WHITENESS ASSESSMENT OF PAPER SAMPLES AT THE VICINITY OF THE UPPER CIE WHITENESS LIMIT

Coppel L., Lindberg, S., and Rydefalk, S.

STFI-Packforsk, Stockholm, Sweden

ABSTRACT

The perceived whiteness of commercial paper samples was evaluated under three different illumination conditions. Several samples were found to be outside the region of validity of the CIE whiteness although they were perceived as acceptably white by most observers. If the limits are disregarded, these samples are assigned high whiteness values, leading to a low correlation between instrumental and visual whiteness since these samples are not perceived as the most white. Non-linear whiteness models defined in the whole colour space have recently been proposed by Aksoy and Uchida. These were tested together with two models proposed by the authors. These models are modifications of the Aksoy model. In the first model, W_{NEW}, the maximum whiteness is at a lower b^* value than the CIE whiteness. It correlated well with ranking and scaling ($R^2 > 0,7$). The higher correlation obtained with this model indicates that the upper whiteness limit in the CIE whiteness could be extended, as was proposed by Uchida. The second model, W_{eCIE}, keeps the CIE whiteness formula within its region of validity and applies a penalty function similar to the one used by Aksoy outside this region. In this case the maximum whiteness is determined by the CIE whiteness upper limit. The performance of this model was slightly inferior (Rank correlation $R^2 = 0,56$ for a first set of samples and 0,69 for a second set) but its main advantage is that all samples within the CIE whiteness limits are given the same whiteness values as with the CIE whiteness formula. The results showed that the introduction of a penalty function replacing the CIE whiteness limits is a promising way to handle white materials at the vicinity of the upper CIE whiteness limit.

Keywords: whiteness perception, CIE whiteness

1. INTRODUCTION

Whiteness is an attribute of colours of high luminous reflectance and low purity, located in a relatively small region of the colour space. Many evaluation methods and numerous whiteness formulae have been proposed over the years, but these formulae gained little agreement among users. The CIE recommended their whiteness formula [1] as an assessment method of white materials in 1986. This formula was found to correlate with visual estimation of whiteness for many white samples having similar tint or fluorescence [2]. The CIE whiteness formula is a linear function of the chromaticity coordinates *x, y,* and the *Y* tristimulus value. It is only valid within a defined region of the *xyY* space.

With the extensive use of fluorescent whitening agents to enhance optical properties and appearance, the upper whiteness limit is often violated. Although samples near but outside the whiteness limit might not be perceived as the whitest, most of them are perceived as acceptably white by observers. The CIE whiteness however, gives a zero value because of the limits. Recently, Uchida [2] and Aksoy [3] presented non-linear whiteness formulae replacing sharp limits with penalty functions. In the meantime a new ISO standard introduced the concept of "indoor whiteness" [4].

This article presents the results of testing these models for paper samples at the vicinity of the CIE upper whiteness limit. Some modifications of these models are also proposed. Two sets of paper samples with CIE whiteness values ranging from 140 to 160 were chosen. The samples were evaluated in a laboratory for visual evaluation with controlled illumination and viewing conditions.

2. WHITENESS MODELS

The CIE recommended in 1986 an equation for the whiteness in outdoor daylight (D65/10°) related to the CIE tristimulus measurements of the form

$$W_{\mathrm{CIE}} = Y + 800(x_{\mathrm{n}} - x) + 1700(y_{\mathrm{n}} - y), \qquad (1)$$

where x_n and y_n are the chromaticity coordinates for the perfect reflecting diffuser under the given illumination. To prevent application of the whiteness formula to chromatic samples, the equation is only valid within given boundaries in the colour space defined by:

$$\begin{matrix} 40 < W_{\mathrm{CIE}} < 5Y - 280 \\ -3 < T < 3 \end{matrix}, \qquad (2)$$

