity coordinate differences

In many commercial ray tracers, as well as in [4], colour distributions are presented in chromaticity coordinates as a function of angle or spatial direction. A uniformity perception judgment is not intuitive as the chromaticity coordinates have to be analysed further and provide not much information when presented individually. Representing a function of two spatial or angular dimensions will typically result in a false colour representation or a surface plot. This leads to the problem that small changes of chromaticity coordinates, which may cause noticeable colour non-uniformity, will be hard to notice or may be dominated by peaks in the false colour bar or surface plot. Figure 1 shows an artificial colour distribution, which is projected in the half sphere as a function of the angles $\varphi\in[-180°\ 180°]$ and $\theta\in[0°\ 90°]$. The centre point at $\theta=0°$ corresponds to the main radiance direction of the light source. The artificial distribution consists of alternating small colour changes (hard to notice in the printed version) and one strong inhomogeneity at $\theta=45°$. Figure 2A and B shows the corresponding chromaticity coordinate distributions u' and v' of Figure 1 as a function of the angles φ and θ. They do just reveal the strong inhomogeneity but not the small colour differences. Another disadvantage is that a direct comparison of chromaticity coordinates u' and v' with different luminance levels Y, which is often the case in general lighting applications, will also result in a misinterpretation of perceived colour uniformity [15].

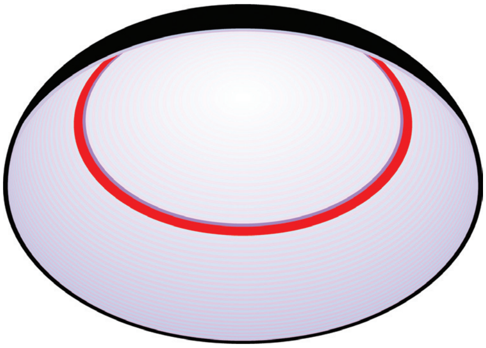

Figure 1 Artificial colour distribution with alternating colours of slightly different hues and increasing saturation over θ and one strong inhomogeneity at $\theta=45°$.

The improved method chromaticity coordinate differences is, for example, used in a data sheet [7], where it describes the angular colour homogeneity of a rotationally symmetric light source. Instead of chromaticity coordinates $u'v'$, the difference of each chromaticity coordinate from a reference coordinate $u'v'_{\mathrm{ref}}$ as a function of the polar angle is used. While the number of colorimetric and geometric dimensions remains and the sensitivity towards outliers still exists, the colour bar may be scaled as necessary to identify small, medium and strong colour differences. If the coordinates of the reference are given, the absolute chromaticity coordinates or at least the direction of the colour shift (if the colour bar is scaled) could be reconstructed.

There are three disadvantages left. First, to get an impression of the colour uniformity, it is still necessary to interpret at least two connected figures. Second, a global reference coordinate implies a comparison of chromaticity coordinates with completely different luminance levels Y. Third, different spatial regions are compared to the same reference. While in some applications like a wall-washer this may be reasonable, in other applications like a flood light, the physiologically observed radiation is just a section of the whole distribution.

The chromaticity difference distributions of the artificial colour distribution are shown in Figure 2C and D. The distributions show the strong inhomogeneity and its reddish colour shift as well as the small increasing colour differences over θ, which lie within the range of noticeable colour differences. Despite the disadvantages, a judgment based on chromaticity coordinate differences is better suited to compactly and intuitively describe spatial colour homogeneity, than the previous mentioned methods correlated colour temperature and chromaticity coordinates.

2.3 Global chromaticity coordinate distances

By converting the two separate chromaticity coordinate differences $\Delta u'$ and $\Delta v'$ into a Euclidian distance, the

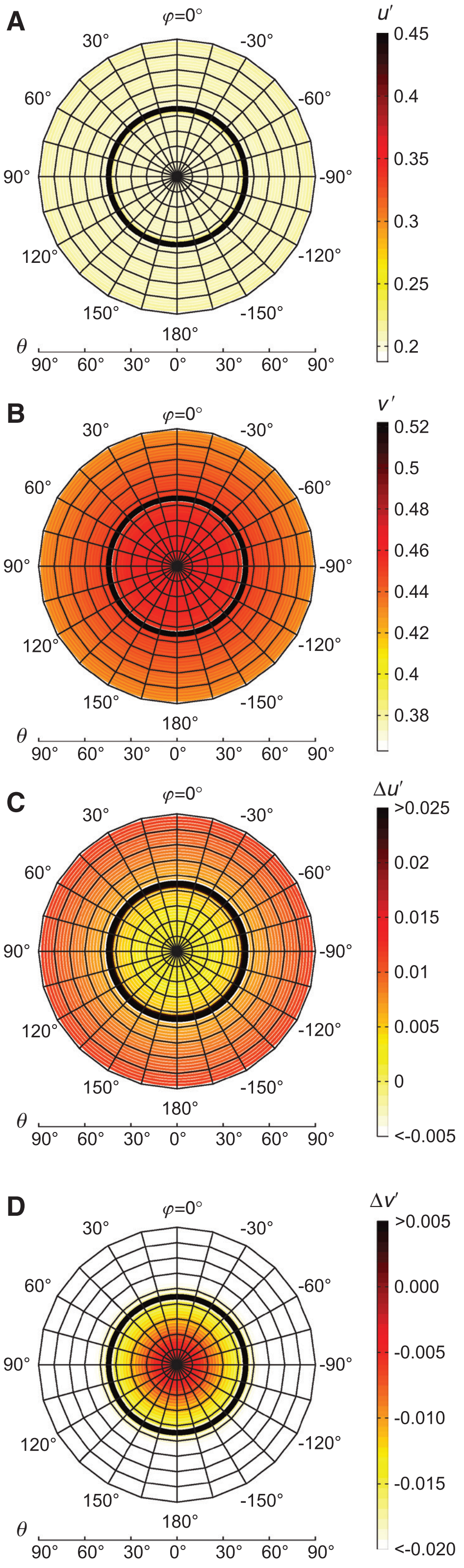

Figure 2 Exemplary analysis of chromaticity coordinates and chromaticity coordinate differences: (A) and (B) chromaticity coordinates u' and v' of Figure 1; (C) and (D) chromaticity coordinate differences $\Delta u'$ and $\Delta v'$ of Figure 1 with the global reference coordinates $u'_{\text{ref}}=0.19784$ and $v'_{\text{ref}}=0.46832$.

