COLOUR APPEARANCE MODELLING

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Abstract: At TAGA 1989 a paper was presented discussing the preliminary findings of an experiment to evaluate models for colour appearance. Since that time we have completed the data analysis and confirmed that both Hunt and Nayatani models do not perform particularly well, principally with respect to lightness predictions. The Hunt model has been modified in the light of these findings and a significant improvement in prediction is demonstrable. The revised model is now believed to be a good predictor of appearance and is being used to produce colour matches between colour monitor and print for five different conditions of viewing. Those viewing conditions consist of four levels of chromatic adaptation, one of which (D5000) has white and black borders around the page.

The matching has necessitated converting tristimulus data to CMY dot area or density for a variety of output devices. The problems of achieving this will be reviewed and techniques used in this project described.

A new program of work has been initiated to follow on from this initial study which will extend the range of viewing conditions to include transparency samples and expand on the range of illumination levels. The work proposed for this extension will be briefly reviewed.

Introduction

A paper was presented at TAGA last year, Johnson (1989), outlining the potential advantages of colour appearance modelling to the Graphic Arts Industry. It was suggested that such techniques could provide the foundation for a definition of optimum colour reproduction. Work was in hand at that time to evaluate two appearance models which had

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been proposed by Hunt and Nayatani and preliminary results were discussed. The work has now been completed and in part 1 of this paper last year's report is updated. A further work programme is now commencing to extend the range of viewing conditions investigated. The data obtained so far covers colour monitors and reflection materials but needs extending for transmissive materials. Also the range of illumination levels for reflection copy was small. For general applications this needs to be extended. A brief description of the work proposed is given later.

The appearance modelling work was, however, only part of the project. The overall objective was to demonstrate a system in which hard copy output from a proofing system had the same colour appearance as a monitor under various viewing conditions. This necessitated converting tristimulus values derived from the appearance model into colorant amounts and vice versa. Such work is very relevant to the current standardisation efforts in colour data exchange. Part 2 of this paper consists of a discussion concerning the advantages and disadvantages of various methods to achieve conversion and how it was undertaken for this project.

Part 1 - Optimising Colour Reproduction with Appearance Modelling

Evaluation of Appearance Models

It was shown in last year's TAGA paper that neither the Hunt nor Nayatani models succeeded in satisfactorily predicting lightness when compared to our database. Figure 11 from that paper showed a performance very similar to L* and this was significantly different from the lightness obtained with our scaling experiments. In the Hunt model the correlate of brightness Q of a colour is a function of a parametric constant Nb, the value of which depends upon the inducting field. Hunt proposed values for Nb ranging from 400 for small areas of colour seen in a uniform white background to 10 for colours seen in pictures projected in dark backgrounds. 100 was suggested for reflecting colours in normal scenes. Since this was the only parametric constant which could be modified without affecting any other of the perceptual functions it was adjusted in our evaluation to improve the fit of the data. This was shown in figure 12 of last year's paper where a value of Nb = 900 was used. This was of some concern since it was contrary to earlier studies, in which brightness scaling was undertaken, and we could not, by adjusting Nb, provide a fit to Bartleson's brightness data at the same time as matching our lightness data.

Hunt (1989) has now proposed a modification to the lightness calculation based on the scaling data obtained in our experiments which resolves this difficulty. Lightness is, of course, a derivative of brightness defined as the brightness of an area judged relative to that of a similarly illuminated area which appears white. Generally a simple relationship is assumed and hence lightness is expressed as:

$$J = 100\ (Q/Q(W))$$

where Q and Q(W) are the correlates of brightness for the colour and the reference white respectively.

This equation had been used in the original model but it is now proposed that lightness be expressed as:

$$J = 100\ (Q/Q(W))^{n}$$

where $n = 1+(Y(b)/Y(W))^{0.5}$ for luminance factors of Y(b) for the background immediately surrounding the colour and Y(W) for the reference white.

