Chromaticity of White

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Introduction

"White" is an important and widespread concept in lighting and colour vision science. In psychophysical research, *unique white* specifically refers to a "colour devoid of any hue sensation". It is thus the point at which the r-g and y-b opponent channels are balanced (and the stimulus is sufficiently intense to not be perceived as gray or black). Because of this, *unique white* is often used as an internal reference in colour constancy and chromatic adaptation research. Despite this exact specification of the meaning of "white" there is considerable ambiguity with regards to its exact chromaticity. For example, *white light* can refer to illumination with a wide variety of correlated colour temperatures. Popular choices are the equal-energy-white, which is the standard white point of the CIECAM02 colour appearance model, it is also the stimulus that corresponds to a dark adaptation state; or any of the CIE daylight phases, in particular D65. Recently Rea & Freyssinier [1] found a "line of whites" for lighting that lies above the blackbody locus at correlated temperatures (CCT) higher than 4000 K and below for lower CCTs. In a similar experiment, Ohno & Fein [2] found a line of whites that was located completely below the blackbody locus at a Duv of approximately -0.013. However, it should be noted that such a "line of whites" is most likely an experimental artifact [3]. In both visual experiments the most white lighting was identified by varying the chromaticity of the test illuminant along loci of constant CCT. The line of whites was then obtained by taking these whitest illuminant chromaticities at each investigated CCT. This approach, however, does not take into account possible differences in perceived whiteness as a function of CCT. A more general approach would be to have observers rate a random sequence of chromaticities taken from a uniform 2D grid spanning the blackbody locus. In this paper, the chromaticity of white was investigated in a "*unique white*"- *adjustment* and -*rating* experiment.

Methods

The experiment consisted of two parts. In the first part observers were asked to adjust the chromaticity of a test stimulus along the axes of the CIE 1976 *u'v'* diagram until it appeared white, i.e. until it showed neither red, nor green, nor yellow, nor blue tint. The first part had 9 runs (1-3: practice). In the second part, the test stimulus was presented in 59 different chromaticities chosen at random from a uniformly spaced grid in CIE *u'v'* diagram that enveloped the blackbody locus. Observers were asked to rate the perceived whiteness of the test stimulus on a 0-10 scale. Twelve observers (7 male, 5 female, average age: 31), with normal colour vision as determined by the Ishihara 24 plate test participated in the experiments. Both parts were performed under dark adaptation conditions, with the luminance of the test stimulus at 2000 cd/m². The test stimulus was a real 3D cube (width = 8.5cm) with non-selective spectral reflectance illuminated by a data projector. By changing the pixels associated with the geometric projection of the 3D cube, the illusion was created that the cube itself changed colour, i.e. unique white was investigated in *object mode*. Future experiments will also use an *illuminant mode*. The pixels associated with the background were set to black (cfr. a dark adaptation condition). After each adjustment the spectral radiance of the test stimulus was measured with an Ocean Optics QE65000 Pro spectrometer. The cube-observer distance was approximately 100 cm, providing a stimulus field of view (FOV) of ±6°. As the FOV was larger than 4°, all chromaticity values were determined using the CIE 1964 observer.

Results & Discussion

Figure 1a shows the results of the first part, the unique white *adjustment*. The coloured dots show the 9 settings for each observer. The coloured ellipses are the observer Standard Deviation ellipses. The average SD-ellipse (solid black line) and the SD 95% confidence interval (95% CI) ellipse (dashed black line) are also shown. It is clear that the intra- and inter-observer variations are quite large, which is consistent with results for unique white settings under dark adapted conditions reported in literature [4]. The CCTs corresponding to the center of the SD-ellipses range from 4000 K to 10000 K (*note that reported CCTs and Duvs, like the test stimuli chromaticities, are calculated with the CIE 10° observer*). Most observers had unique white settings with negative Duv, in agreement with the results obtained by Ohno & Fein, but not with those from Rea & Freyssinier. The center of the average SD-ellipse had a CCT and Duv of respectively 5442 K and -0.009, which is very close to the equal-energy-white (CCT,Duv = 5480 K, -0.004).

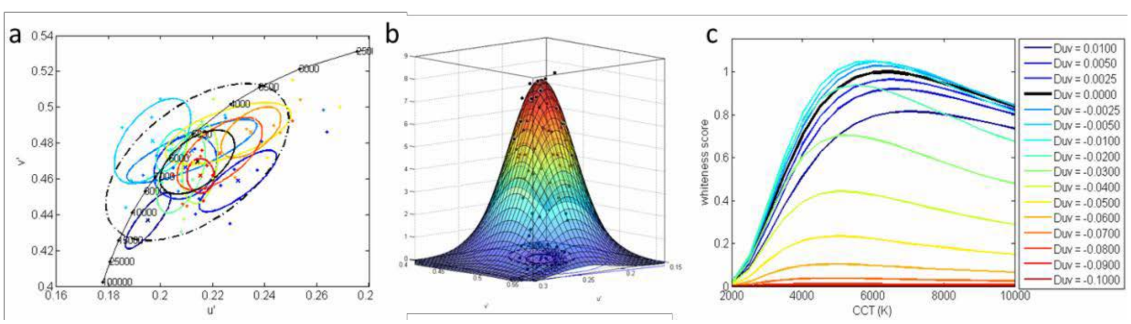

Figure 1. Results of adjustment (a) and rating (b) experiment. The degree of whiteness as a function of CCT for different Duvs under dark adapted conditions obtained from the rating data is also shown in c.

Figure 1b shows a bivariate Gaussian fitted to the 59 averaged observer ratings. The Standardized-Residual-Sum-of-Squares (STRESS) of the fit is 0.16, which is smaller than the mean inter-observer STRESS value of 0.31 indicating a satisfactory fit given the data. It is clear that 1) whiteness is defined by a region rather than a line as reported by Ohno or Rea, 2) the degree of whiteness is not equal for all CCTs. The latter is further illustrated in Figure 1c, which shows the degree of whiteness in function of CCT for different Duv. The (CCT,Duv) pair corresponding to the center of the bivariate Gaussian function is (5962 K, - 0.009). The difference between the results of part 1 and 2 might be due to chance (unique white of part 2 lies within the SE 95% CI-ellipse of part1), or it might e.g. be due to a difference in the degree of chromatic adaptation to the stimulus itself, as observers had a longer time to adapt while performing the adjustment than when doing the rating, or it might be that some skew might need to be introduced to the fit.

Conclusion

The chromaticity of *unique white* was determined in a two-part experiment. The CCT of the unique white of part 1 was found to be close to that of the equal-energy-white. That of the second part was shifted towards higher CCT, but still within the 95% CI obtained in part 1. In both cases, the Duv was negative supporting the work of Ohno & Fein [2], but not that of Rea & Freyssinier [1]. In contrast to those studies, which reported a *line of whites*, the results of part 2 clearly supported a *region of whites*. It was also shown that the degree of whiteness is not constant along the blackbody locus. Finally, it should be noted that inter-observer differences for unique white under dark adapted conditions were quite large. Future experiments, will also investigate unique white in an illuminant mode.

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Author Biography

Kevin Smet received his Ph.D. (on memory colours and colour rendition evaluation) from Leuven University (2011). As a postdoctoral fellow at the University of British Columbia, Canada (2012) he continued his work on colour rendition. Currently he's a postdoctoral fellow of the Research Foundation Flanders at the Light and Lighting Laboratory (Leuven University). His research interests focus on chromatic adaptation, colour appearance, brightness perception of self-luminous stimuli, colour rendition and memory colours.