AN ASSESSMENT METHOD FOR EVALUATING COLOUR RENDERING PROPERTIES OF LIGHT SOURCES

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Abstract

We present an assessment method to evaluate how the spectral power distribution of light influences the perception of colours and small colour differences. Included in the method are several ways to measure properties of reflected light with a spectroradiometer, visual assessments of perceived colours, and a visual performance test that aims at identifying an individual minimum colour contrast visibility threshold.

In a first application of the assessment method, we used a colour contrast test chart printed on paper and studied it under the illumination of three LED light sources, halogen light and daylight. We concluded that the visual performance test was effective for reviling visibility thresholds for colour contrasts and that the method has potential for understanding the influence of spectral power distribution on perceived colour and visual performance. The methodology can be useful for optimizing illumination for individual needs.

Keywords: colour contrast, colour rendering, visual performance, assessment methods

1 Introduction

The spectral power distribution (SPD) of lamps through history has been determined by the available technology at any given time. In recent years, with the development of light-emitting diode (LED) based light sources, there are unique possibilities to customize the SPD to better suit the needs in different contexts (Wei et al 2014).

Today, in 2015, the most commonly used principle in white LED technology is to convert the power from a short wavelength LED into longer wavelengths with phosphors, to cover most of the visible light spectrum. At present, focus is to develop LED light sources that produce as high luminous efficiency as possible, to defeat rival technology. However, there are other aspects on light except luminous efficiency that deserve attention, for example colour rendering, spectral homogeneity and naturalness. Colour rendering is important for many daily tasks like judging skin tones, quality of food etc., but also for detecting objects on a background with similar colours.

Different kinds of metrics and assessment methods are used in colour and lighting research to describe how different light sources affect colour appearance (CIE 2004, Smet et al 2011, Hårleman et al 2007). Many studies aim at defining preference, attractiveness and naturalness of colour appearance under illumination of different light sources (Smet et al 2011, Islam et al 2013). Another kind of test is based on judging the visual clarity or feeling of contrast of colours under a specific illumination (Kenijiro 2007). These methods don't take visual performance into account i.e. when observers are forced to perform a task other than assessments. The most common performance tests are colour vision tests and common for these tests are that they are all designed to detect colour vision deficiencies. Our ability to detect and discriminate different colours across the entire visual spectrum is not necessarily covered by these tests.

Few tests on colour rendering are based on visual performance and to define how illumination can support human vision. One example is Mahler et al 2009, who have mapped colour rendering of LED light sources. In their study, a sorting test was applied where the task was to arrange coloured capsules in a colour circle under illumination from different light sources. They describe for example how RGB LED distorted colour appearance so that patches were falsely saturated, i.e. more colourful but less efficient to discriminate between.

Our research aims at better understanding on how illumination can support human vision, for example to optimize illumination for people with impaired vision. We think a visual performance based method evaluating colour appearance on an individual basis is missing. In the presented study, we have evaluated how different SPDs affect the perception of small colour contrasts by using radiometric measurements, visual assessment and performance methods.

The visual performance method is based on observers' identification of coloured symbols against a similar coloured background on a test chart, which we hereafter refer to as a *colour contrast chart*. The symbols differ in orientation so that both a detection threshold and an identification threshold can be determined by the test. The symbol colour is surrounded by the background colour and the two colours will affect each other when seen together. This phenomenon is called simultaneous contrast (Chevreul 1855) and is a feature of human vision that actually facilitates the perception of small colour differences.

We will describe the whole methodology, including characterization of the colour contrast chart and the visual performance test in particular. To exemplify the possibilities with the method and what kind of results that can be expected, we will present results from a pilot study where five light sources with different SPD's are investigated.

2 Design of the colour contrast chart

The colour contrast chart consisted of 12 horizontal ribbons of different background colours and twelve Landolt C symbols on each row. The Landolt C (or Landolt ring) is one of the standardized symbols (optotypes) for testing vision. The symbol consists of a ring with a gap that can be oriented in various positions (usually left, right, bottom and up) and the test person task is to decide the direction of the gap. Both the gap width and the stroke width is 1/5 of the symbol outer diameter.

