Modelling the effect of simultaneous contrast on perceived whiteness

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Abstract
The perceived colour from a surface does not only depend on its optical properties and the illumination. Several studies have demonstrated the simultaneous contrast effect that makes the appearance of coloured patches depend on neighbouring colours. In this study the perceived whiteness of white patches surrounded by induction fields of different shades was evaluated by asking observers to give a magnitude estimate of perceived whiteness of the patches in comparison to a white reference. The perceived whiteness of patches with identical tristimulus values was highly dependent on the shade of the induction field and the patch size did not significantly affect the perceived whiteness. The recent CIECAM02-m2 colour appearance model was tested together with two whiteness equations. A combination of CIECAM02-m2 and a non-linear whiteness equation defined in the whole colour space predicted much of the observed simultaneous contrast effect. However, the model performed better for dark induction fields than for light induction fields. The model rated patches surrounded by light blue and light yellow equally, whereas the observers clearly rated the patches with light yellow induction field as whiter than the patches with light blue induction field. A deeper analysis of the CIECAM02-m2 model indicated that the simultaneous contrast model used cannot accurately predict the change in hue for high lightness induction fields. A potential improvement for predicting contrast simultaneous effect would be to base the calculations not only on the difference between the induction field and the background, but on the difference between the patch stimulus and the induction field.

Introduction
It is tempting to say that a certain wavelength of light or a certain object has a certain colour and then treat colour only as a physical quantity. However, a surface colour may change appearance depending on the illumination. This is why any colour measurement must be performed and communicated with a known illumination. Colour is a visual sensation that depends on three interacting components: the light source, the object, and the observer. Due to the complexity of the human visual system, several colour appearance phenomena that cannot be physically measured influence the way an observer perceives colour. One effect is simultaneous contrast that causes a stimulus to shift in colour appearance when the background or adjacent colours are changed.

This simultaneous contrast can affect the perceived whiteness of paper samples so that a pair of samples are ranked differently depending on the background and the shade of the other samples in the set to be evaluated. This means that perceived whiteness is a function of the illumination, background, and neighbouring colours. The perceived whiteness (of unprinted areas) will hence depend on what is printed. Since it is a simultaneous effect, the shade of the unprinted areas on the paper will also influence the appearance of the printed colours on the paper. It is therefore of interest to quantify and model the effect of simultaneous contrast on the perceived whiteness of printed papers and the effect of the shade of the unprinted paper on print quality.

The CIE recommended a whiteness equation in 1986 to be used with a D65 illumination. To prevent application of the whiteness equation to chromatic samples, the equation is only valid within given boundaries in the colour space. Replacing sharp limits with penalty functions, Uchida [1] and Coppel et al. [2] recently proposed non-linear whiteness equations that apply to the whole colour space. However, these models do not take simultaneous contrast into account and cannot predict the perceived whiteness of a surface surrounded by other colours (the induction field) and viewed against different backgrounds (the background).

Of the proposed colour appearance models (CAM), only the Hunt model [3] is capable of directly accounting for simultaneous contrast and assimilation effects. Hunt suggested that the chromatic adaptation process is influenced by the local colours of the induction field and background and proposed an algorithm for calculating the adjusted white point. A simplified version of the Hunt model, CIECAM02, was accepted in 2003 [4]. Since the simultaneous contrast prediction part showed poor correlation to visual assessment [5], the effect was not included in CIECAM02. Wu and Wardman [6] recently proposed a modification of the Hunt model in which the white point is modified differently for lightness than for hue and chroma. They reported that CIECAM02-m2 predicts the simultaneous contrast effect satisfactorily when applied to their own data set and to the LUTCHI data [5].

The present study aims at quantifying the influence of a coloured induction field on the perception of whiteness and testing the performance of the CIECAM02-m2 model for the prediction of perceived whiteness of two sets of samples consisting of a white patch surrounded by an induction field of varying colour.