It is clear that this new model has no effect on the correlate of brightness; that is unaltered. Thus it retains the fit to the earlier proposals of Bartleson (1980). At the same time it produces excellent predictions of our scaling experiments. Despite this we believe that this is an area worthy of further investigation since it is debatable whether brightness and lightness can be non-linearly related in this way. In our future work we plan to gather data for both correlates in order to confirm this part of the model.

Other parts of the Hunt model have been modified in his latest paper to provide a better balance between the contributions from rods and cones. The model has been adapted such that at photopic levels of illumination the perceptual correlates of hue, saturation, colourfulness and brightness are largely unchanged from the previous model but predictions are significantly improved at scotopic and mesopic levels. This is probably of little significance to our viewing conditions, however.

In last year's paper it was shown that the Hunt model had a significantly improved coefficient of variation for lightness, when the induction factor Nb was modified as described earlier. That data is repeated below as table 1 with the addition of the Hunt '89 data. The ACAM model is that with the modified Nb described last year and should not be confused with the Hunt-ACAM model described later which is based on the Hunt '89 model, but with a minor modification for colourfulness to improve the fit to our data.

Table 1

Summary of Lightness Performance Using Mean CV Values

Experimental Type	I	II	III	Overall Ranking
No. of Phases	3	3	5	
CMC	66	30	39	6
CIE 1976	41	13	18	3
Nayatani	45	15	20	4
Hunt '87	47	16	24	5
ACAM	19	11	11	2
Hunt '89	14	10	10	1

Type I results:	the mean CV values calculated from white surround phases
Type II results:	the mean CV values calculated from black surround phases
Type III results:	the mean CV values calculated from all grey surround phases.

It is clear from these results that the new Hunt model provides a significant improvement in lightness prediction over the previous model and is now producing coefficients of variation which are deemed very acceptable. Figures 1-4 show the correlation between our visual results and those predicted by the Hunt-ACAM model (based on the Hunt '89 model) for phases 2, 5, 8 and 10 of the 23 phases of the experiment listed in table 1 of last year's paper. These have been selected as being of particular importance to the graphic arts industry and are summarised in table 2. It can be seen that the most significant deviations occur at the higher illumination levels; for the three lower levels all results are generally very consistent. In the next phase of the study we plan to increase our database at high levels of illumination which will enable us to see whether further modifications to the model can improve it further and confirm whether colourfulness is as difficult to scale at high levels as our initial experiments suggest.

Table 2

Phase	2	5	8	10
Illuminant	D50	D50	D50	D50
Luminance Level (cd/m^2)	High (252.0)	Low (42.2)	Low (44.5)	Low (44.5)
Surround	Grey	Grey	Grey	Grey/White border
Mode	Non-luminous	Non-luminous	Luminous	Luminous
No. of Colours	105	105	100	100
No. of Obs.	6	6	6	6
No. of Estimations	1890	1890	1890	1890

Colour Match Prediction

Having produced an acceptable colour appearance model the next stage of the work was to test it for colour reproduction purposes. By definition such a procedure has to be subjective so the results cannot be quantified by any colour measure.

The general matching procedure is shown in figure 5. It can be seen that four transforms are involved. T(1) and T(4) are conversions to or from device dependent data into a colorimetric data set, T(2) and T(3) are conversions from the psychophysical data to psychoquantitative parameters Hue, Chroma and Lightness. The latter transforms are defined by the Hunt-ACAM colour appearance model described earlier and it's inverse. Obviously the parametric constants in the model can be defined for any specific viewing condition. Thus it is possible, for example, to define a colour match between a sample seen in one state of chromatic adaptation, or surrounded by a white or black border and a matching sample seen in another surround or adaptation state. Clearly the psychophysical (and hence psychometric) measure of each sample will be different if they match. The matching criteria is that H, C and L are identical.

