



International Commission on Illumination
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3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
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Die Arbeit der CIE wird durch Technische Komitees geleistet, die in sieben Divisionen organisiert sind. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtenwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.

Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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CIE Central Bureau
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CIE Central Bureau
Babenbergerstrasse 9
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PERCEPTION OF ILLUMINATION WHITENESS

Perz, M.¹, Baselmans, R.¹, Sekulovski, D.¹

¹ Philips Research Lighting, Eindhoven, NETHERLANDS

Gosia.perz@philips.com

Abstract

Two perception experiments exploring the relation between chromaticity of illumination and perceived whiteness are presented. Relative whiteness was measured using a two alternative forced choice methodology with constant points. Adaptation to a point in between the forced choice stimuli was used. In the experiments, carried out with both expert and naïve participants, it is demonstrated that the points that are perceived to be the whitest for CCTs of 2700 K, 4100 K, and 5000 K, are located 0.003 to 0.008 $\Delta u'v'$ below the BBL. Thus, there is a possibility of specifying a “white body line” to characterize light sources. However, a comparison of the results with the previously reported studies: Ohno (2014) and Rea (2011), points towards the need of more extensive discussions on basic questions and methodologies used.

Keywords: whiteness, perception of white, methodology, correlated colour temperature, white body line, black body line

1 Introduction

LEDs allow for easy control of their emission properties, including their spectral composition, giving almost arbitrary control over the chromaticity of the emitted light. With this freedom, the communication of the chromaticity to the users of the light sources can be challenging. To simplify this communication, the lighting industry uses a quantity called the Correlated Colour Temperature (CCT) of the emitted spectrum or a classification of CCTs using natural language terms (e.g. warm, cold). The Correlated Colour Temperature of a source is the temperature of a black body radiator with a chromaticity that is closest to the chromaticity of the source. Taking all black body radiators for different temperatures one gets a line in chromaticity space called the Black Body Line (BBL), that has dominated the characterization of “white” light sources. In LED lighting the points on the BBL are used to specify the chromaticity in the whole production chain, from the LEDs themselves to luminaires. As sources with the same CCT can have widely different appearance it is natural to question if the BBL is the most appropriate reference.

An often heard argument for the choice of the BBL as a reference is that it represents natural light sources or white light sources (usually meaning sources without perceived tint). In recent years, however, a number of studies contested both the perceived whiteness (Rea, 2011; Liu, 2015) as well as the perceived naturalness and preference (Ohno, 2014 and 2016) of sources having a chromaticity on the BBL. Rea (2011) found that perception of white illumination is associated with positions of the chromaticity that fall above BBL for high CCTs (above 4000 K) and that fall well below BBL for low CCTs (below 4000 K) and for all CCTs different from 4000 K the points on BBL appeared tinted. Similar results were obtained by Liu (2015). Partially agreeing with those results, Ohno (2014 and 2016) demonstrated that for CCTs ranging between 2700 K and 6500 K, points below the BBL appear more natural and are more preferred than points on the BBL. Similar results were obtained by Feng (2016), who showed that, in a retail application, for the CCT of 3000 K, observers prefer light from LED sources with chromaticity below BBL, and they also judge it as being whiter. These studies show the possibility of adding a “white body line” and a “natural/preferred illumination line” additional to the BBL to specify the chromaticity of light sources.

The differences in the setups of the above mentioned studies clearly demonstrate the most important aspects of illumination chromaticity perception that have to be taken into account. In the study of Rea, participants were instructed to identify the tint of a large, uniformly illuminated viewing box for a number of stimuli having the same CCT but different

chromaticities. Using one stimulus, this study was aimed to define the whitest point in an absolute sense. Contrary to this, the study of Ohno always showed two different stimuli to the participants and asked for the more natural of the two. Similarly, in the study of Feng two scenes were showed, but the reference scene was kept constant across all the comparisons. Even though it is logical that the point of equal choice between the stimuli in the second approach is equivalent to the point of the least tint in the first approach, this equivalence is not necessarily true. Second important difference between the studies is in the way that chromatic adaptation is controlled for. In the study of Rea all the stimuli were presented in a random order and the adaptation state is treated as a nuisance factor and added to the error. In the second study, adaptation was controlled for and participants were given enough time to adapt to a point in between the two stimuli. As adaptation to a specific chromaticity greatly changes the perception of the following light stimulus, this consideration is very important. The last difference important for this work is the inclusion of coloured objects in the experiment. The first study was done in an empty white box, while the second and third ones were done in a more realistic environment having a number of objects with different colours.

In the present study, we aim to understand the basic perception of whiteness of light sources. We performed 2 perception experiments. Due to large influence of chromatic adaptation, we used a methodology that does not measure absolute whiteness, but a relative one. Instead of answering the question “Which light source with a CCT of x is the whitest when seen in isolation” we aim to answer the question “Which light of CCT x is whiter than any other source with the same CCT when directly compared”. As a first step in the study, we used only white surfaces and no coloured objects. Lastly, similar to the work of Ohno, we control for adaptation by giving time to the participants to adapt to a point between the stimuli to be compared.

