Prediction of Lightness in Mesopic Vision

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Abstract

A new lightness predictor has been developed to give improved performance under mesopic conditions, where rod vision becomes more active. The new predictor is modified from CIECAM02 and includes a rod contribution to the achromatic signal. It is shown that a modified equation gives better performance and predicts two colour appearance phenomena observed under mesopic vision.

Introduction

In this study the lightness predictor of CIECAM02 was modified to include mesopic vision. Modification was based on psychophysical experimental data obtained by observations of a CRT monitor with four luminance levels covering the range 0.1 to 90 cd/m^2 and two different stimulus sizes with viewing angles of 2 degrees and 10 degrees. Analysis indicated that lightness contrast increased as the luminance level decreased and that the 10-degree stimulus showed higher lightness than the 2-degree stimulus[1]. Also there was found to be a hue dependency in lightness change by stimulus size, and there was a colourfulness increment by luminance level and stimulus size increment. Hue was little affected by these two factors.

Current models of colour appearance do not account for the change in colour appearance caused by stimulus size, and only a few models consider rod contribution. However colour appearance data gathered under mesopic vision suggests that the effects of rod contribution and stimulus size cannot be ignored, especially at low luminance levels. In this paper only the lightness predictor is considered, since lightness is the attribute most directly affected by the rods. It is believed that increased lightness resulting from rod contribution evokes higher colourfulness; therefore a better lightness predictor should produce correspondigly better colourfulness predictions.

Experiments

Figure 1 illustrates the experimental geometry and the viewing patterns of the stimuli, which were presented in a dark room on a 20"-diagonal CRT monitor, the Barco *Calibrator V*. The distance between the screen and observer or spectroradiometer was set to approximately 52 cm, such that the test colour at the centre of the two patterns had corresponding viewing angles of 2 and 10 degrees.

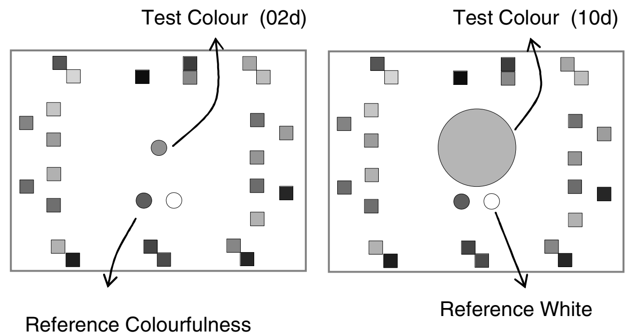

Figure 1. Viewing patterns (2-degree and 10-degree)

Table 1 shows the details of each phase. In the names, "-02d" indicates that 2-degree patches were used in that phase and "-10d" means that 10-degree patches were used. The successive reduction in luminance level was achieved by fitting one, two or three large sheets of neutral density filter, of density 0.9, over the monitor faceplate. The number shown after "Filter" represents the number of neutral filters used. Because of the slightly non-uniform transmittance of the neutral density filter over the wavelength range, the input digital values of the Filter1, Filter2 and Filter3 phases were adjusted using the GOG display model to have the same chromaticities as those of the Filter0 (without any filter) phase. Ten to twelve observers participated in each phase of the experiment and made judgements of lightness, colourfulness and hue of the circular test colour patches.

The observer's visual task was not constrained, i.e. it was binocular and not fixated on the test patch, and there was no limit on the time allowed for an observer to complete the three estimations (*L,C,H*) for each test patch. For lightness the observer was asked to place the test colour on an imaginary scale between the reference white (maximum) with a lightness of 100, and perfect black with a lightness of zero. All test colours were measured with a Photo Research PR-650 spectroradiometer directly from the screen. The 2-degree CIE standard observer colour matching functions were applied to measure the small patch and the 10-degree standard observer CMFs for the large patch. The "Reference White" for -02d phases in Table 1 is the standard photopic luminance Y, whereas values of -10d phases represent Y_{10}.

Table 1. The eight experimental phases (10-degree phases are shaded).