In our study, we have divided the colour contrast chart in two parts, in order to provide two easy manageable panels, c.f. Figure 1a. These were printed on A2 paper and the diameter of the symbols were 25 mm to suit for a viewing distance of 2,0 meters. Converted into visual acuity the symbol size i.e. the width of the gap, corresponds approximately to a decimal value of 0,1 (logMAR=1,0). This is well below the acuity limits of normal subjects and thus the colour contrast sensitivity was the dominant factor and not the visual acuity. When detecting the orientation of a Landolt C, the relevant visual angle compared to a grating is found to be two-times the angle of the gap (Danilova 2013, McAnany 2006).

The symbols were randomly orientated and printed in colours with varying colour contrast to the background. The background colours were approximately the eight first colours in the series of test colour samples: TCS01–TCS08 (CIE 1995) for determination of the colour rendering Index (CRI), c.f. Table 1. We also added four background colours that we found decisive for the test.

Table 1 – List of the background colours used on the colour contrast chart.

	ID	Appearance in daylight	NCS-code	CMY-value	Row
	TCS01	Light greyish red	3124-Y87R	21, 48, 38	B
	TCS02	Dark greyish yellow	3728-G96Y	33, 35, 74	C
	TCS03	Strong yellow green	2268-G46Y	46, 17,100	D
	TCS04	Moderate yellowish green	2642-G08Y	64, 7, 67	E
	TCS05	Light bluish green	3129-B39G	60, 11, 33	G
	TCS06	Light blue	2044-R84B	56, 22, 1	H
	TCS07	Light violet	2043-R57B	39, 43, 0	I
	TCS08	Light reddish purple	2042-R39B	24, 52, 0	J
	TCS09	Strong red	1480-Y98R	23,100, 98	K
	TCS13	Light yellowish pink	1220-Y53R	1, 25, 31	A
		Moderate bluish green	2545-B70G	73, 4, 48	F
		Moderate orange	2050-Y50R	1, 57, 75	L

The colours of the symbols were varied schematically based on the Natural Colour System (NCS) coding (HÅRD et al 1996), in order to step-wise differ from hue. The hue of every second symbol was tuned clockwise along the NCS colour circle and the symbol in between was tuned counter-clockwise c.f. Figure 1b. This caused an increased perceived colour contrast because of the simultaneous contrast effect. This is illustrated in Figure 1b by the outer grey arrow covering a much larger distance than the inner grey arrow.

A special case of simultaneous contrast occurred for the bigger hue differences on the colour contrast chart. It is called vibrating edges and occurs when colours of equal lightness, but of distinct difference in hue, meet in the same plane (Albers 1979).