Method
In a first magnitude estimation experiment twenty white 7 cm \( \times \) 7 cm square patches surrounded by different shades were printed on A5 sheets. In a second experiment a narrower whiteness span consisting of eight white patches with sizes 1.5 cm \( \times \) 1.5 cm, 4 cm \( \times \) 4 cm, and 7 cm \( \times \) 7 cm was used with 10 different induction fields. The samples were printed on 170 g/m2 Canon matt photo papers (MP-101) with a Canon BJ-C-8200 Photo inkjet printer.

The reflectance factor of the patches and induction fields was measured with a Photo Research PR-650 SpectraColorimeter under an overhead illumination having a correlated colour temperature of 5000 K. The same illumination was used for the visual assessments. Twenty observers participated in the first experiment and twenty new observers participated in the second experiment. All the observers scored within the average for colour.
discrimination in the Farnsworth-Munsell 100 hue and dichotomous tests for colour vision [7]. The samples were randomly presented one by one to the observers on a neutral grey table (Figure 1). The observers were instructed to report the perceived whiteness of the patch in relation to a reference white denoted 100 in perceived whiteness. If the observers perceived the patch to be half as white as the standard they had to report the value 50, if they perceived it to be twice as white they should report 200. The observers were seated at the table at a distance of 40 cm from the sample.

![Induction field](image)

**Figure 1.** Layout of the experiments.

The geometric mean of the 20 observers was taken as the rating of the whiteness of the patches. A total of 70 samples was evaluated in the first experiment. In the second experiment 120 samples were evaluated as well as 20 duplicates to check observer consistency. The observers had a break of approximately 15 minutes after 75 sample evaluations and, unaware of this, began the second session by re-evaluating the last five samples. In both experiments the observers were asked to only rate the white patches without paying attention to the fact that the patches were surrounded by different background colours.

**Colour appearance models**

CIE TC1-34 agreed on the following definition of a colour appearance model [4]: a model that includes predictors or at least the relative colour appearance attributes of lightness, chroma, and hue. For a model to include reasonable predictors of these attributes, it must include at least some form of a chromatic adaptation transform. This definition means that the CIE 1976 \( L' a' b' \) colour space (CIELAB) can be considered a colour appearance model since it includes a simple chromatic adaptation transform and predictors of lightness, chroma, and hue.

All CAM begin with the specification of the stimulus and viewing conditions in terms of CIE \( XYZ \) tristimulus values. At least the tristimulus values of the light source are required. More complex models will take as input the induction field, background, surround, and other spatial or temporal information. The first step in a CAM is a chromatic adaptation transform, which refers to the human visual system’s capability to adjust to widely varying colours of illumination in order to approximately preserve the appearance of object colours. The adapted signals are then combined, usually after the opponent theory of colour vision. These higher-level signals are then combined in various way to produce predictors of appearance attributes (such as lightness, hue, and chroma).

CIELAB is a well-established international standard that performs well as a CAM in many applications. The major limitations of CIELAB reported in the literature are due its simplified chromatic adaptation transform. Moreover, CIELAB cannot predict luminance-level dependency or cognitive effects, such as discounting the illuminant, which is important in cross-media colour reproduction. Neither does it provide correlates for the absolute appearance attributes of brightness and colourfulness. For applications restrained to reflective materials viewed in an average daylight illumination, the limitations discussed above are often not of concern. On the other hand, the lack of induction field-, background-, and surround dependency obviously makes CIELAB inadequate for our purpose.

Of the numerous CAM proposed over the years, only the Hunt model is capable of directly accounting for simultaneous contrast. Hunt suggested that the chromatic adaptation process is influenced by the local colour of the induction field and background in addition to the colour of the reference white. He proposed an algorithm for adjusting the reference white signals from the cone responses of the background and induction field

\[
R'_w = R_w [(1 - p) p_R + (1 + p) / p_R]^{1/2},
\]

\[
G'_w = G_w [(1 - p) p_G + (1 + p) / p_G]^{1/2},
\]

\[
B'_w = B_w [(1 - p) p_B + (1 + p) / p_B]^{1/2},
\]

where \( R_w, G_w, B_w \) are the cone responses for the reference white, \( R_p, G_p, B_p \) from the induction field, and \( R_b, G_b, B_b \) from the background, \( p \) is taken to be between 0 and -1 when simultaneous contrast occurs, and

\[
p_R = R_b / R_w,
\]

\[
p_G = G_b / G_w,
\]

\[
p_B = B_b / B_w.
\]

The value of \( p \) will depend on the extent of the simultaneous contrast effect. If the stimulus viewing area is large, no simultaneous contrast will occur, and if the stimulus viewing area is small, the \( p \) values will go towards -1.