Name of Phase	Reference White Y_w	CCT	Back-ground	No. Test Colours	No. of Observers
Filter0–02d	87.37cd/m^2	6800K	19.8 %	50	12
Filter0–10d	96.24	6800K	19.8 %	50	12
Filter1–02d	8.856cd/m^2	6700K	19.5 %	50	13
Filter1–10d	9.683	6700K	19.0 %	50	12
Filter2–02d	1.007cd/m^2	6700K	20.9 %	50	10
Filter2–10d	1.099	6700K	20.9 %	50	11
Filter3–02d	0.097cd/m^2	6700K	19.8 %	50	11
Filter3–10d	0.105	6700K	19.8 %	50	10

Figure 2 shows the relationship between measured luminance (Y_{10} in the case of 10-degree patch) and mean visual lightness data. These are the datasets which need to be matched by the newly-derived lightness predictor. The horizontal line in the diagrams corresponds to the average lightness (=50) of the background grey of the viewing pattern, and the vertical lines represent the measured luminance level of the grey background at each of the four filter conditions. Average retinal illuminance for the lowest luminance level (Filter3 phase) was approximately 1 troland.

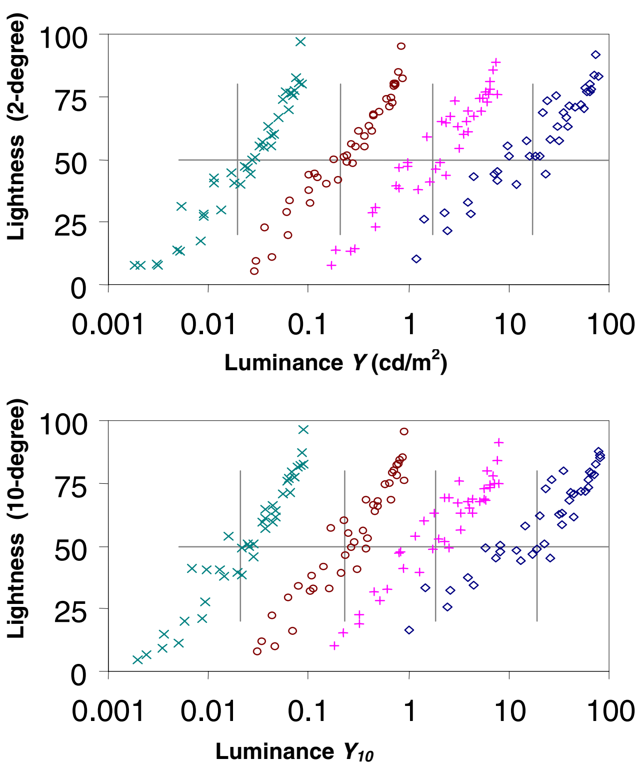

Figure 2. Mean visual lightness vs. luminance.

Modelling the New Lightness Predictor J_{p+s}

The aim of developing a new lightness predictor is to combine both cone (photopic) and rod (scotopic) signals to predict lightness, which is important in real-world viewing conditions at low luminance levels when the observer is in a state of mesopic vision. The new lightness predictor is represented as J_{p+s} and is modified from CIECAM02 [2].

Lightness Predictor *J* in CIECAM02

In CIECAM02, tristimulus values are transformed to the Hunt-Pointer-Estevez cone space after chromatic adaptation as introduced in Equation (1). F equals 1.0 for average and 0.9 for dim and dark surround conditions respectively. L_A means luminance of the adapting field.

$$\begin{vmatrix}R\\G\\B\end{vmatrix} = M_{CAT02}\cdot\begin{vmatrix}X\\Y\\Z\end{vmatrix} = \begin{vmatrix}0.7328 & 0.4296 & -0.1624\\ -0.7036 & 1.6975 & 0.0061\\ 0.0030 & 0.0136 & 0.9834\end{vmatrix}\cdot\begin{vmatrix}X\\Y\\Z\end{vmatrix}$$

$$R_C = \left[D\cdot\left(\frac{100}{R_W}\right)+1-D\right]\cdot R\ ,\ G_C = \left[D\cdot\left(\frac{100}{G_W}\right)+1-D\right]\cdot G \tag{1}$$

$$B_C = \left[D\cdot\left(\frac{100}{B_W}\right)+1-D\right]\cdot B\ ,\ D = F\cdot\left[1-\frac{1}{3.6}\cdot e^{\frac{-L_A/100-42}{92}}\right]$$

$$\begin{vmatrix}R'\\G'\\B'\end{vmatrix} = M_H\cdot M_{CAT02}^{-1}\begin{vmatrix}R_C\\G_C\\B_C\end{vmatrix} = \begin{vmatrix}0.7410 & 0.2180 & 0.0410\\ 0.2854 & 0.6242 & 0.0904\\ -0.0096 & -0.0057 & 1.0153\end{vmatrix}\cdot\begin{vmatrix}R_C\\G_C\\B_C\end{vmatrix}$$