homogeneity information is reduced to only one parameter called chromaticity coordinate distance $\Delta u'v'$, which is an established term in physiology and colour science. Based on a chosen reference coordinate, the chromaticity coordinate distance was recently used as spatial homogeneity criterion in [5, 8] as a function of spatial directions and in [9, 13] as a function of angle. Reducing the homogeneity to only one dimension is more intuitive. However, there occur huge disadvantages from using those global chromaticity coordinate distances.

The first one is the definition of a reference chromaticity. Figure 3 shows two chromaticity coordinate distance distributions of the same artificial colour distribution with the mean chromaticity coordinate as a reference point according to [5] and the main radiance direction chromaticity coordinate as reference point according to [8, 9]. In practical application, those colour distributions occur in phosphor-converted white LEDs. While the mean chromaticity coordinate $u'v'_{\text{mean}}$ as reference leads to a more homogeneous evaluation of the initial colour distribution, the main radiation direction $u'v'_{00}$ rates the distribution more inhomogeneous. This huge difference is caused just by the definition of the reference point, which has no physiological meaning.

An even larger fundamental problem is visualized in Figure 4. While within a chromaticity coordinate difference distribution the choice of the reference point is less critical, the influence on the chromaticity coordinate distance distribution is strong. Owing to the principle of chromaticity coordinate distances, the direction of the changing chromaticity coordinates does not matter anymore but just the distance from the reference as illustrated by the circle in Figure 5. That is why the two artificial colour distributions in Figure 4 result in almost the same classification, although in terms of homogeneity, they are completely different. The strong inhomogeneity and the small changes of the left distribution cannot be highlighted because the distance from the global reference is the same. In practical application, this problem can occur due to chromatic aberrations, for example, in a head light. The disadvantage of comparing different spatial regions with the same reference in terms of the field of view and different luminance levels remains as described in the subsection for chromaticity coordinates.

3 Local chromaticity coordinate distance

As an intuitive and physiologically meaningful assumption, the inhomogeneity of a light distribution is

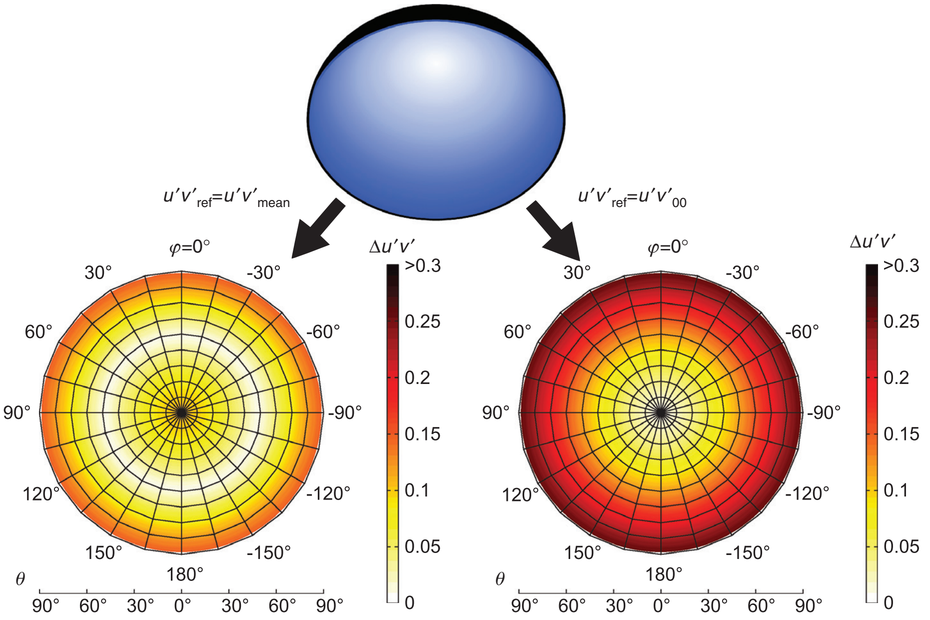

Figure 3 Exemplary analysis of the influence of the reference point in global chromaticity coordinate distances $\Delta u'v'$. The artificial colour distribution with increasing saturation over θ produces two different global chromaticity coordinate distance distributions. The distribution on the left side results from the mean chromaticity coordinate $u'v_{\text{mean}}$ as reference and the distribution on the right side from the main radiance direction chromaticity coordinate $u'v'_{00}$.