One problem with the Hunt model is that it cannot be easily inverted. Wu and Wardman [6] recently proposed to implement the Hunt algorithm for simultaneous contrast in the invertible CIECAM02 model. This is done by calculating the different cone responses needed, modifying the cone response of the reference white, and transforming this adapted signal to the adapted tristimulus values for the reference white before applying the CIECAM02 chromatic adaptation transform (Figure 2). Wu and Wardman showed that the simultaneous contrast effect is larger on lightness than on hue and chroma and suggested that a smaller \( p \) value should be used for hue and chroma calculation than for lightness calculation. With this CIECAM02-m2 model the lightness \( J \), hue \( h \), and chroma \( C \) of the stimulus can be computed from the tristimulus values of the background, induction field and stimulus. Since there is no accepted whiteness model based on these attributes, we propose then to compute the tristimulus values of the stimulus as if it were seen on a neutral background and to apply established whiteness equations on these adapted tristimulus values (Figure 3). The CIE whiteness equation, \( W_{CIE} \).
applied with the 5000 K illumination disregarding its limits of application, and the non-linear whiteness equation proposed in [2], $W_{\text{NEW}}$, were applied. $W_{\text{NEW}}$ is defined in the whole colour space and uses penalty functions instead of the sharp CIE whiteness boundaries.

Figure 2. Scheme of the CIECAM02-m2 colour appearance model. CIECAM02 is applied after modification of the white point with the Hunt algorithm. Different $p$-values are applied for lightness ($p_1$), and for hue and chroma ($p_2$). CIECAM02-m1 corresponds to $p_1 = p_2$.

Results and discussion

Observer consistency

The inter-correlation between observers was low ($R = 0.5$ in the second experiment), which is common for the evaluation of whiteness. As shown previously in [2] observer inter-correlation is often low but the mean ratings of different groups often correlate well. This implies that many observers are required to get a significant rating of the perceived whiteness. However, the mean whiteness difference between identical samples evaluated before and after the break was 6 units with only 2 observers having an average difference larger than 10, and the mean rating difference for the 20 duplicates was 8 units with 4 observers having a mean difference larger than 10. This relatively good observer consistency suggests that low inter-correlations are due to different observer preferences.

Parameter estimation

CIECAM02-m2 was tested for different values of $p_1$ (lightness) and $p_2$ (hue and chroma). The correlation coefficients ($R^2$) between rating and predicted whiteness with $W_{\text{NEW}}$ are shown in Figures 4-5. Similar curves were obtained when applying the CIE whiteness equation. A higher correlation was obtained for the first set, which spans over a larger whiteness range. The first case, $p_1 = p_2$, corresponds to CIECAM02-m1 where lightness, hue, and chroma are computed with the same modified white point. As proposed by Wu and Wardman, the results confirmed that hue and chroma are not affected as much as the lightness by an induction field and that different $p$ values should be used. For the second set the best correlation was obtained for $p_2 = p_1/8$ as obtained by Wu and Wardman but for $p_1 = -0.25$ whereas Wu and Wardman obtained $p_1 = -0.4$ for patches of size $2^\circ$, corresponding to the smallest patches in this study. However, Wu and Wardman performed their experiment on CRT display at lightness values ranging for 20 to 100. Moreover, the correlation they obtained between computed lightness and perceived whiteness for $L^*$ between 80 and 95 was actually better for $p_1 = -0.25$.