2 Method

In the two experiments the same set-up, stimuli and procedure were used as detailed below.

2.1 Set-up

A viewing box, with two chambers having dimensions of 62 cm x 62 cm x 68 cm (depth), was used. The edges of the box were covered with black cardboard that resulted in a visible window of 56 cm x 54 cm (height). The cardboard was used to lower the edge effects and make a separation between the two sides of the viewing box of 10° visual angle. The walls of the chambers were painted with defuse neutral white paint, the floor was covered with diffuse black paper and in the middle of each of the chambers on the floor there was a white sheet of paper, having optical whiteners. Philips HUE lamps were mounted on top and in the centre of each of the chambers. Each bulb had 3 different channels that could be independently controlled with 12 bits of precision. The bulbs included an amber LED, with a peak at 627 nm, a lime LED with a peak at 545 and a blue LED with a peak at 452 nm. The chambers were uniformly illuminated. The viewing box, used in the experiments, is shown on Figure 1.



Figure 1 – Viewing box used in experiments 1 and 2

2.2 Stimuli

In order to be able to compare the current results with the previously conducted studies, 3 CCTs were used: 2700 K, 4100 K and 5000 K. These CCTs are also among the most commonly used in office and home applications in Europe and North America. For each of the CCTs 9 different iso-illuminant stimuli were generated: 4 positioned above the BBL, 4 positioned below BBL, and 1 positioned on the BBL. Due to hardware limitation the last point for 5000 K was not used in the experiment. The stimuli ranged between $-0.0179 \Delta u'v'$ (we use a convention where a negative distance means a chromaticity above the BBL) to $0.0152 \Delta u'v'$ from the BBL. In addition a reference (adaptation) light spectrum with a chromaticity point in the middle of the pair of the stimuli was used. The distance between the stimuli was equal to CIE $L^*a^*b \Delta E = 3$ below and above the reference point. Table 1 shows the reference light conditions, together with their xy values, peak wavelengths, Colour Rendering Index (CRI) , (CIE 13.3, 1995), and Colour Saturation Index (CSI) (Teunissen, 2016) and distance to BBL.

Table 1 – Reference stimuli used in experiment 1 and 2

	CCT	CIE 1931 x	CIE 1931 y	Peak Wavelength (nm)	CRI	CSI	$\Delta u'v'$
1.	2700	0,419	0,366	628	91	115	-0.0092
2.	2700	0,425	0,379	628	92	113	-0.0060
3.	2700	0,431	0,392	627	92	111	-0.0030
4.	2700	0,437	0,404	627	92	109	0.0000
5.	2700	0,443	0,416	627	91	107	0.0028
6.	2700	0,448	0,428	627	91	105	0.0055
7.	2700	0,454	0,439	627	90	102	0.0081
8.	4100	0,362	0,320	627	89	113	-0.0162
9.	4100	0,366	0,335	627	91	109	-0.0107
10.	4100	0,370	0,350	627	90	105	-0.0053
11.	4100	0,374	0,366	627	87	102	0.0000
12.	4100	0,378	0,382	627	83	98	0.0052
13.	4100	0,383	0,399	626	80	94	0.0103
14.	4100	0,386	0,416	626	77	90	0.0152
15.	5000	0,340	0,298	452	86	114	-0.0179
16.	5000	0,342	0,313	452	90	108	-0.0119
17.	5000	0,343	0,328	452	88	102	-0.0059
18.	5000	0,345	0,344	452	83	97	0.0000
19.	5000	0,345	0,360	452	77	91	0.0059
20.	5000	0,348	0,377	452	73	85	0.0117

All the spectra of the reference stimuli and their respective colour points plotted on CIE 1931 chromaticity diagram, are shown of Figure 2.

2.3 Procedure

Participants were seated 0.5 meter away from the viewing box, in an otherwise dark room. For each pair of stimuli, the reference light, having a chromaticity between the two stimuli, was shown in both chambers for 10 seconds, after which time the stimuli were shown. In total 7 pairs of stimuli were used. Participants were instructed to indicate on a portable numerical keyboard, which of the two stimuli is whiter; they were instructed to press the right arrow key, if the stimuli in right chamber was whiter and otherwise the left arrow key. Each pair of stimuli was repeated 10 times in the first experiment and 6 times in the second experiment. All the stimuli were randomized. The experiment took about 30 minutes per participant.