The next stage applies a dynamic adaptation function to normalised cone signals R', G', B'. Dynamic adaptation means adaptation of cone signals according to luminance level by changing the normalised values to absolute cone signals using a luminance-level adaptation factor F_L and a non-linear function. The output values are represented as R_a', G_a', B_a'. The equation for R_a' is shown in (2). Similar equations are applied for G_a' and B_a'.

$$F_L = 0.2\cdot k^4\cdot(5L_A)+0.1\cdot\left(1-k^4\right)^2\cdot(5L_A)^{1/3}\ ,\ \ k = 1/(5L_A+1)$$

$$R_a' = 400\frac{\left(F_L R'/100\right)^{0.42}}{\left(F_L R'/100\right)^{0.42}+27.3}+0.1 \tag{2}$$

The lightness predictor in CIECAM02 is calculated from the achromatic signal, as a linear combination of R_a', G_a', B_a'. Equations (3) are for the achromatic signal and lightness predictor in CIECAM02. A_w is the achromatic signal of reference white and parameter c equals 0.59, 0.59 and 0.525 for average, dim and dark surround respectively.

$$A = \left[2\cdot R_a' + G_a' + 0.05\cdot B_a' - 0.305\right]\cdot N_{bb}$$

$$A_w = \left[2\cdot R_{aw}' + G_{aw}' + 0.05\cdot B_{aw}' - 0.305\right]\cdot N_{bb}$$

$$N_{bb} = \frac{0.725}{n^{0.2}}\ ,\ n = \frac{Y_b}{Y_w} \tag{3}$$

$$J = 100\left(\frac{A}{A_w}\right)^{cz}\ ,\ \ z = 1.48+\sqrt{\frac{Y_b}{Y_w}}\ ,\ \ c:\text{Surround parameter}$$

New Lightness Predictor with Rod Contribution

Our modelling of the rod contribution to lightness follows the assumption of Hunt in his Hunt94 model[3], in which it was assumed that the compressed rod signal is combined with cone signals in the achromatic channel by simple addition. However the rod signal does not contribute to the colour opponent signals. Equation (4) shows the new equations to calculate the total achromatic signal A_{Total} and hence lightness J_{p+s}. A is the cone (photopic) contribution to the achromatic signal and A_s is the rod (scotopic) contribution. The equation to calculate A_s is from Hunt94. Rod signal was calculated using normalised scotopic luminance and the same dynamic function was applied as for cone signal but with a new luminance-level adaptation factor F_{LS}. Scotopic luminance Y' was calculated using the CIE standard scotopic luminous efficiency function, $V'(\lambda)$.

$$A_{Total} = A + \alpha \cdot A_s$$

$$A = 2 \cdot R'_a + G'_a + 0.05 \cdot B'_a - 0.305$$

$$A_S = 400 \cdot \frac{(F_{LS} Y'/100)^{0.42}}{(F_{LS} Y'/100)^{0.42} + 27.3} \qquad (4)$$

$$\text{Scotopic Luminance} \quad Y' = 1700 \int V'(\lambda) \cdot P(\lambda) \cdot d\lambda$$

$$\text{where} \quad P(\lambda): \text{Power spectrum of test colour}$$

$$F_{LS} = 3800 \cdot j^2 \cdot \left(\frac{5 \cdot L_{AS}}{2.26}\right) + 0.2 \cdot (1 - j^2)^4 \cdot \left(\frac{5 \cdot L_{AS}}{2.26}\right)^{1/6}$$

$$j = \frac{1}{5 \cdot L_{AS}/2.26 + 0.00001}$$

$$J_{p+s} = 100 \cdot \left(\frac{A_{Total}}{A_{Total,w}}\right)^{k \cdot z}, \quad z = 1.48 + \sqrt{\frac{Y_b}{Y_w}}$$

Equation (4) has two unknown quantities: α is a weighting factor for the rod signals, which varies as a function of luminance; k corresponds to the surround parameter c in CIECAM02, which is usually set equal to 0.525 in the case of dark surround. However k is also treated as an unknown to compensate for the change in lightness contrast by stimulus size.