Simultaneous contrast effect on perceived whiteness

The patches were rated differently depending on the induction field. They were perceived whiter, the darker and more yellowish the induction field. The mean whiteness rating difference was up to 15 units between a patch surrounded by a blue or yellow induction field (Figure 6a). Lighter induction fields had a larger influence on the perceived whiteness of the patches in the

![Figure 3. Scheme for calculating the perceived whiteness of a stimulus viewed on a background with a induction field.](image)

![Figure 4. Correlation coefficient ($R^2$) between rating in the first experiment and calculated whiteness for different values of $p_1$ in the CIECAM02-m2 model. $p_1 = p_2$ corresponds to CIECAM02-m1.](image)

![Figure 5. Correlation coefficient ($R^2$) between rating in the second experiment and calculated whiteness for different values of $p_1$ in the CIECAM02-m2 model. $p_1 = p_2$ corresponds to CIECAM02-m1.](image)
second experiment (Figure 7a). The induction field had a large effect on perceived whiteness but the patch sizes used in this experiment did not have a significant effect.

Patches surrounded by light induction fields were ranked the least white. Due to induction effects these patches are perceived less white when viewed with the surrounding induction field than when viewed alone on the grey table. Patches with the same appearance on the grey table would thus have lower lightness values.

**Whiteness models**

The performance of the two whiteness models applied on the adjusted tristimulus values obtained from CIECAM02-m2 with $p_1 = -0.25$ and $p_2 = p_1 / 8$ were compared. For the first set of samples, the correlation between perceived and predicted whiteness was high for both $W_{CIE}$ and $W_{NEW}$ (Figure 6b-c). However, in the whiteness range above 80 the correlation was higher with $W_{NEW}$ ($R^2 = 0.66$) than with $W_{CIE}$ ($R^2 = 0.35$). $W_{NEW}$ performed also better ($R^2 = 0.53$) than $W_{CIE}$ ($R^2 = 0.44$).
low induction fields. Since the L\* values are slightly higher for both the light blue and the light yellow induction fields, this indicates that CIECAM02-m2 fails to predict a blue induction field as whiter than the patches with light light blue induction field (Figure 9). However, the corrected b\* values are perceived bluer with a yellow induction field and yellower with a blue induction field (Figure 9). It should be noted that the Hunt algorithm used in the CIECAM02-m2 model does not take the patch stimulus as input to calculate the modified white point due to the induction field. Thus the simultaneous contrast effect is predicted only from the difference between the induction field and the background table. A light yellow induction field has a larger Z value and hence a larger B cone response than the background. Thus B_p > B_b in this case and the Hunt model adjusts the white point to a larger Z_m, i.e. bluer (Equation 3). Therefore the model predicts that a patch appears yellower when it is viewed with a light yellow induction field, which contradicts the visual experiments. This observation suggests that a better model for predicting contrast simultaneous effect should be based on the difference between the patch stimulus and the induction field.

Conclusions and suggestions for further work

Patches with identical instrumental whiteness were rated more or less white depending on the colour of the surrounding induction field. The perceived whiteness of a white patch surrounded by light blue was up to 30 units lower than the perceived whiteness of the same patch viewed with a grey background. The induction field had a large effect on perceived whiteness but the patch sizes used in this study did not have a significant effect on perceived whiteness. Hence the same p values were used for all patches and optimised to get the best fit between predicted and perceived whiteness. The best results were obtained for p_1 = −0.25 and p_2 = p_1/8 (one eighth of p_1 as proposed by Wu and Wardman).

The results showed that a combination of CIECAM02-m2 and a non-linear whiteness equation defined in the whole colour space explains much of the observed simultaneous contrast effect. The model predicted well the lightness simultaneous contrast effect but failed to predict the more bluish perceived colour of a white patch surrounded by a light yellow induction field. This discrepancy was shown to depend on the fact that the Hunt model used to model the simultaneous contrast effect only takes background and induction field as inputs. This suggests an improved model in which the white point is modified depending on the difference between the tristimulus values of the patch stimulus and the induction field.
Future work should include larger and smaller patches and induction fields and develop a new model based on the difference between the tristimulus values of the patch and the induction field. Different configurations with e.g. the induction field in the middle of the sample would be a step towards more complex situations like a typical magazine page. This study clearly shows that the perceived whiteness of paper will be dramatically changed when the paper is partially printed. A refined model will allow predicting the noticeable whiteness difference of paper printed with different images and designing paper for print reproduction rather than for unprinted whiteness.

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References

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