The model was used to test the appearance modelling routines for four states of chromatic adaptation. A series of three-colour proofs were made and viewed under illuminants approximating to A, D50 and D65; together with a white fluorescent illuminant having a colour temperature of approximately 3500 kelvins. The white points of the four illuminants were measured spectroradiometrically and the tristimulus values of the proof calculated for each pixel using the transform T(1). The Hunt-ACAM model T(2) was then used to calculate Hue, Chroma and Lightness for each point of the image for each of the illuminants.

We considered various options for primary evaluation of the model; the choice of option is to a large extent governed by the factors which one wishes to evaluate. For example, if we are interested in chromatic adaptation predictions then the image can be viewed under one illuminant and the reproduction (predicted via the model) viewed under another. If interested in the effect of background induction then the image and reproduction can be viewed with each having different backgrounds and a judgement made on how well the model predicts a match. If the model works we should also be able to combine different influencing factors and still obtain a colour match. Ideally we would have tested the system for each of those conditions, independently and combined, but practical difficulties and, more importantly, time prevented us from doing this. We therefore chose to consider only the situations which are of particular practical importance to us and defer the others until later. Basically we restricted our inverse transform to take account of the changes in appearance obtained when viewing colours on colour monitors compared to prints. This latter difference was discussed in last year's TAGA paper and since the predominant change is in lightness it is critical to obtaining good tone reproduction.

For each of the chromatic adaptation conditions the XYZ values, under the illuminant approximating to D50, were predicted from T(1). The forward colour appearance model was then used to correct for the illuminant which effectively tests the chromatic adaptation part of the model. The resultant psychoquantitative HCL data was converted back to psychophysical data using T(3) but modifying the parametric variables associated with lightness induction to take account of the differences in viewing condition. The monitor RGB values were then predicted by T(4). For all states of chromatic adaptation a reasonable tonal rendition was achieved but it was certainly not ideal.

Overall the colour match between proof and monitor was as good as I have seen on any system with no subjective "tweaking" of the colour transform. However, some of that improvement was undoubtedly attributable to the transforms T(1) and T(4) and only partly from the colour appearance model. (These transforms will be discussed in part 2 of this paper). Certainly the modification to lightness as predicted by the model produced a significant improvement against that with no correction but it was still a little disappointing. The reasons for this are still being investigated but are most likely due to the influence of flare conditions, one of the most significant problems in colorimetry when applied to colour appearance.

What was quite impressive was the accuracy of colour match, showing the effectiveness of the chromatic adaptation routines. Nevertheless, some problems still remained particularly with the low colour temperature reproductions. The main problems arose in the reproduction of dark neutrals under these conditions; in general they lacked red. These errors could be coming from a number of sources; the chromatic adaptation routines used in the model, the Helson-Judd correction or the flare correction, used to correct for lightness, described in part 2. Such errors are unlikely to be from T(1) or T(4), particularly since the colour errors for D50 and D65 were small. This implies that the errors probably correlate with the magnitude of chromatic adaptation correction in T(2).

Some different colour problems arose from errors in the transform T(1). This had been established at the start of the project using a cromalin proof. When reproductions made some 2 years later were used for the evaluation it quickly became clear that our proofing characteristics had changed significantly. We therefore tried to correct the database to take account of this as will be described in part 2. Having done this the "match" was altered but not significantly improved.

All these problems, whilst relatively minor practically are clearly of theoretical interest and hence are still being investigated.

The other colour problems which arose were from gamut differences, particularly trying to display images viewed under illuminant A on the monitor. However, we made no attempt in this work to correct for that, this study is part of our next phase of the work.

In summary, therefore, we can conclude that overall the colour match between proof and print was as good as we have ever seen from the models currently in use in the industry. The major problems arising came from significant chromatic adaptation corrections which would not normally be required in practice. Thus the model can be said to perform well. However, this performance is obtained at the expense of considerable computational complexity and it is desirable that the remaining inaccuracies be reduced further to fully justify this computation. Further work is in hand to investigate both the colorimetry and the appropriate parametric constants and determine precisely where the errors are arising. Essentially we are moving from the macro to the micro analysis of appearance models. We have demonstrated that they provide a significant improvement over conventional colorimetry in optimising colour reproduction but have yet to show that they can fully replace the empirical techniques which have been developed over many years. The signs are promising but the case is, as yet, unproven. However, we are encouraged enough to significantly increase our effort in this area over the next few years.