Table 2 Optimised parameters and comparison of performance with and without rod contribution.

Name of Phase	Optimised α	Optimised k	A_s/A_T %	A only CV	$A+A_s$ CV
Filter0–02d	0.768	0.4797	19.96	13.43	12.92
Filter0–10d	0.629	0.4575	15.45	13.47	13.24
Filter1–02d	0.566	0.5801	19.23	16.62	16.11
Filter1–10d	0.498	0.5134	18.31	14.73	14.38
Filter2–02d	0.571	0.6729	19.79	12.48	11.56
Filter2–10d	0.597	0.6291	30.05	13.13	11.64
Filter3–02d	0.999	0.7178	27.64	12.09	9.80
Filter3–10d	0.697	0.6452	34.12	12.31	9.96

Note that the visual lightness data in Figure 2 showed higher contrast for the 2-degree than 10-degree stimulus[1]. Optimised values of α and k were obtained by regression to minimise prediction errors. The results are shown in Table 2, represented as a function of luminance of reference white in Figure 3. Along with optimised values of α and k, the rod contribution to the achromatic signal is represented as a percentage using the equation $A_s/A_T \times 100$. Performance of the lightness predictor using optimised parameters was tested both excluding (A only) and including ($A+A_s$) rod contribution, represented by CV values.

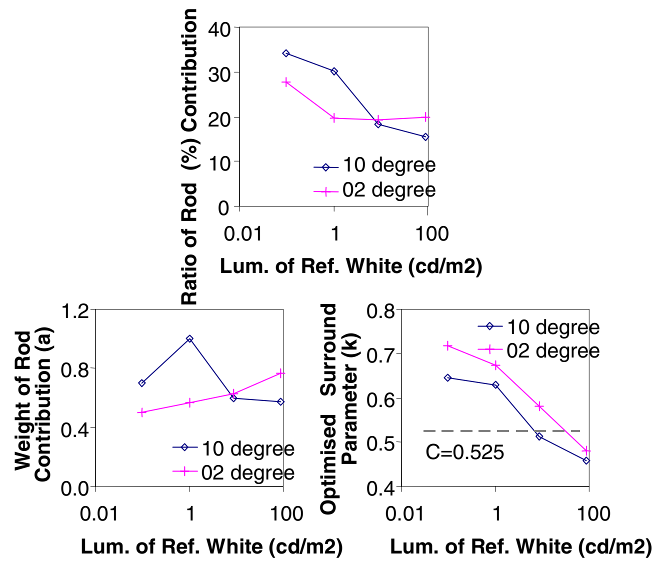

Figure 3. Optimised parameters in J_{p+s} as a function of luminance of reference white.

Comparison of CV values in Table 2 clearly shows that including rod contribution improved the performance of the lightness predictor. Average CV across all 8 phases was reduced from 13.54 to 12.45 when the rod contribution was added. However analysis of the optimised parameters shows some unnatural features. Firstly there is around 15 to 20% rod contribution even for the highest luminance level and it seems to be approaching a constant value as luminance increases. Also the weighting factor of rod contribution in the achromatic signal, α, showed irregular change for the 10-degree experiments and actually decreased at lower luminance levels for the 2-degree experiments, although the total ratio of rod contribution was increasing. These findings suggest that the proposed structure of the lightness predictor is not mathematically stable. This is an area for further investigation.

In the case of the optimised surround lightness induction parameter k, the 10-degree stimulus showed lower values at all luminance levels, borne out by lower lightness contrast compared to 2-degree stimulus in the mean visual lightness data. There is a noticeable trend in the change of optimised values with luminance level. Both CIECAM02 and previous CIECAM97s models treat the surround lightness induction factor c as a constant and lightness contrast change by luminance is compensated in a dynamic function, but this new result suggests that CIECAM02 cannot com-pensate for lightness contrast change by luminance level.