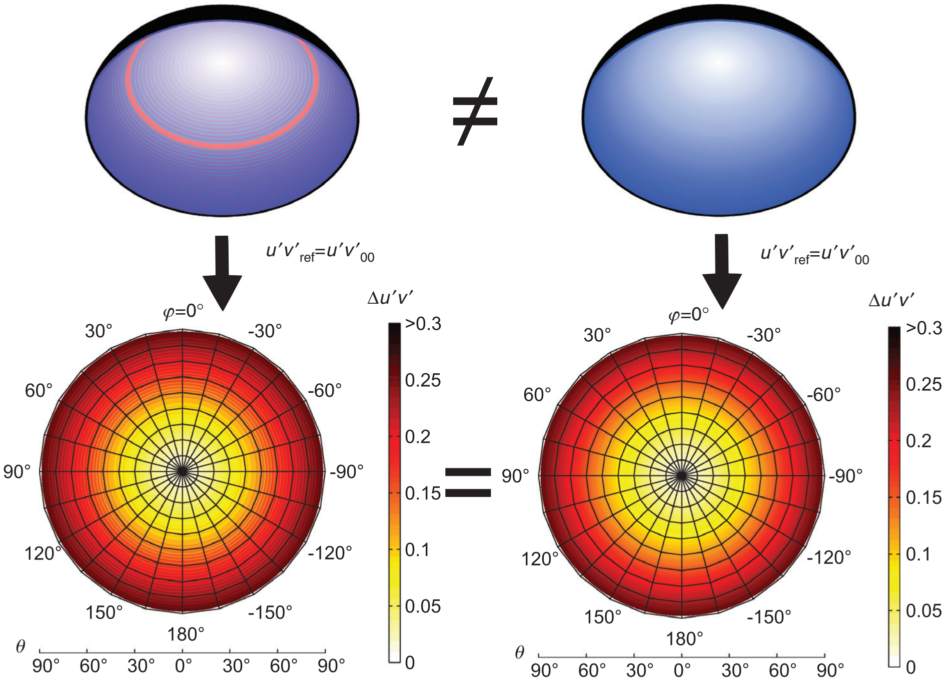

Figure 4 Exemplary analysis of the reference point in global chromaticity coordinate distances $\Delta u'v'$. Two, in terms of homogeneity, completely different artificial colour distributions with increasing saturation over θ produce almost the same global chromaticity coordinate distance distribution.

described by the strongest contrast within the foveally perceived surrounding of this section and does not depend on a global reference. This assumption is the background of the local chromaticity coordinate distance method, which is described in the following section.

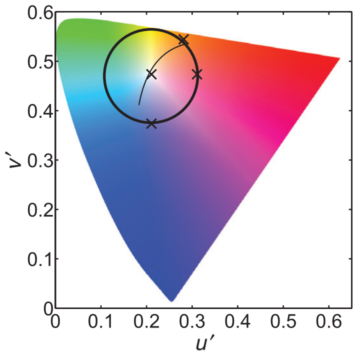

Figure 5 Visualization of the global chromaticity coordinate distance uncertainty. All points on the circle have the same distance from the reference point, although they present completely different colours.

Figure 6 shows an angular (or spatial if referred to an area) interval, which corresponds to the observer's field of view of the application. The highlighted area contains n chromaticity coordinates $u'v'_n$. The chromaticity coordinate distance $\Delta u'v'_{nm}=[(u'_n\text{-}u'_m)^2+(v'_n\text{-}v'_m)^2]^{\frac{1}{2}}$ describes the distance between the chromaticity coordinates $u'v'_n$ and $u'v'_m$. An interval matrix $u'v'_{\text{view}}(\theta, \varphi)$ according to Eq. (1) describes the amount of chromaticity coordinate distances between all coordinates within this interval.

$$u'v'_{\text{view}}(\theta,\varphi)=\begin{vmatrix} 0 & \Delta u'v'_{1,2} & \dots & \Delta u'v'_{1,n} \\ \Delta u'v'_{2,1} & 0 & \dots & \Delta u'v'_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta u'v'_{n,1} & \Delta u'v'_{n,2} & \dots & 0 \end{vmatrix} \qquad (1)$$

Within the matrix, a representative figure of merit for the perceived colour homogeneity of this section has to be chosen. On the assumption that the inhomogeneity detected by the human eye is described by the strongest contrast in the field of view, the largest chromaticity coordinate distance of $u'v'_{\text{view}}(\theta, \varphi)$ has to be chosen. If the set $M(\theta, \varphi)$ is defined as the set, which contains the m=0.5 (n^2-n) different chromaticity distances of the matrix $u'v'_{\text{view}}(\theta, \varphi)$ or rather all chromaticity distances in the interval surrounding the centre coordinate (θ, φ), the value $u'v'_{\max}(\theta, \varphi)$ is defined by Eq. (2).

$$u'v'_{\max}(\theta,\varphi)=\max[M(\theta,\varphi)] \qquad (2)$$

The colour homogeneity distribution as a function of angle or spatial direction is then described by each section's largest chromaticity coordinate distance according to Eq. (3). Notice that the largest chromaticity coordinate distance is unique for a given interval size, as it does not depend on a reference. Also note that the error, which occurs from a mathematical comparison of the chromaticity coordinates $u'v'$ without accounting their different luminance levels Y [15] in the local area, is always equal or less than in the global comparison as the luminance difference will always be equal or smaller than in the global comparison. However, if strong luminance gradients exist inside the local interval, there will still be an error. An interval size enlargement results, independently of the resolution of the data points, in constant or increasing largest chromaticity coordinate distances.

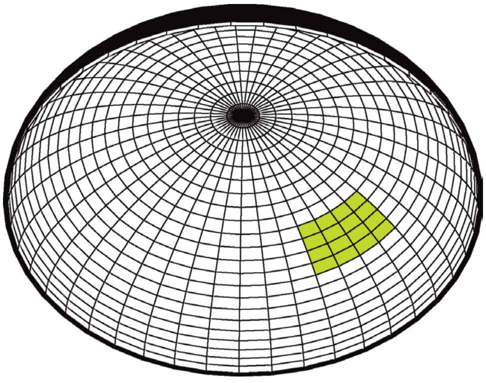

Figure 6 Principle of local chromaticity coordinate distances. The largest chromaticity coordinate distance within the highlighted interval $\Delta u'v'_{\text{view}}(\theta, \varphi)$, which represents the field of view, is assigned to the angular direction (θ, φ). The highlighted area scans the whole distribution.