Future Work

The evaluation of appearance models to date has been somewhat limited. We initially restricted ourselves to the matching of monitors and prints and by so doing were able to ignore high levels of illumination and problems of gamut compression without significantly influencing our judgements. However, to quantify a total system we cannot be so restrictive. We are therefore embarking on a further 3 year study in which the database will be enlarged to cover high illumination levels (this will also encompass photographic transparencies and prints viewed under ISO viewing conditions and brighter). Such conditions make it essential that we can model preferred gamut compression in colour appearance domains which is another key part of our study. In addition we will continue to investigate the sources of errors described earlier to establish to what extent they can be minimised.

Part 2 - Device Calibration (Colour to Colorant Conversion)

Conventional Methods

Historically colour conversion in the graphic arts industry has been empirically defined. Colour separation filters have been selected which largely fall within the primary absorption bands of the three dyes in the original (hence minimising crosstalk between channels) and these are reproduced directly as ink amounts. Differences in colour between the two colorant sets are corrected by empirically optimised equations in a scanner which are also used for achieving gamut compression between original and reproduction. The data defined by the scanner used in virtually all conventional graphic arts systems are therefore the amounts of each of the four inks (CMYK). The colour is never defined directly; it is implicit in the method used that colours in the original will be matched in the reproduction but only because the colorants for both are similar. Deviations from this may well lead to severe differences in colour which are corrected by "tweaking" the empirical correction routines to add ink amounts which are weighted locally in different regions of the "colour" space defined by the reproduction colorants.

Various attempts have been made to define mathematical models for colour reproduction which are not empirically optimised but based on a physical model. The best known are the Neugebauer and Masking equations. The latter have been extended beyond a simple physical model to try to correct for errors and can be defined as a set of polynomial equations of order n which are determined by finding the best fit to a finite number of points in colour space. However, the special case of first order equations can be solved algebraically if additivity and proportionality behaviour is assumed for density values as the simple model suggests.

The Neugebauer and Masking equations have significantly different theoretical bases. The former assumes an additive mixture of eight randomly distributed colours derived directly from the halftone structure which are integrated by the eye. The latter is based on the subtractive behaviour of the inks. Thus the former uses reflectance values to compute ink amounts; the latter densities. However, it should be noted that the spectral characteristics of the scanner used to determine these values need not be colorimetric; similarity of colorants still enables us to use these models with any reasonable spectral sensitivity although the scope for empirical correction is generally much lower than for typical scanner equations when the colorant match is different.

An alternative technique for defining the relationship between the tristimulus values (colorimetric or otherwise) is the approach proposed by Korman and Yule (1971) which involves measuring the 512 colours arising from printing eight levels each of Cyan, Magenta and Yellow in all combinations. This is then used to define a look-up table relating dot percent to reflectance (or density) for each point. Intermediate colours are then determined by interpolation. To achieve this it is simplest to use the scanning device as the measuring instrument since that eliminates errors attributable to different measuring instruments.

There are distinct advantages and disadvantages to each of these methods. Empirical controls are, by definition, user-friendly. They must have some reasonable meaning to the operator if they are to be of any value. On the other hand optimising them is generally an iterative process and does imply a modicum of skill for good matching with no artefacts such as contouring.

Mathematical models are unambiguous and, if accurate, better suited to an automated environment such as Desk Top Publishing. However, they are all based on measuring a limited number of colours and trusting that the hypotheses defining the models are reasonable. If this is not the case substantial colour errors can be expected. This can clearly be overcome by interpolation between a larger number of colours at the expense of measurement complexity. Clearly if this can be automated by undertaking it on the scanner it appears to be a highly practical method. The practical problem associated with this method is that of printing the chart consistently for the range of substrates, inks, etc which may be encountered and repeating it if any of these change. Empirical methods can generally handle this relatively easily.