where $T = 900(x_n\text{-}x) - 650(y_n\text{-}y)$ is the tint for a D65/10° illumination and observer. Uchida [2] argued that the upper whiteness limit should be extended to $W_{\mathrm{CIE}} < 5Y\text{-}275$ and proposed in 1998 a modified CIE whiteness formula, W_{UCHIDA}, using a penalty function beyond this limit. In Uchida's model the tint is explicitly taken into account by reducing the whiteness value by twice the square of the tint value. This makes the tint inequality conditions unnecessary. Aksoy and Fleming [3] proposed a model, W_{FA}, based on the $L^*a^*b^*$ values where the whiteness decays exponentially along the a^*- and b^*-axes. The Fleming-Aksoy whiteness is however symmetrical in the a^*b^*-plane, which gives relatively high whiteness values for red and green-tinted samples. We therefore propose a new formula (Figure 1, left) based on the same form but with a higher decrease rate along the red-green axis than along the yellow-blue axis:

$$W_{\mathrm{NEW}} = W_0 0.5^{\left(\frac{(a' - a_1^*)^2}{C_3^2} + \frac{(b' - b_1^*)^2}{C_4^2}\right)}, \qquad (3)$$

where the a' and b' variables are the coordinates in a coordinate system aligned with the CIE whiteness. C_3 is the distance in a' at which the function decays to half its maximum and C_4 is the corresponding distance in b'. C_3 was set as the maximum absolute a^* in the whiteness region determined by the tint inequality and Equation 3. C_4 and b^*_1 were determined by requiring $W_{\mathrm{NEW}} = W_{\mathrm{CIE}}$ at maximum whiteness and at $L^*a^*b^*$ ={100,0,0}. An alternative (W_{eCIE}) to the previous whiteness model is to keep the CIE whiteness within its region of validity and use a penalty function only for samples outside the limits. We chose to use a convex function similar to the one proposed by Fleming and Aksoy instead of Uchida's concave penalty function, as the latter makes the whiteness value drop dramatically after the maximum point.

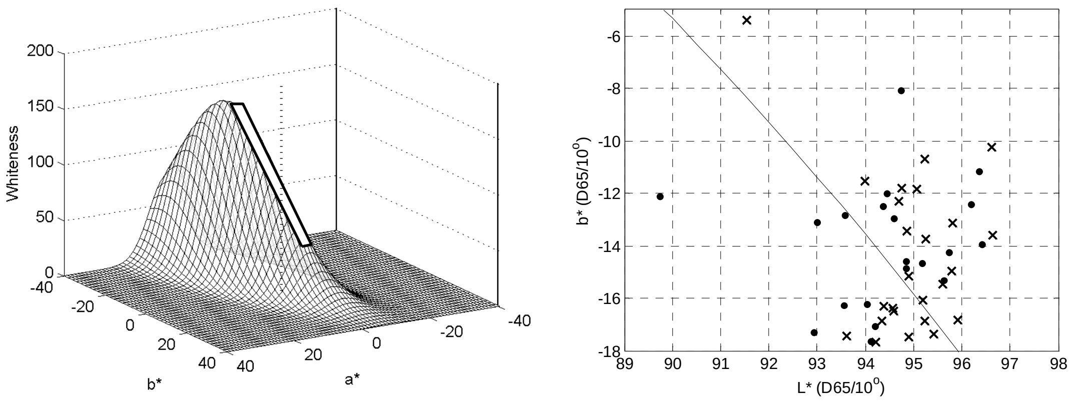

Figure 1. (Left) Comparison of the CIE whiteness to W_{NEW} for $L^* = 95$. The CIE whiteness is the white rectangular like area and is only defined in the region delimited by the whiteness inequality conditions. W_{NEW} is the continuous function. The vertical dot line is at $a^*=b^*=0$. (Right) L^* and b^* values (D65/10°) of the samples. The samples in the first set of papers are represented by dots and those in the second set by crosses. The line is calculated for $a^* = 0$ and delimits the CIE whiteness region defined by the upper whiteness inequality in Equation 2. According to the CIE whiteness formula, all the samples below this line are not white.