Modified Achromatic Signal A'

The authors' study[4] of colour appearance phenomena has found that performance of the lightness predictor was improved when a new photopic achromatic signal was used, having cone signals in the ratio 2:1:0.5 instead of the usual 2:1:0.05 for R_a':G_a':B_a'. A modified achromatic signal A' (= $2R_a' + G_a' + 0.5B_a' - 0.35$) was therefore tried in a new lightness predictor J'_{p+s} and the same analysis was repeated. Table 3 and Figure 4 show the results using A'.

Table 3. Optimised parameters and performance comparison with and without rod contribution (A').

Name of Phase	Optimised α'	Optimised k'	A_s/A'_T %	A' only CV	$A'+A_s$ CV
Filter0–02d	0.000	0.4843	0.00	12.00	12.00
Filter0–10d	0.000	0.4602	0.00	12.33	12.33
Filter1–02d	0.000	0.5851	0.00	15.09	15.09
Filter1–10d	0.000	0.5179	0.00	13.39	13.39
Filter2–02d	0.000	0.6711	0.00	10.96	10.96
Filter2–10d	0.190	0.6266	6.65	11.35	11.30
Filter3–02d	0.085	0.7162	5.36	9.77	9.71
Filter3–10d	0.232	0.6437	13.03	10.12	9.90

Comparison of the CV values between Table 2 and Table 3 shows that using A' improved the performance significantly, with average CV values reduced from 13.53 (for A) to 11.88 (for A'). The trends of the optimised parameters in Figure 4 are quite different from those shown in Figure 3. Both the ratio of rod contribution and the weighting factor of the rod component increase for lower luminance, as expected since the role of the rods becomes more important as luminance decreases. In the case of the 2-degree stimulus, the rods start to contribute only at the lowest luminance level and the effect of the rods is more significant for the 10-degree stimulus. At the highest luminance level, even the 10-degree stimulus does not have any rod contribution according to this analysis. Unlike α' or A_s/A'_T, the optimised surround lightness induction factor k' does not change very much.

Predicting Colour Appearance Phenomena

The performance of the revised lightness predictor J'_{p+s} was investigated, especially for prediction of the colour appearance phenomena observed in mesopic vision. Optimised parameters were used directly in the model for this task. No attempt was made at this stage to derive equations to fit the optimised values. Two colour appearance phenomena were considered in this study: (1) hue dependency of lightness change by stimulus size; and (2) Purkinje shift. Colour appearance phenomena found in the visual data were compared with the predictions of CIECAM02 and of the new lightness predictor J'_{p+s}.

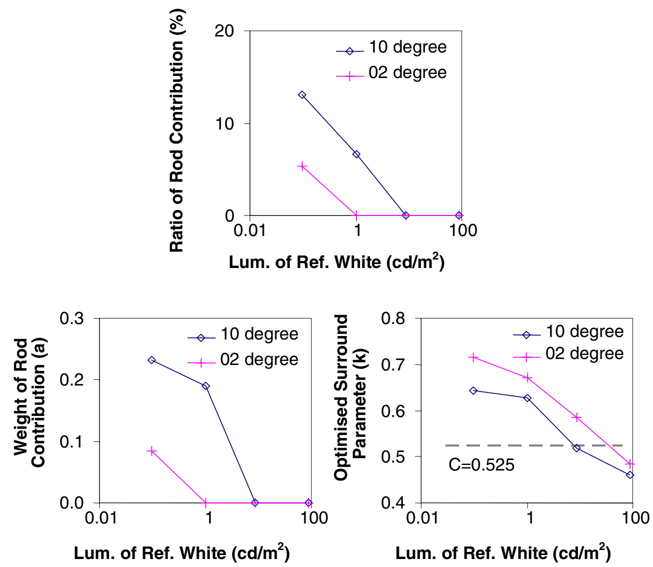

Figure 4. Optimised parameters in J'_{p+s} as a function of luminance of reference white (A').