Colorimetric Conversions

It was stated earlier that the procedures described above are all applicable to <u>any</u> spectral sensitivity if the colorants of original and reproduction are similar. However, this is correct <u>only</u> if the conditions of viewing are similar also and the gamut of the reproduction encloses that of the original. If the former is not the case we are faced with the appearance difficulties defined earlier and for the latter we need to compress the gamut in some defined way. Clearly appearance modelling should minimise these problems but it is necessary to then recognise the need to convert tristimulus values into ink amounts and this is quite different to the conventional scanner routines which are optimised around the spectral sensitivity of the scanner. Demonstrating the advantages of appearance modelling therefore raised a question; how should we best undertake colour conversion?

Empirical matching was clearly not desirable; the principal objective of the work was to define a method independent of any subjective assessments. We were therefore faced with the choice of trying to model the performance of our devices (hard copy and monitors) or using the look-up table approach. We chose the latter.

One of the principal reasons for this lay in some work undertaken by Pira, part of which was published by Birkenshaw et al (1985). The primary objective of that work was to evaluate mathematical models for just such conversions; how given a set of colorimetric tristimulus values would we best convert them to ink amounts? A number of models were evaluated. Four printing conditions were chosen and a set of 112 combinations of ink colour were measured for each of these conditions. Included in the set of colours were the calibration colours for all of the models evaluated.

The evaluation was based on the RIT Printing Ink Gamut chart of Elyjiw and Yule (1970) and thus provided most combinations of 0, 25, 50, 75 and 100% dot areas. The colours including black ink were ignored for this study.

The models evaluated included first and second order masking equations; the former being solved algebraically from the densities of the three solid inks, Yule (1938), and both being computed, as suggested by Clapper (1961), from a least squares fit on 27 colours. An alternative correction to the first order equation was attempted by correcting for additivity and proportionality failure which are generally both present in a halftone image. This involved measurement of an additional 15 colours above that for the first order calculation. Proportionality failure was corrected with and without iteration in the calculation and was established from the five single ink values. Additivity failure was modelled by the behaviour described in Yule (1967) by which overprinted colours are defined by the function:

$$y = a + b - (kab)$$

where a and b are the densities of the two inks respectively and k is the reciprocal of the convergence point postulated in this model. The correction was evaluated with k optimised for each ink combination and also as the mean of the individual ones.

Neugebauer equations were evaluated using a variety of n correction factors as proposed by Yule and Colt (1951). Each was combined with the same Yule-Nielsen factor for defining dot area, Yule and Nielsen (1951).

Table 3

	CYAN		MAGENTA		YELLOW	
	MAE	VAR.	MAE	VAR.	MAE	VAR.
Algebraic	4.28	59.84	7.65	166.66	10.40	292.35
1st Order	4.64	44.40	7.13	102.75	10.93	224.78
2nd Order	1.66	5.07	4.15	52.47	4.73	62.82
Prop. Corr. (no iteration)	3.01	43.63	6.67	144.70	10.19	286.51
With Add Corr. 1	2.75	35.69	6.91	149.36	5.86	107.00
With Add Corr. 2	3.11	32.66	6.05	123.27	4.71	72.72
Prop. Corr. (with iteration)	2.98	44.00	6.70	146.23	10.25	288.28
With Add Corr. 1	2.73	35.45	6.95	151.35	5.87	107.50
With Add Corr. 2	3.04	31.47	6.03	123.26	4.68	72.03
Neugebauer						
(N = 1)	1.30	3.66	1.96	6.68	3.01	21.12
(N = 1.65)	1.60	4.77	2.18	7.45	3.56	30.66
(N = 2.0)	1.80	5.77	2.23	8.14	3.78	35.83
(N = 2.05 etc)	1.78	5.86	2.15	7.90	3.71	33.30

Table 3, taken from Birkenshaw et al (1985) is fairly typical of the results found. The mean absolute errors in dot area calculated and the resultant variances are given for each of the inks. It is clear that the second order equations perform better than any other masking equation derivative but not as well as the Neugebauer equations. In general the prediction of Yellow was least accurate although the exception was for a set of data for an uncoated paper.