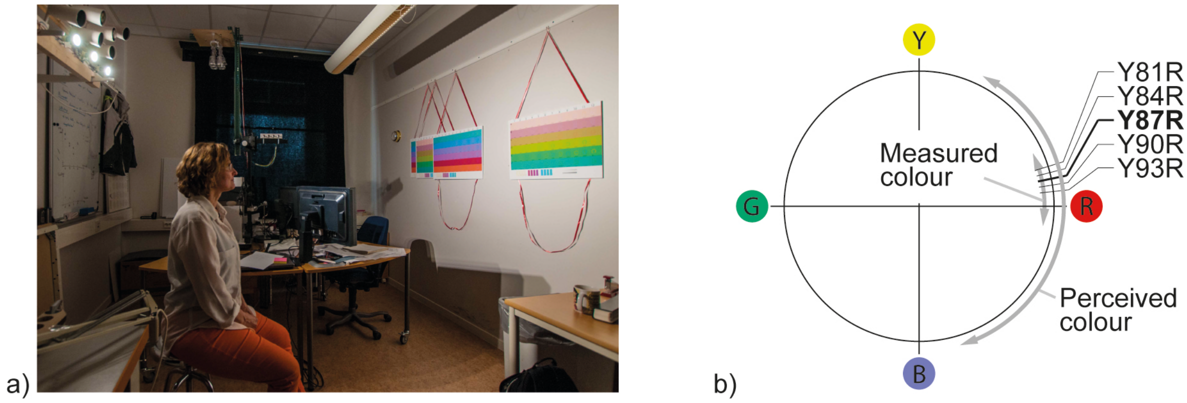

Figure 1 – a) View inside the test room. b) NCS Colour Circle with the first five hue values for row B marked in the colour contrast chart. The difference between measured and perceived colour is also illustrated.

All symbols where carefully designed to appear equal in lightness against the background by compensating an increase of colourfulness (chromaticness) with a decrease of blackness and vice versa. However, at this stage we did not succeed in achieving equal lightness for all symbol and background combinations on the printed charts, despite that all colours were perceived equal in lightness on the computer screen. We also encountered problems in printing some of the signal colours red and yellow due to limited capacity of our plotter. To get enough room for colour adjustments, we therefore had to choose a slightly less colourful background colour than TCS09 describes (row K), at this ribbon.

An example of the first two ribbons on the colour contrast chart is shown in Figure 2. The colours of the chart are not exactly equal to our plotted colour contrast chart because of printing uncertainty in this proceeding.

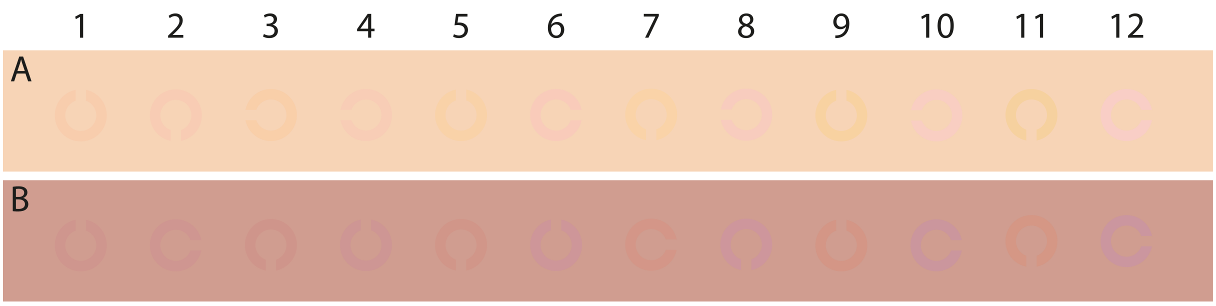

Figure 2 – Detail of colour contrast chart. The colours will differ from the chart that was used in the experiments due to printing uncertainty, here contrasts are exaggerated.

3 Evaluation of the assessment method using colour contrast chart

The assessment method was evaluated by characterization of the colour contrast chart under illumination of three different LED light sources and two reference light sources (halogen and daylight). First, the light sources were characterized. Second, the reflected light from the chart under illumination of the five light sources was measured. Third, the colour appearance of colours of the chart was visually assessed. Fourth, we conducted a visual performance pilot study with seven observers. Finally, we let one experienced observer examine selected symbols from the chart to find the required distance for identification of the symbols in the different light sources.

3.1 Characterization of light sources

We used four artificial light sources and daylight for evaluating the assessment method. The light sources were all spot lights with 36° beam angle, but with different correlated colour temperature (CCT) and colour rendering (Ra) properties. Parameters for all light sources are shown in Table 2. The *Halogen* lamp was used as reference. *Anslut* and *Soraa* were both warm white but had differed pump wavelength (NAKAMURA 2013) and were supposed to resemble halogen lamp. *Osram* lamp was cold white and expected to more resemble daylight.

Table 2 – List of the light sources used in the study.