Hue Dependency of Lightness Change by Field Size

The comparison of visual lightness data between two stimulus sizes at each luminance level showed a slight lightness increment for the 10-degree stimulus. In the diagrams of Figure 5, CIELAB L^* is represented together with visual data. CIELAB values were calculated using XYZ for the 2-degree patch and $X_{10}Y_{10}Z_{10}$ for 10-degree patch. Therefore comparing CIELAB values gives an indication of the performance of colour matching functions.

Another finding related to the lightness increment for the larger stimulus size was that it was hue dependent. The ratio of mean visual lightness for each colour between 10-degree and 2-degree stimuli was calculated and represented as a function of visual hue as shown in Figure 6a. Most points are located above 1.0 confirming generally higher lightness for the 10-degree stimulus. This effect became larger at lower luminance levels. Another distinctive feature is the much higher lightness increment for green-blue colours (hue range 200-300) than for other hues, especially for the Filter3 experiment.

Figures 6b and 6c show the predictions of CIECAM02 J and J'_{p+s}. There is a slight increment of the ratio in the blue region in the predictions of J but no other change is found in the green-blue region (Figure 6b). This change in blue colour arises from the difference between 2-degree and 10-degree colour matching functions rather than from some other characteristic in J. In the case of J'_{p+s} a similar trend with visual data was found in the predicted data (Figure 6c). There is a clear change in green-blue colours though the effect is smaller than for the visual data. It is found that both rod contribution to the achromatic signal and applying different surround lightness induction parameter values for different stimulus sizes are needed to predict hue dependency of lightness change. Rod contribution to the achromatic signal increases the lightness of 10-degree patches with green-blue hues, and lower exponents in the lightness predictor for 10-degree patches emphasise effect.

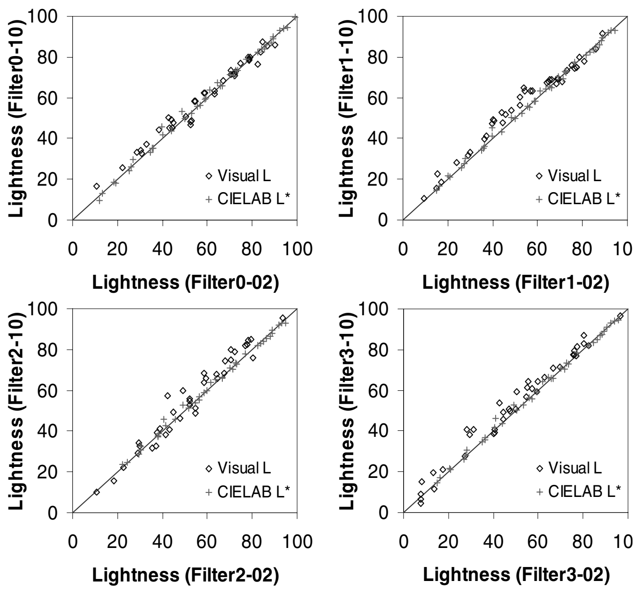

Figure 5. Visual lightness comparison between 2° and 10° patches

Prediction of Purkinje Shift

The Purkinje shift is the reduction in the perceived brightness of a predominantly long-wavelength colour stimulus relative to that of a predominantly short-wavelength colour stimulus, when the luminances are reduced in the same proportion from photopic through mesopic to scotopic levels, without changing the respective relative spectral power distributions of the stimuli involved.[5] This phenomenon may be explained by the change in peak spectral sensitivity toward shorter wavelengths during the transition from photopic to scotopic vision. It explains why blue objects that look darker than red objects in daylight tend to look relatively lighter at very low luminance levels.[6]

We investigated whether the Purkinje shift could be observed in the observer experimental data. Spectrally pure red and blue colours are expected to show the effect most effectively, and therefore the red and blue test stimuli of highest purity were examined. The digital input values to the display were (255,51,51) and (51,51,255) respectively for the Filter0 phase, and their average visual hues over all four phases were 6 and 304 for both 2-degree and 10-degree patches. The spectral power distributions of the test colours did change with luminance level because of the transmission characteristics of the neutral filter used to reduce luminance, but the change in visual stimulus was not significant.[1]