What is not shown in this data is the regions in which errors were arising. The figures are for absolute error and are not proportional to the original error. Thus a 5% error on a highlight dot is given no greater significance than for a shadow dot. When the results were weighted it generally caused the Neugebauer results to worsen and the high order masking equations to improve. Thus, as a general rule the Neugebauer equations tended to suffer from significant errors at the highlights but generally provide reasonable predictions in the middle to full tones whereas for the masking equations the reverse was true. Such findings are borne out by practical experience.

Clearly there are many ways of improving these models; some have been reported in the literature (e.g. Laihanen (1987), whereas others are deemed proprietary and have not. Unfortunately they generally require more measurements to be carried out which tends to reduce the advantages of such methods when compared to the Korman-Yule method.

In the light of these errors for halftone processes, and bearing in mind that we would also be attempting to characterise the performance of non-halftone devices in this work, we opted for the Korman-Yule approach. Our normal matrix size in such work would be 16x16x16 levels of each of the three primary colorants, producing 4096 points in colour space. Where such images can be scanned and automatically calculated such a matrix size is quite straightforward but we were not able to do that. We had to rely on conventional colorimetry which is tedious and for our Bentham telespectroradiometer requires fairly large areas. We actually did most of the measurements on a Macbeth spectrophotometer but needed squares of about 1 inch width for our calibration to the telespectroradiometer. The combination of size (bearing in mind the requirement to include small A4 printers) and measurement time led us to compromise on a smaller matrix of 9x9x9. Levels equivalent to dot percents of 0, 5, 10, 20, 30, 40, 60, 80 and 100 were selected. The higher precision at the highlight end was selected because of practical experience with such techniques; maintaining highlight accuracy is generally important in colour reproduction in order to ensure good modelling is achieved.

The correction for converting spectrophotometric data to telespectroradiometric data is interesting and is of significance to our appearance data also. The problem is that conventional colorimetry is based on viewing conditions which are wholly unreal (0/45, 0/d, etc). Tele-colorimetry is quite different; here the eye is replaced by the measuring device in a real environment where more flare is present. Because conventional measurment was simpler for reflecting samples we measured all our samples on the Macbeth and a few were also measured on the Bentham Telespectroradiometer. We hypothesised that the flare correction would be equivalent to adding white light and derived a function to achieve this, based on measurements of a number of grey colours made on both instruments. A function of the form:

$$y = 1.27 + 0.9068\ x + 0.0022\ x^2 - 0.0000\ 1395\ x^3$$

was used where x is the Y tristimulus value. Obviously the X and Z weightings were modified to take account of the X:Y:Z ratios of the illuminant. This we refer to as a flare correction. Clearly, since our appearance data was based on Bentham measurements they should have the inverse of the flare correction applied if we wish to compare them with conventional measurements.

For the transform from XYZ to RGB we considered using a simple 3x3 matrix obtained from the assumption that the monitor is linear. However, it is known that internal flare and crosstalk cause deviation from this behaviour so we also used a similar matrix approach for the monitor transform.

At the start of the project we decided to concentrate on Cromalin proofing as our main output media although the Iris ink jet proofer was also included. The 9^3 colour chart described above was therefore produced and the transform from CMY to (flare corrected) XYZ established. At the conclusion of the project we needed to compare proofs and monitor images and for this purpose proofs of new images were made. The first results were very disappointing and investigation quickly showed a significant difference between proofing characteristics. Both were within our normal tolerances but these had accumulated in such a way to produce excessive changes in colour.

Clearly such problems are significant in defining transforms based on measuring a large number of colours without any usable physical model. Unfortunately printing and proofing are rarely stable enough to permit a single printed sample to be representative of the process as a whole; great care needs to be taken that any such print is the mean of the process and this is frequently not done as is clear from the discussion above! One of the major advantages, in practice, of empirical techniques is that they permit simple modifications to be made to the colour transform as changes to ink, paper or press conditions arise in the field.