Light Source	Electrical Power [W]	Voltage [V]	Colour Rendering Ra	Luminance [lm]	CCT [K]	Properties
Haloge	35	12	100	315	2800	Filament lamp, halogen
Anslut	6	12	> 80	310	2700	Pump wavelength: 440 nm
Soraa	11,5	12	> 90	445	3000	Pump wavelength: 400 nm
Osram	5,5	230	> 80	350	4000	Pump wavelength: 440 nm
Dayligh					6500	Cloudy sky

The SPDs of all light sources are shown in Figure 3. The SPDs were measured with a spectroradiometer (SpecraScan 650, Photo Research, Inc.) and the reflected light from a white paper was registered. Figure 3a shows the SPDs, normalized to have the same luminance so that the power value at each wavelength could be compared. Figure 3b shows the same SPDs weighted to the V(λ) function (CIE 1932).

Note that the higher CCT of Osram is designed by converting less power from the pump diode to longer wavelengths. There is a strong peak at 450nm that makes the SPD "unbalanced". In the V(λ) weighted graph, the 450nm peak is not visible, but we expected it to influence the reflected light from the chart.

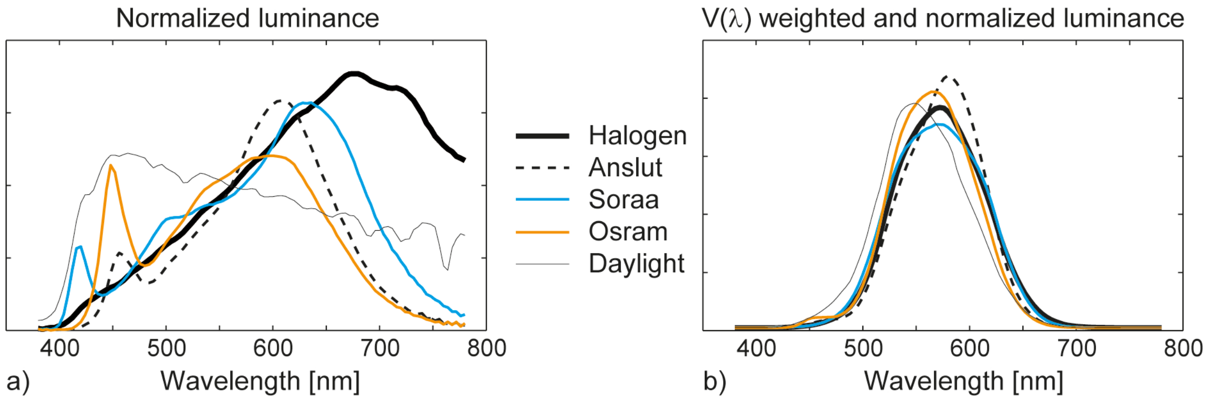

Figure 3 – SPD of the light sources used in the tests. a) SPD normalized to equal luminance. b) The SPD in a) weighted with V(λ) function.

3.2 Measurements of reflected light from colour contrast chart

The SPDs of the reflected light from both background and symbols of the colour contrast chart illuminated by all light sources were measured. Figure 4 shows the set of SPDs from symbol A2 and B10. Each graph shows symbol and background SPD overlaid.

By comparing the SPDs for A2 and B10 it is obvious that the SPD of symbol A2 and background colours virtually overlap, indicating that the colour difference is not distinguishable for the instrument. However, a human eye could detect a difference large enough to identify the symbol orientations, which will be discussed section 4.

The SPDs of symbol B10 and background differ much more, indicating that the colour difference is larger. Despite this fact, the symbols were still difficult to identify for the observers, which is also discussed in section 4.