3. METHOD

3.1 Paper samples

Two sets of paper samples were selected for visual evaluation under different illumination conditions from a larger set of commercial copy papers in order to get a relevant span of the CIE whiteness of commercial copy papers. Optical measurement of whiteness and CIE *L*a*b** were performed on a Technidyne Color Touch 2 instrument in compliance with the ISO 11745 standard (Figure 1, right). Several samples were outside the CIE whiteness region and failed to fulfil the blue tint condition defined by the upper inequality (Equation 2).

3.2 Visual evaluations

Three experiments were performed by 45 observers, 15 for each experiment, with no previous experience in psychophysical scaling or paper related issues:

1) The first set of 20 papers was evaluated in three illumination conditions: light booth illumination with correlated colour temperature about 5000 K and 6500 K, and the 6500 K illumination with additional UV lamp tube. The observers were asked to rank the samples according to their perceived whiteness. All the observers had an average colour discrimination in the Farnsworth Munsell 100 Hue test.

2) The second set of 25 papers was evaluated in 6500 K illumination only. The observers were first asked to sort the samples in an increasing order of whiteness and then to use magnitude estimation to scale the magnitudes of their perceived whiteness [5]. A rating of the samples was then calculated by taking the antilog of the mean of the common logarithm of the individual estimates. The observers had normal colour vision in the Ishihara Test for Colour Blindness.

3) All 45 samples were scaled in 6500 K illumination. The observers were asked to group the samples according to their similarity in appearance and to give a scale value for the perceived whiteness of each group using the method of magnitude estimation [6]. The observers had normal colour vision in the Ishihara Test for Colour Blindness.

4. RESULTS

The mean observer cross-correlation (R^2) was 0,66 in a 5000 K illumination, 0,63 in a 6500 K illumination, and 0,46 in a 6500 K illumination with additional UV. An important observation in line with previous research [7] was the lack of agreement between observers, leading to a low cross-correlation between individual assessments. Despite this low cross-correlation, the median rankings obtained in the three illumination conditions were highly correlated (R^2=0,9). A one-way analysis of variance (ANOVA) applied on each sample showed that only three samples were significantly ranked differently (p-value < 0,05). The maximum median rank difference for these three samples was 2 positions. From this we can conclude that the three illumination conditions did not have an impact on the ranking of the samples.

The median ranking of the paper samples in experiment 1 and 2 are plotted against the non-limited CIE whiteness in Figure 2 and the performance of the six whiteness models tested is summarised in Table 1. The rank correlation between the D65/10° CIE whiteness and the ranking of the paper samples that lie within the CIE whiteness limits was 0,05 for the first set of samples and 0,85 for the second set. When taking into account the samples outside the whiteness limits, the rank correlation between whiteness ranking and CIE whiteness values was poor for both sets. The use of the indoor CIE whiteness did not improve the correlation because its main effect was to move samples that were outside the outdoor CIE whiteness limits inside the indoor CIE whiteness limits.

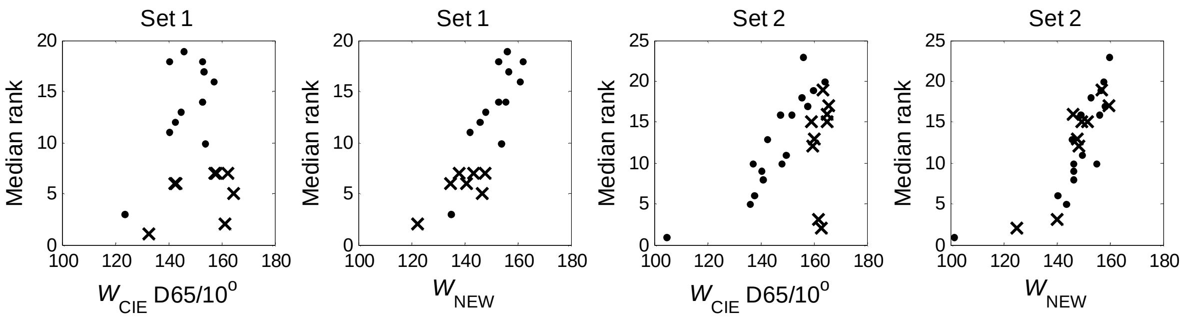

Figure 2. Median ranking of the papers versus W_{CIE} and the proposed W_{NEW}. The W_{CIE} values are given disregarding the CIE whiteness limits. The samples in crosses were outside these limits.