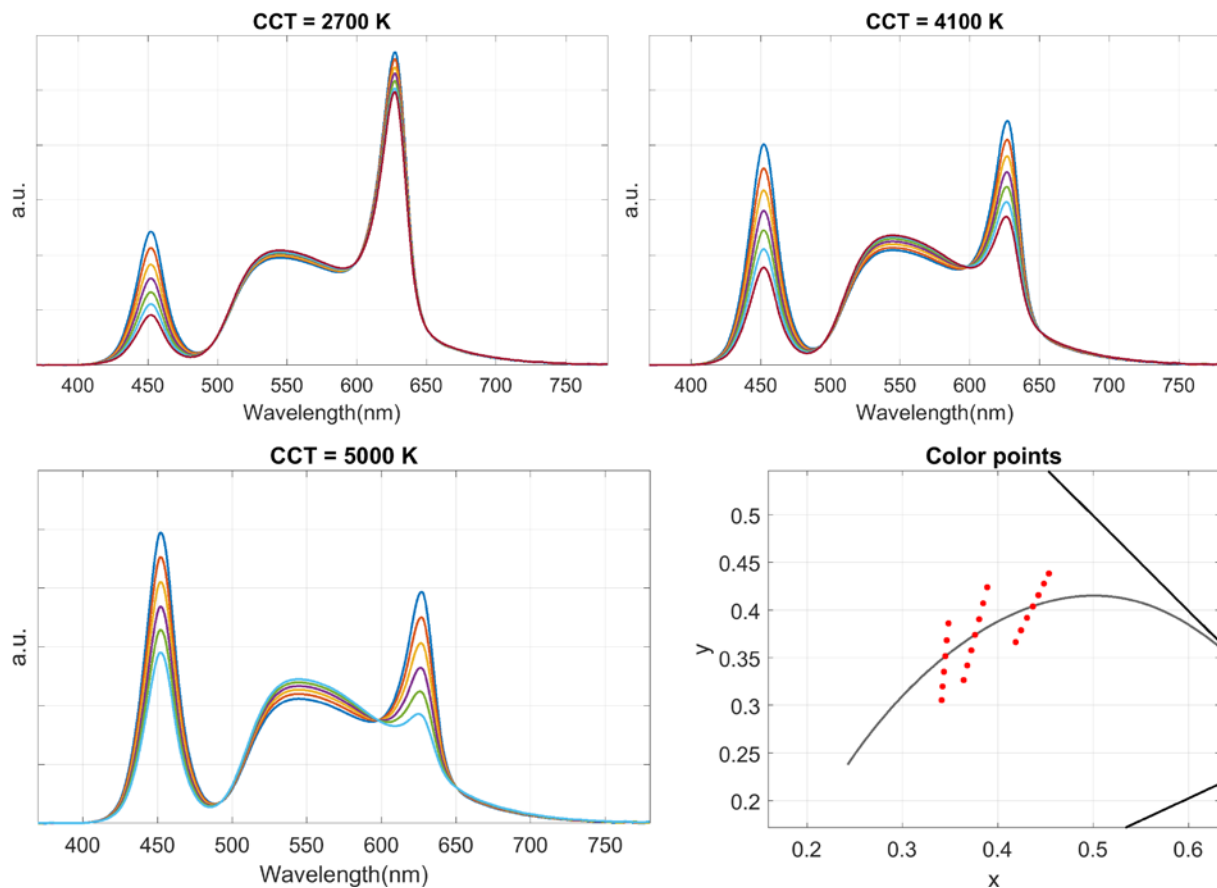


Figure 2 – Spectra of reference stimuli and their respective colour points, plotted on CIE xy diagram

2.4 Participants

In the first experiment 24 participants were used, recruited internally from Philips Research employees and interns. In the second experiment 27 non-Philips participants were used, recruited via an external agency. They were 13 males and 14 females, with their age ranging between 25 and 53 years. The normal vision of the participants was ensured by Ishihara colour vision test.

3 Results

The experiments resulted in the probability that participants picked the stimulus “above the reference” as being whiter. The data from all participants per point per experiment was pooled. Figure 3 depicts an example series of probabilities for experiment 1 and at one CCT of 4100 K.

Using these probabilities as model data, we fit a generalized linear model using a binomial distribution and a Probit link function. From the fit we can find the point of equal probability for the participant to pick the point below the reference and above the reference. We take this point to be the resulting “whitest” point per CCT. The stars in Figure 3 depict the probability results and the line the Probit fit. The circle denotes the resulting 50 % probability point.

Due to the large difference in variance between the experiments, a separate generalized linear model was fitted to the data from each experiment using *fitglm* in Matlab. For experiment 1 a Wald test showed a significant effect of CCT ($t(2) = 8.267$, $p_{\text{Wald}} < 0.0001$) and a significant effect of chromaticity ($t(6) = -38.45$, $p_{\text{Wald}} < 0.0001$). For experiment 2 no significant effect of CCT was found ($t(2) = 0.862$, $p_{\text{Wald}} = 0.3884$), while a significant effect of the chromaticity was found ($t(6) = -15.97$, $p_{\text{Wald}} < 0.0001$). No effect of demographics such as age, gender and education level was found in experiment 2 where demographic data was collected.