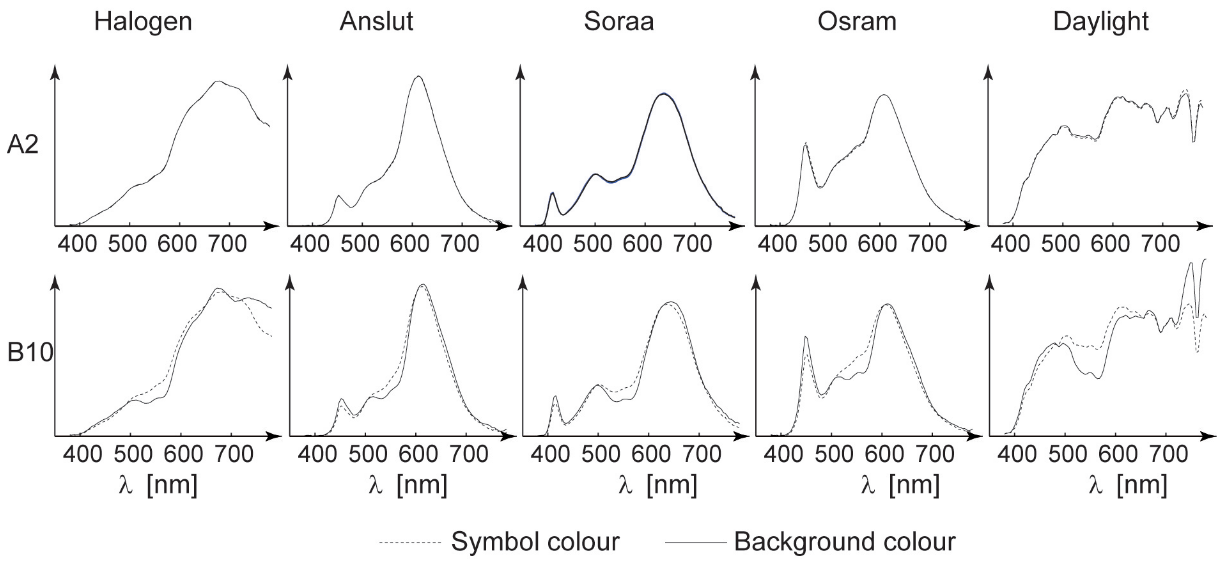

Figure 4 – SPDs of the reflected light from symbols A2 and B10 and their backgrounds, under different illumination.

The CIE-XYZ, CIE-xy coordinates and luminance were calculated from the SPDs. An example of CIE-xy coordinates for background and symbols 2, 4, ..., 12 at row B at illumination from the four artificial light sources are shown in Figure 5. Note that the coordinate points virtually lay on a straight line, confirming the design with increasing colour difference.

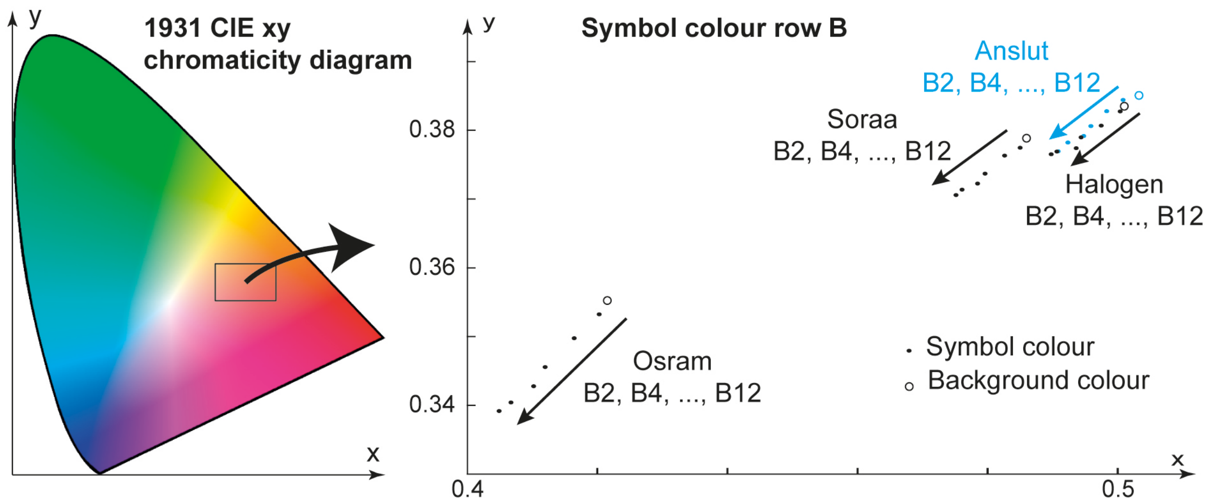

Figure 5 – CIE-xy chromaticity coordinates for symbols B2, B4, B6, B8, B10, B12 and background colour under illumination by four light sources.