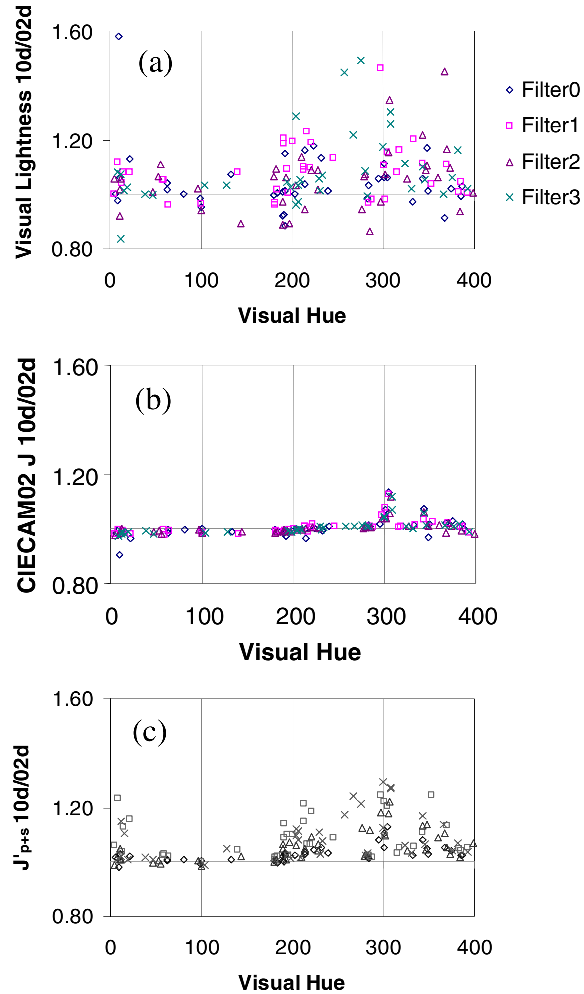

Figure 6. Hue dependency of lightness change by stimulus size and the predictions by J and J'_{p+s}

The top graphs in Figure 7 show the visual lightness changes of the red and blue colours for 2-degree (left) and 10-degree (right) patches. Both graphs strongly suggest the Purkinje shift. There is a greater degree of lightness change at low luminance levels for the red colour. The middle and bottom graphs show the predictions of J and J'_{p+s}. There is no difference between red and blue for J but a slight change is predicted by J'_{p+s}.

Another means of comparison was employed to demonstrate the Purkinje shift more effectively. The mean visual lightness of the blue colour was divided by that of the red colour to calculate the lightness ratio. It is clear from the results in Figure 8 that blue colours look relatively lighter (higher ratio in the diagram) as the luminance decreases, and this effect is more significant for the larger colour patches. The lightness predictor J in CIECAM02 completely failed to predict the Purkinje shift, because there is no ratio change by luminance level. The newly derived lightness predictor J'_{p+s} shows slight ratio increments at lower luminance levels but the predicted effect is smaller than found in the experimental visual data.

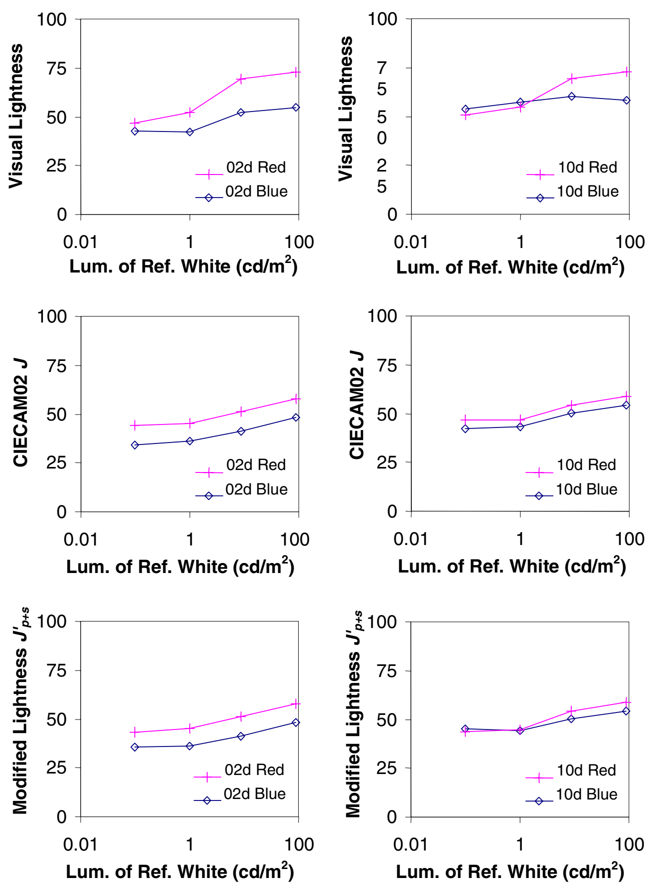

Figure 7. Lightness change of red and blue colours by luminance level.