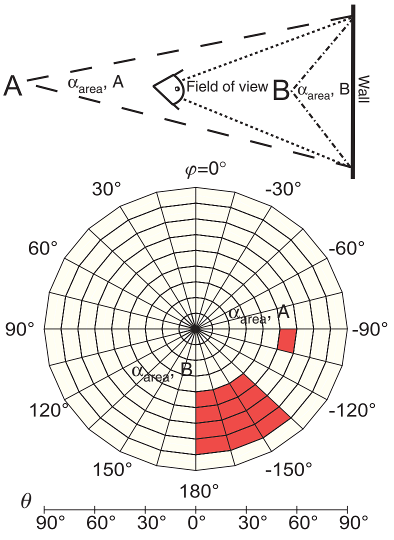

Figure 7 Correlation between interval size and field of view. While the observer's field of view accounts just a small fraction of object A's radiance angle, object B's radiance angle, which has to be considered in the observer's field of view, is much larger. The interval size can be chosen according to the application.

$$\Delta u'v'_{\text{LD}} = \begin{vmatrix} u'v'_{\max}(\theta_1,\varphi_1) & \dots & u'v'_{\max}(\theta_1,\varphi_n) \\ \vdots & \ddots & \vdots \\ u'v'_{\max}(\theta_m,\varphi_1) & \dots & u'v'_{\max}(\theta_m,\varphi_n) \end{vmatrix} \tag{3}$$

Furthermore, the intervals have to overlap. If not, it is possible to think of a colour distribution, which consists of differently coloured homogenous intervals (for example, a chess board). In the worst case, such a distribution results in a completely uniform $\Delta u'v'_{\text{LD}}$ if the chosen resolution results in intervals, in which each contains just one square. As there is no physiological reason to account some chromaticities more often to a field of view than others, the overlap has to be at least 50% in each spatial or angular dimension. Under this condition, each chromaticity coordinate is attributed to the same amount of intervals (with exception to those at the edge and corners).

The size of the interval is the only free parameter and strongly depends on the application to be analysed