Measures for the colour difference between symbol and background colour, were calculated in three ways: vector distance for CIE-XYZ and CIE-xy coordinates and difference in luminance. (ΔXYZ, Δxy and ΔL, respectively). An example of these three measures for row B, is shown in the histogram plot in Figure 6. Note that ΔXYZ and Δxy are increasing smoothly, but that ΔL shows that the colours were not isoluminant.

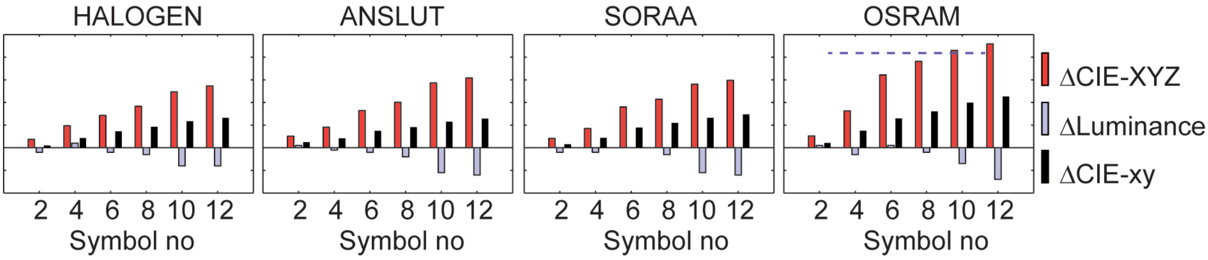

Figure 6 – Histogram of measured colour difference at row B. The dotted line indicates the identification threshold. Symbol 10 was possible to identify for all observers with normal colour vision, in Osram illumination.

3.3 Visual assessment of perceived colour of the colour contrast chart

The radiometric characterization of the colour contrast charts were complemented by a visual characterization. Methods for identifying the perceived colour have been developed in the field of colour research during the last 20 years (Xiao 2010, Fridell Anter 2000). These methods all depend on visual assessment of human observers which make them uncertain, therefore a combination of techniques is preferable (Billger 1999) to increase the accuracy. In our study, one experienced observer used the following assessment techniques:

1) Semantic descriptions of the colours. Symbol and background colours were described using everyday language and the terminology in Natural Colour System (NCS).
2) Magnitude estimation (c.f. Table 3, column 4-6). The hue of the colour was estimated according to its resemblance to the four chromatic elementary colours, and the nuance was estimated according to the degree of whiteness, blackness and chromaticness (Hård et al 1996).
3) Comparison of the colours with reference colour sample. (c.f. Table 3, column 3 and 7). The chart were viewed at approx. 2m distance and compared to a colour reference sample viewed at approx. 30cm distance. (Fridell Anter 2000).

Table 3 – Visual assessments of symbol and background colours. Column 3 and 7: estimation of perceived colour expressed in NCS code (technique 3). Column 4-6: magnitude estimation with column 3 as reference. Bl=Blackness, Chr=Chromaticness, B=Blueness and UC=Unchanged. (+), + and ++ means grades of distance from reference colour hue. Ident. dist. = Distance required for identification of symbols.