The Purkinje shift can be predicted mathematically only when some rod signal is added into the achromatic signal, and the experimental evidence shown in Figure 7 and Figure 8 cannot be ignored. It strongly suggests that a rod contribution needs to be included in any colour appearance model to improve its performance at low levels of luminance. Under-prediction of the Purkinje shift in J'_{p+s} also suggests that the real rod contribution must be stronger than is predicted by Equation (4).

Conclusions

In this study a new lightness predictor J'_{p+s} was developed, based on the Hunt94 and CIECAM02 models, especially to give better predictions in mesopic vision and to compensate for change in lightness contrast by stimulus size. It was found that better results were obtained if the ratios between the three cone types (L,M,S) contributing to the achromatic signal were changed from 2:1:0.05 to 2:1:0.5. Also including a rod contribution in the achromatic signal helped to improve the performance at lower levels of luminance. It is important to compensate for change in lightness contrast by stimulus size by allowing the surround lightness induction factor to vary for 2-degree and 10-degree patches and as a function of luminance level.

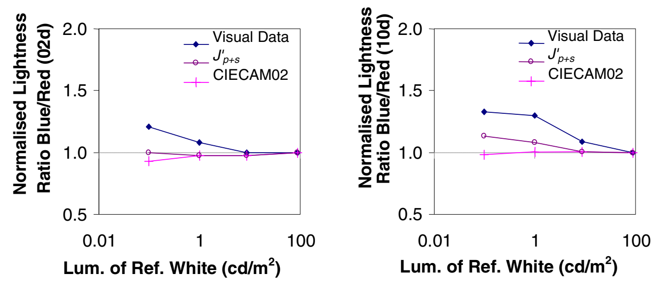

Figure 8. Normalised lightness ratio change of red and blue colours by luminance level.

The new lightness predictor J'_{p+s} showed better performance than J in CIECAM02 by predicting colour appearance phenomena in mesopic vision, including hue dependency of lightness change by stimulus size and Purkinje shift. These two phenomena can be predicted only when a rod contribution is included in the lightness predictor. The predicted lightness has decreased contrast for 10-degree compared with 2-degree stimuli, in agreement with the experimental observer data.

References

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Biographies

Youngshin Kwak received her BSc (physics) and MSc (physics) degrees in 1995 and 1997 from Ewha Womans University, Seoul, South Korea. From 1997 until 1999 she worked as a researcher at the Ewha Colour and Design Research Institute. In September 1999 she joined the Colour & Imaging Institute as an MPhil/PhD student. She completed her PhD study in July 2003 and joined the multimedia laboratory at Samsung Advanced Institute of Technology, South Korea. Her main research topics are colour appearance modelling and device characterisation.

Lindsay MacDonald is Professor of Multimedia Imaging at the Colour & Imaging Institute of the University of Derby in the UK. He is actively involved in many research projects related to digital imaging, and is leading the European project 'Veridical Imaging of Transmissive and Reflective Artefacts' (VITRA).

He has been co-author or co-editor of seven books in the past eight years on the subjects of colour, displays, interaction and digital imaging. He has been closely involved with the IS&T/SID Color Imaging Conference (CIC) since its inception in 1993, and this year he has been made a Fellow of IS&T.

M. Ronnier Luo is the Director of the Colour & Imaging Institute and Professor of Colour Science at University of Derby, UK. He received his B.Sc. in Fibre Technology from the National Taiwan Institute of Technology in 1981 and his Ph.D. in Colour Physics from the University of Bradford in 1986. He has published over 140 papers in the field of colour science. He is the chairman of the CIE TC 8-02 on colour differences in images and CIE1-52 on chromatic adaptation transforms.