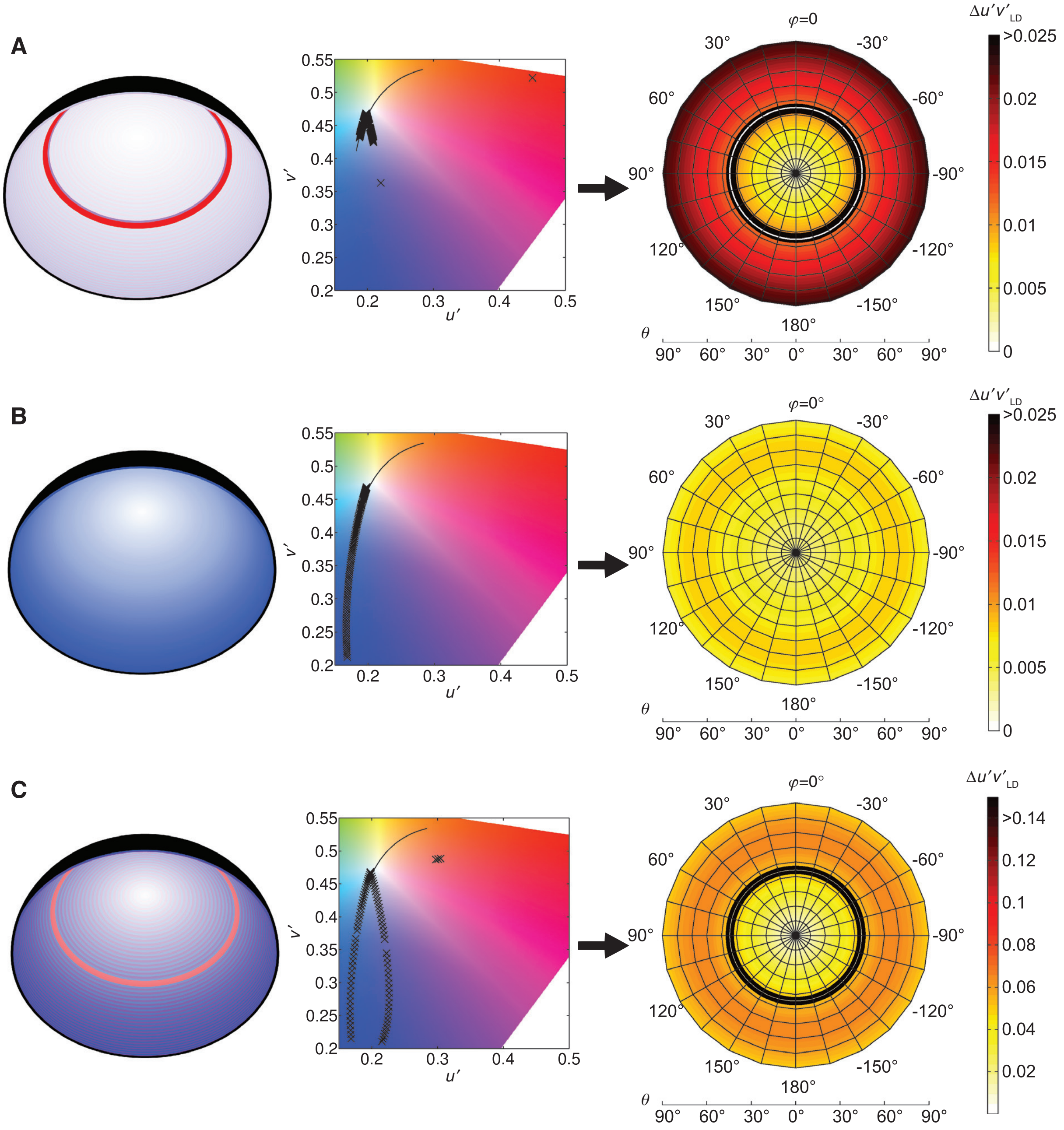

Figure 8 Artificial colour distributions, their chromaticity coordinates and application of the local chromaticity coordinate distance method (A) local chromaticity coordinate distance distribution of Figure 1 with $\theta_{\text{area}}=2°$ and $\varphi_{\text{area}}=10°$;(B) and (C) local chromaticity coordinate distance distribution of Figure 4 with $\theta_{\text{area}}=2°$ and $\varphi_{\text{area}}=10°$.

as an overlap larger than 50% in each geometric dimension results just in a higher resolution of $\Delta u'v'_{\mathrm{LD}}$. Figure 7 shows how the parameter interval size presented as α_{area} is influenced by the application. While object A, which may, for example, be a flood light has a larger distance from the illuminated area compared to the observer, object B has a much smaller distance, which may be reasonable for a wallwasher. These geometric viewing conditions result in different radiation angles, which have to be considered within the observer's field of view. Figure 8 shows the $u'v'_{\mathrm{LD}}$ of the synthetic colour distributions in Figures 1 and 4. All colour distributions and each inhomogeneity are characterized correctly according to their strength.

4 Experiment

In this section, we present the application of the local chromaticity coordinate distance method on two different LED lamps (Figure 9). The data was acquired by a spectral resolved measurement on a near-field photo goniometer with a test distance of 30 cm.

The first light source consists of 48 circular arranged phosphor-converted white LEDs (Figure 9A). Figure 10 shows its measured correlated colour temperature, chromaticity coordinates, chromaticity coordinate differences and global chromaticity coordinate distances with different references as function of the polar angles. All methods lead to an evaluation as non-uniform (if colour perception thresholds in the range $\Delta u'v' \in [0.001\ 0.02]$ according to [1, 11, 12] are used). The light distribution has a very extended and smooth colour shift due to higher phosphor conversion lengths with increasing θ angle, which results in a changing additive colour mixture for the blue chromaticity coordinate of the LEDs and the yellow chromaticity coordinate of the phosphor as seen in Figure 10A). However, the perception in applications depends on the relative location between the light source and the white wall as seen in Figure 7. If the distance between source and wall is large, respectively, the distance between wall and observer is small, the distribution is uniform with the exception of $\theta > 80°$. However, the colour shift is quite perceptible if the distance between source and wall decreases or the distance between observer and wall increases. The effect is not surprising due to the changing field of view with respect to the change of accounted solid angles of the light source.

All state-of-the-art methods cannot take into account this simple physiological effect. But it can be visualized within a local chromaticity coordinate distance evaluation as shown in Figure 11A). Two $\Delta u'v'_{\mathrm{LD}}$ distributions with different interval sizes are illustrated in Figure 11A). While a smaller interval than $\theta_{\mathrm{area}}=3°$ results in a very uniform classification, a larger interval than $\theta_{\mathrm{area}}=10°$ distinguishes the inhomogeneities, which may occur in applications with a short distance between this light source and the illuminated area. The comparison of the two interval sizes, as well as the comparison with Figure 10F, confirm that the colour distribution of lamp one consists of a global gradient, which will result in enlarged colour discrimination thresholds [14].

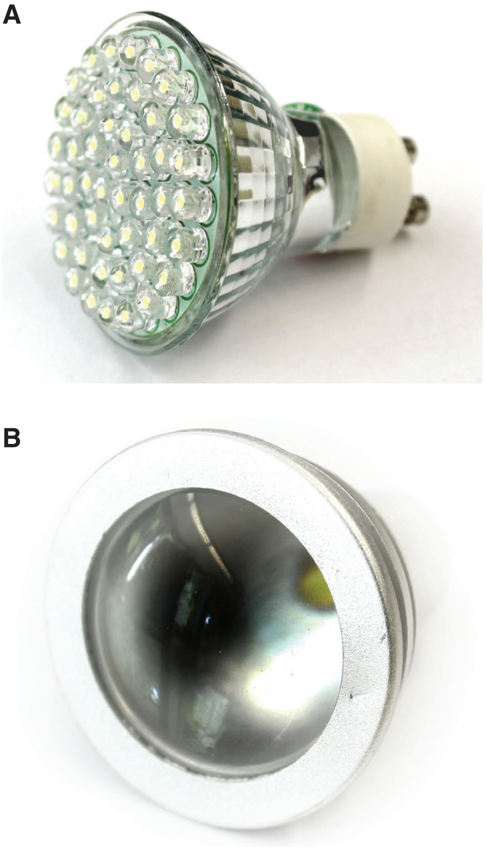

Figure 9 Measurement lamps: (A) lamp one, (B) lamp two.