Symbol colour	Parameters	Light Source				
		HALOGEN	OSRAM	ANSLUT	SORAA	DAYLIGHT
B0 3124-Y87R	**NCS est. 2m**	2030-R30B	B + +	B -	B +	2030-R20B
	Bl / Chr		UC / -	UC / UC	UC / UC	
B8 3025-R	**NCS est. 2m**	1040-R55B	B +	B (+)	OF	0540-R60B
	Bl / Chr		(-)/(+)	OF / OF	(-) / (+)	
	Ident. dist.	80	120	90	100	160
B10 3124-R03B	**NCS est. 2m**	1243-R60B	B +	B (+)	B (-)	1045-R65B
	Bl / Chr		(-) / (+)	UC / UC	(-) / (+)	
	Ident. dist.	130	150	130	140	180

3.4 Pilot study: Visual performance test

We let seven observers do a visual performance test on the colour contrast chart. The observers were between 41-78 years old and each subject was tested for visual acuity (VA), contrast sensitivity (CS), and colour vision prior to the visual performance test on the colour contrast chart. VA and CS were tested using Landolt C optotypes at two meters distance with an online test (FrACT) (Bach 2015), displayed on an Apple MacBook Pro computer. During the CS measurements the size of the Landolt C was equal to the symbols on the printed colour contrast chart. The colour vision test was performed using a calibrated online Farnsworth-Munsell 100 HueColor Vision Test (Colbindor 2015) presented on a LaCie324 display.

All four females had normal colour vision (score: 11 to 56), but three of the four males had moderate to severe colour deficiency (score: 112 to 404, one Protan, two Deutan). Decimal visual acuity (Landolt C with no crowding) ranged between 1,0 and 2,0. The extreme value (VA=2,0) was confirmed using a Snellen chart. Contrast sensitivity ranged from 139 to 447 (Michelson definition).

The visual performance test on the colour contrast chart followed the procedure: The observers viewed the chart at two meters distance. They started the identification after 1-5 minutes of adaptation to the illumination. Three kinds of answers were allowed: 1) not detectable, 2) detectable symbol but not identifiable direction and 3) identifiable direction. In case 2) we asked the observers to guess the orientation.

The illumination was 350-400 lux and the four artificial light sources were presented in random order but the daylight test was carried out separately at 400 lux.

3.5 Distance required for identification of symbols

In an attempt to overcome the problems with the insecurity between detection and identification of objects, we let one experienced observer judge at what distance she clearly could identify the symbols. To verify her statement we also switched back and forth between light sources until she was sure about the difference in appearance. Note that no judgement was done until satisfactory adaptation to a new light.

Results are shown in Table 3. The observer was allowed to move as close as necessary to identify a symbol and move further away from the chart to find the distance, just enough for identification.

4 Analysis and results of visual performance tests

In this section we only give few examples of analysis and results from the visual performance test with the five observers with normal vision. Two of the observers made the test twice with several weeks in between; in total we have seven observations. Despite the small number of observers, we identify patterns in visual performance, which will be addressed below. The discussion is left to section 5.

In the analysis of the results we treat symbol colours that deviate from the background colour to the right and left in the NCS colour circle as separate groups. It was evident that the symbols on most of the rows on the chart were either too difficult or too easy to identify. On some rows there was a sharp threshold where symbols were clearly identified and not detectable at all. Ideally, the symbols should gradually vary in colour so an increasing number of observers could identify them, the more colour difference there was. Row A and B are examples of this situation, c.f. Table 4.

Table 4 – Example of test protocol for observers with normal colour vision.

Light Source	Proportion correct answer						
	Symbol colour						
	A2	A4	A6	A8	B8	B10	B12
Halogen	15%	30%	70%	85%	0%	60%	60%
Anslut	15%	60%	100%	70%	0%	70%	70%
Soraa	30%	45%	100%	85%	0%	85%	70%
Osram	70%	30%	100%	85%	0%	100%	85%

When comparing the outcome of the visual performance test to the SPD measurements, we found that it is not possible to directly judge from the SPDs if the symbol is possible to identify or not, c.f. Figure 4. As an example, the SPDs for symbol A2 and background overlap for all light sources. Anyway, most observers could identify A2 under Osram illumination. On the other hand, the SPDs for B10 and background are not overlapping to the same extent, but B10 is still not possible to identify for some observers. The perceived hue difference between symbol B10 and background was large (c.f. Table 3) but the symbol shape disappeared with increasing viewing distance, possible due to the phenomena of vibrating edges c.f. Section 2.