Table 1. Correlation coefficients (R^2) between the ranking/rating and the whiteness models. The numbers in parentheses are the correlation for samples within the CIE whiteness limits (D65/10° or C/2° depending on the instrumental illumination).

	Set 1, ranking R^2_{rank}	Set 2, ranking R^2_{rank}	Set 2, rating $R^2_{pearson}$	Set1 + Set 2, rating $R^2_{pearson}$
W_{CIE} D65/10° (outdoor)	0,05 (0,05)	0,25 (0,85)	0,28 (0,84)	0,14 (0,65)
W_{CIE} C/2° (indoor)	0,10 (0,00)	0,08 (0,15)	0,19 (0,32)	0,19 (0,35)
W_{FA} D65/10°	0,67 (0,58)	0,08 (0,07)	0,27 (0,23)	0,49 (0,26)
W_{UCHIDA} D65/10°	0,52 (0,03)	0,69 (0,83)	0,76 (0,83)	0,70 (0,72)
W_{NEW} D65/10°	0,74 (0,55)	0,76 (0,78)	0,74 (0,72)	0,74 (0,7)
W_{eCIE} D65/10°	0,56 (0,05)	0,69 (0,85)	0,73 (0,84)	0,58 (0,65)

The tested non-linear models performed much better. The rank correlation between the Uchida model and the median ranking was 0,52 for the first set and 0,69 for the second set. The Aksoy model performed very well for the first set of samples (R^2 = 0,67) but failed to predict the median ranking of the more bluish second set (R^2 = 0,08). This discrepancy can be explained by the fact that the Aksoy model has its maximum whiteness at larger *b** values than the CIE whiteness whereas Uchida has its maximum at lower *b** values.

5. CONCLUSION

Many commercial papers were found around and outside the upper whiteness limits defined by the CIE. Although they were not judged as the whitest samples despite their higher CIE whiteness, most of them were perceived as acceptably white by the observers. The use of the indoor CIE whiteness did not help in this case since its main effect was that many samples outside the outdoor CIE whiteness became within the whiteness limits, without having a significant impact on the ranking of the samples. Since the samples outside the D65/10° whiteness limits had relatively high whiteness values and low ranking, the correlation between instrumental and visual whiteness was reduced. However, the results showed that the introduction of a penalty function replacing the CIE whiteness limits is a promising way to handle paper samples at the vicinity of the upper CIE whiteness limit.

REFERENCES

1. ISO 11475 *Paper and board – Determination of CIE whiteness, D65/10° (outdoor daylight)*.
2. UCHIDA, H., A new whiteness formula*, Color Res, Appl,*, 1998, **23**(4), 202-209.
3. AKSOY, B, *Effect of Coating Additives on the Rheological and Optical Properties of Coated Papers*, Ph.D, thesis 2004, Western Michigan University.
4. ISO 11476 *Paper and board - Determination of CIE whiteness, C/2° (indoor illumination conditions)*.
5. STEVENS, S.S., *Psychophysics: Introduction to its Perceptual, Neural and Social Prospects*, New York: Wiley, 1975.
6. DONDERI, D.C., Information measurement of distinctiveness and similarity, *Perception & Psychophysics*, 1988, **44**(6), 576-584.
7. GANZ, E., Whiteness perception: individual differences and common trends, Appl, Opt,, 1979, **18**(17): p, 2963-2970.

ACKNOWLEDGEMENT

This work is part of a consortium project on the appearance of paper and on print quality. Financial support from Holmen, M-real, Norske Skog, and Stora Enso is gratefully acknowledged.

Authors:
Ludovic Coppel, Siv Lindberg, and Staffan Rydefalk
STFI-Packforsk
Drottning Kristinas väg 61, Box 5604, SE-114 86 Stockholm, Sweden
Phone +46 8 676 70 00
Fax +46 8 411 55 18
ludovic.coppel@stfi.se siv.lindberg@stfi.se staffan.rydefalk@stfi.se