The second lamp is a single phosphor-converted white LED enclosed by a reflector and a lens (Figure 9B). The distribution consists of a bright uniform spot and a strong inhomogeneity at $\theta=30°$ caused by chromatic aberration and a darker homogeneous surrounding area. The resulting chromaticity coordinates are shown in Figure 11A. Figure 12 provides the uniformity analysis of the second lamp based on correlated colour temperature, chromaticity coordinates, chromaticity coordinate differences and global chromaticity coordinate distances with different references as function of the polar angles. All methods detect the inhomogeneity at $\theta=30°$. The correlated colour temperature shows differences of around

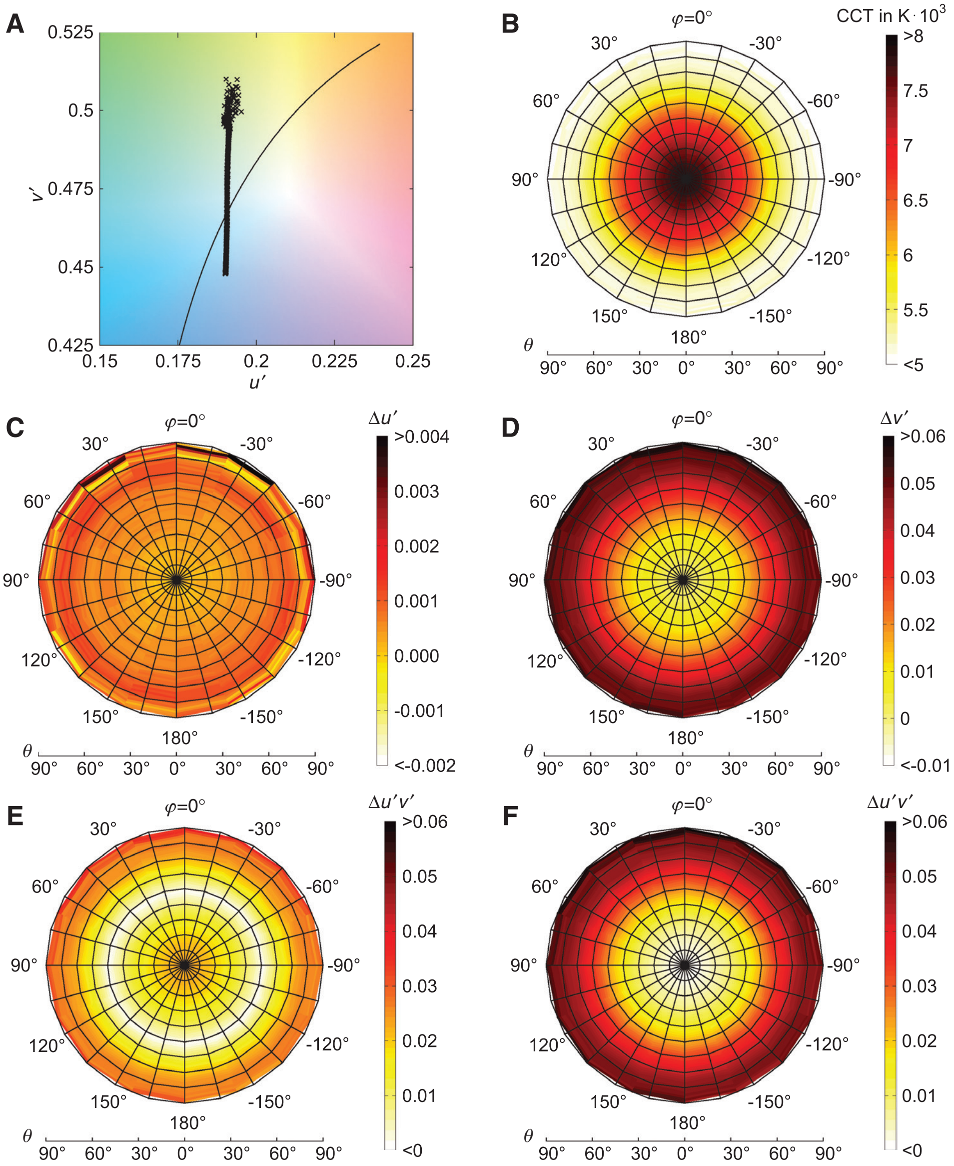

Figure 10 Analysis of light source one: (A) measured chromaticity coordinates in $u'v'$; (B) correlated colour temperature; (C) and (D) chromaticity coordinate differences $\Delta u'$ and $\Delta v'$ of Figure 1 $u'_{\mathrm{ref}}=0.20084$ $v'_{\mathrm{ref}}=0.44813$; (E) global chromaticity coordinate distances with the mean chromaticity coordinate as reference coordinate (F) global chromaticity coordinate distances with the main radiance direction as reference coordinate.

1000 K in the homogenous areas, which are interpreted as non-uniform. A judgement based on global chromaticity distances results in slight non-uniformities as the chromaticity distances are within the range $\Delta u'v' \in [0.001\ 0.02]$.

Although the inhomogeneity is more disturbing than those of lamp one, the absolute distance of the chromaticity coordinates is smaller, which can be verified by comparing the coordinates in Figure 11. If the angle of radiation within the observer's field of view of lamp two is smaller than $\theta_{\mathrm{area}}=3°$, just the chromatic aberration is noticed. The distribution based on a larger $\theta_{\mathrm{area}}=10°$ shows that there are no strong colour gradients, and therefore, the homogenous area remains homogenous with the exception of the certainly noticed chromatic aberration at $\theta=30°$.