The colour difference was also analysed by inspecting CIE-xy chromaticity coordinates. CIE-xy coordinates for row B is shown in Figure 5 and is an example where measurements agreed with visual assessment and performance test results. By inspection, it is clear that Osram light source performed distinctly different from the other three artificial light sources (daylight not included in this comparison). This agrees with colour appearance assessment (c.f. Table 3) where background appeared more bluish and less colourful, thus appeared lighter, in Osram illumination.

Moreover, the distance between CIE-xy coordinates for symbol colours in Osram illumination was larger than for the other light sources, which indicates that symbols ought to be easier to visually identify, which also seems to be the case c.f. Table 4 column B10.

The symbol identification results can also be related to the measurements of colour difference expressed as ΔXYZ, Δxy and ΔL. In Figure 6, which shows results for symbols on row B, we see that the symbol colours differ more from the background under the Osram illumination as the bars are higher. The ΔXYZ and Δxy are increasing smoothly, indicating a gradually increasing colour difference. ΔL shows that the colours B10 and B12 were not completely isoluminant which agreed with perceived lightness judgement in the visual assessment. .

The study of the distance, necessary for clear identification of symbols on the colour contrast chart, turned out to be an efficient method to rank the quality of vision in the different illuminations, c.f. Section 3.5. This method would be interesting to further develop because it was quite easy to judge if a symbol was identifiable at a specific distance or not.

5 Concluding discussion and further questions

The presented colour contrast chart method is useful for determining visibility thresholds of colour contrasts. When the symbols were well designed, i.e. small enough steps on the NCS colour circle, we could identify a gradual ability to identify them. Too big steps lead to inexact determination of threshold levels that don't reveal differences clearly. For example, when no observer could identify the first symbol, but all observers identified the second - we probably miss the exact threshold nuance.

The studies must be extended with more observers in order to make general conclusions and further identify patterns. We are interested in finding possible ways to optimize illumination for individual needs like visual impairment, aging vision, colour deficiencies, etc. Therefore it is important to compare results for an individual observer with herself, i.e. statistical analysis of a heterogenic group is not the best choice.

When the symbols were properly designed, it was possible to compare visual performance in LED lighting and reference lighting (Halogen and daylight). Generally, there were great similarities between visual performances, despite that the light sources gave different perceived colour. This indicates that the colour contrasts were not affected by a change of illumination. In these cases, the perceived relation between background and symbol were preserved, while colour appearance changed. However, we found few examples where certain light source affected the colour contrast more than the other ones.

It was crucial for the design of the colour contrast chart to achieve equal perceived lightness between symbol colour and background. We assumed that symbols should be more easily identifiable, the more hue difference from the background. However, this requires that the lightness difference has to be eliminated; otherwise the observers will identify the symbols due to lightness difference.

The layout of the colour contrast chart could be further developed. The coloured ribbons ought to be separated with white fields to minimize contrast effects between them. The order of the symbols could be arranged in several ways, for example the symbols with the smallest colour difference in the middle and symbols with increasing contrast to the sides.

The production chain for printing the colour contrast chart needs to be developed. During fine tuning of the printed chart, the perceptual judgement needs to be carried out in the same reference light as will be used in the visual performance test. Especially important is to achieve perceived equal lightness between symbols and background. To print the tests charts on a plotter requires full control of colour management.

With the proposed assessment method for surveying the visibility of colour contrasts, we see great potential for investigating properties of light sources. The possibility to define an identification threshold for colour contrasts can be useful for optimizing illumination for individual needs such as visual impairments, ageing eyes and colour deficiencies.

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