5 Discussion and conclusion

To optimize angular or spatial colour homogeneity, first, a valid description is required. The analysis of artificial distributions as well as measurement data has shown that correlated colour temperature and individually presented global chromaticity coordinate distances are not able to present

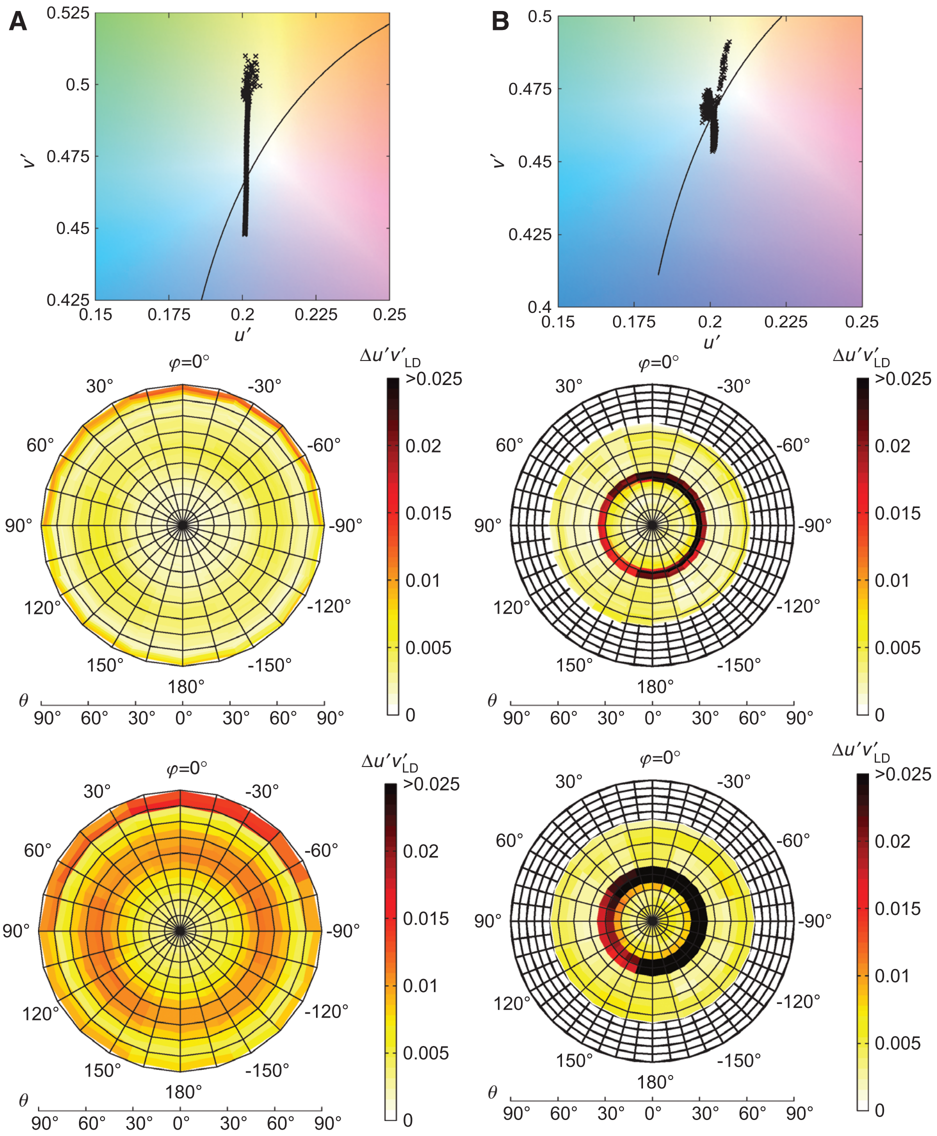

Figure 11 Comparison of local chromaticity coordinate distances of light source one and two with different interval sizes: (A) lamp one: top: chromaticity coordinates, middle: θ_{area}=3° φ_{area}=45°, bottom: θ_{area}=10° φ_{area}=45°; (B) lamp two: top: chromaticity coordinates, middle: θ_{area}=3° φ_{area}=36°, bottom: θ_{area}=10° φ_{area}=36°. (The area with bold grid lines contains no data.)

or validate spatial homogeneity. Their implicit equivocality can strongly mislead. Chromaticity coordinates, on the other hand, are unique; however, they require a high level of abstraction to judge the distributions in terms of physiological homogeneity. Finally, chromaticity coordinate differences are unique as well and more intuitive than the coordinates, but it is still necessary to consider at least two figures at the same time to get an impression of the colour uniformity. Another disadvantage in practical application is the comparison of different spatial regions with the same reference, which does not account different luminance levels, as well as the missing opportunity to include the observer's viewing conditions. This results in the fact that an individual representation of chromaticity coordinates and chromaticity coordinate differences are not sufficient in terms of colour perception in practical applications.

A better interface between physiological studies regarding colour perception, the application of luminaires and the optical design process is achieved by the method of local chromaticity coordinate distances. This concept describes angular or spatial uniformity as a distribution containing the largest chromaticity coordinate distance within overlapping local intervals, which may refer to the luminaire or to the illuminated surface.

The method local chromaticity coordinate distances describes the angular or spatial colour uniformity in a

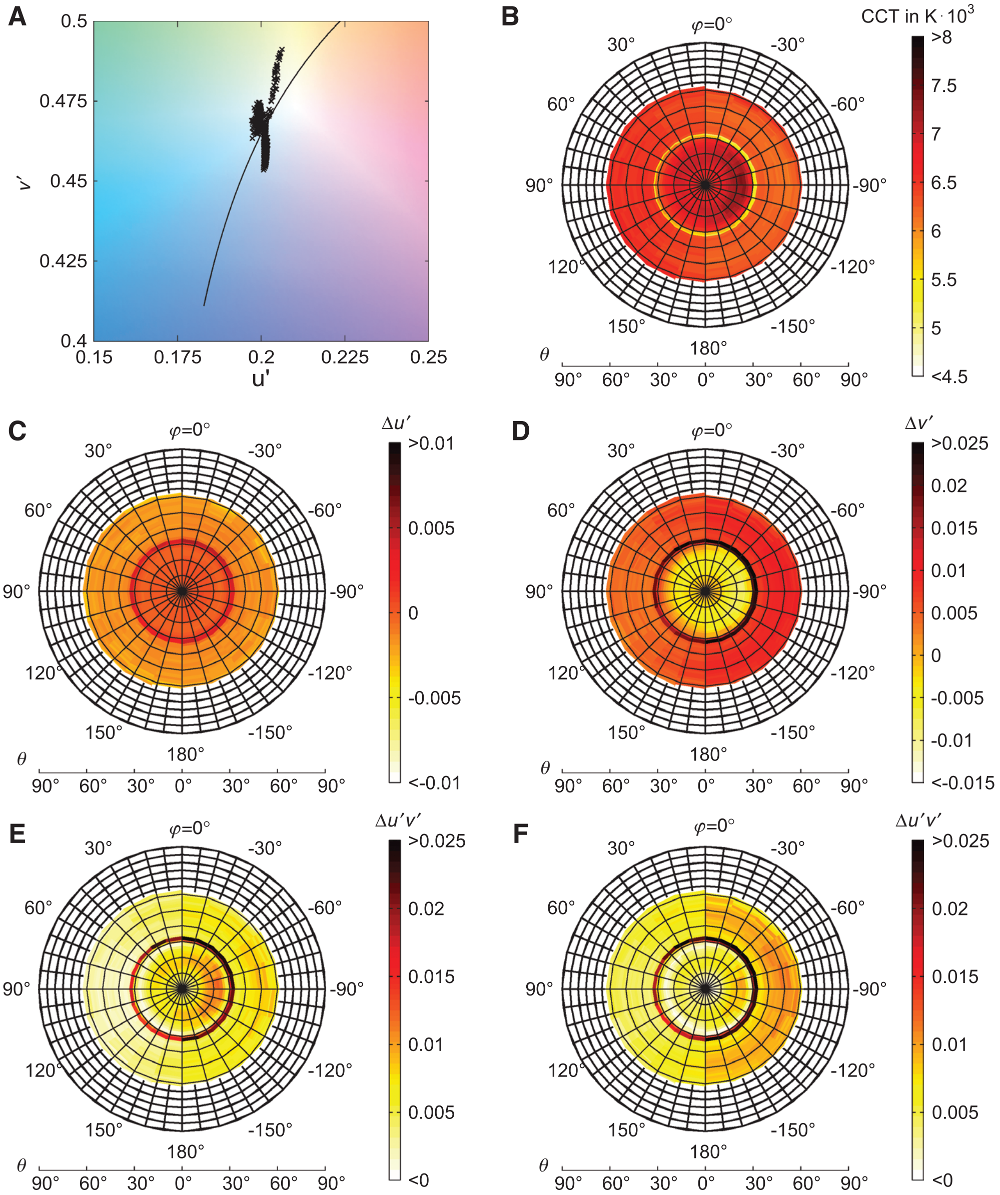

Figure 12 Analysis of light source two: (A) measured chromaticity coordinates in $u'v'$; (B) correlated colour temperature; (C) and (D) chromaticity coordinate differences $\Delta u'$ and $\Delta v'$ of Figure 1 $u'_{\mathrm{ref}}=0.20127$ $v'_{\mathrm{ref}}=0.46335$; (E) global chromaticity coordinate distances with the mean chromaticity coordinate as reference coordinate; (F) global chromaticity coordinate distances with the main radiance direction as reference coordinate.

unique, intuitive and compact way and is, therefore, suited to compare different optical designs within an optimization process or to support lighting designers for planning lighting systems. The adaptability of the interval size and the interval definition is an intuitive opportunity to take viewing conditions into account. Possible interval definitions are constant polar angles (as used in this analysis), constant solid angles, constant conical solid angles or intervals referred to a surface. The colour uniformity is judged in the context of the typical or ultimate application of the luminaire. Assessing optical and lighting designs in connection to its application is recommended, as the viewing conditions have a strong influence towards the homogeneity noticed. The first lamp showed the influence by varying distances from the light source, the illuminated surface and the observer.

As the method, itself, does not need additional measurement information, local chromaticity coordinate distributions for several typical interval sizes can also be included into data sheets of light sources in addition to the currently used uniformity distributions to provide uniqueness regarding global colour gradients. Although the connection between the light distribution of a light source without the optical design and the light distribution of the luminaire is small, the method might help the optical designer to compare different light sources.

For future work, there are some ways to further extend the method of local chromaticity coordinate distances:

1. An extension from largest local chromaticity coordinate distances towards local chromaticity coordinate gradients or local uniformity (for example, as defined in [2]) may result in an improvement of the method without complicating the interpretation. Gradients provide the possibility to take into account the mentioned fact that the same chromaticity coordinate pair appears to have a smaller perception difference if a gradient between the two locally separated points exists.
2. While a local comparison method reduces the problem, which results from the direct comparison of chromaticity coordinates with different luminance levels, the global luminance cannot be included directly. However, in general lighting high global luminance differences will dominate perceived chromaticity distances [14]. To ensure that colour changes in too dark or too bright areas are neither over- nor underestimated, one can use a weighting function depending on absolute and relative as well as local and global luminance. To generate such a function, physiological studies need to be executed.
3. A tailored interval size as a function of relative positions may be obtained based on physiological studies. This will simplify the application of the method in optical and lighting design.
4. Evaluations on the effect of chromatic adaptation in the regime of just noticeable, noticeable and disturbing chromaticity coordinate differences of light sources as well as spatial chromatic adaptation may be carried out to improve the performance of local chromaticity coordinate distances. This extension is motivated by the analysis of [16], which showed that adaptation highly influences the number of discernible object colours. Although the analysis in [16] was done for object colours, this leads to the assumption that chromaticity coordinate distances of light sources have similar dependencies as there will always be a global or local adaptation.

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