In order to minimise the effects of this problem we used Neugebauer equations to compute the colour change required to our database. As noted earlier the absolute accuracy of these equations leave a lot to be desired. However, for computing colour differences we believed they would be quite adequate. For each of the sets of primary colours we therefore computed the tristimulus values for each of the 729 colours and noted Delta X, Delta Y and Delta Z. These were then added to the original database. 36 of the colours used were reproofed and remeasured and these values compared to the original and corrected database. The average CMC Delta E value was reduced from 5.6 to 1.6 by this method.

Conclusions

In converting CMYK values to colorimetric tristimulus data the usual mathematical models generally produce errors which are not acceptable for graphic arts quality levels. Proprietary corrections to these models are, however, used successfully and hence provide a usable tool for such conversions. It seems reasonable therefore to propose a "colour transform field", based on samples needed for these models, which can be communicated to systems who require to undertake the conversion as is currently being discussed by the IT8 committee.

Within a system which is well calibrated throughout an alternative approach is to produce default data sets which define that system. SWOP or FIPP standards are such examples. Defining such conversions from the mean SWOP or FIPP print condition to tristimulus values is not unreasonable but they represent only a limited part of the printing industry output. Defining tables for a wider range of print conditions is a more daunting task.

Even if such definitions are deemed manageable standards can change, wittingly or unwittingly. For example, in my experience few yellow inks in use today come anywhere near conforming to ISO 2846. Thus definitions based on an out of date standard may be quite inadequate. However, a combination of such a definition together with data taken from a "transform field" transmitted with an image would permit a correction to the database which is relatively simple to implement using one of the regular mathematical models.

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Figure 1 - Comparing visual scaling data against Hunt-Acam predictions

(Non-luminous samples - High illumination level (252 cd/m^2)

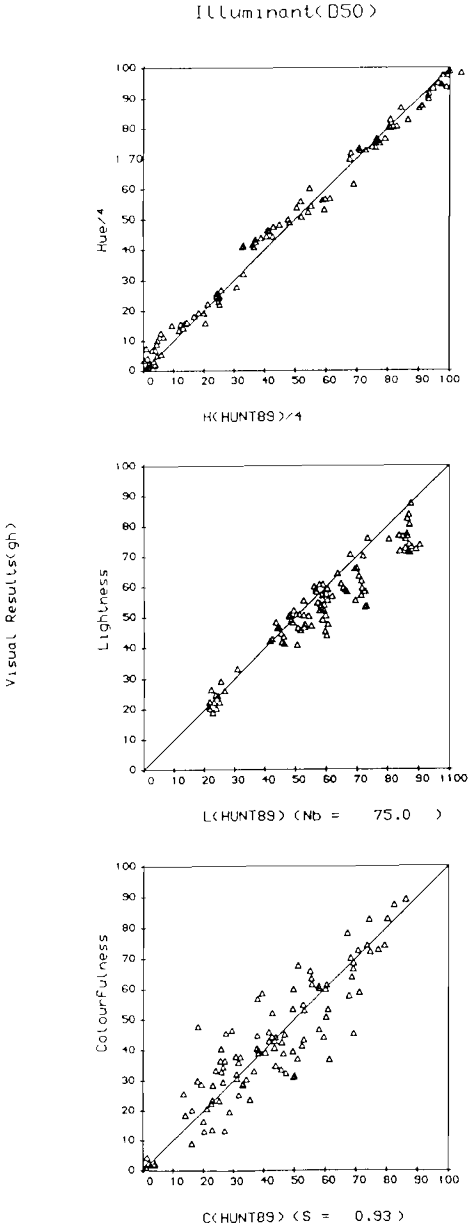


Figure 2 - Comparing visual scaling data against Hunt-Acam predictions

(Non-luminous samples - Low illumination level (42.2 cd/m^2)

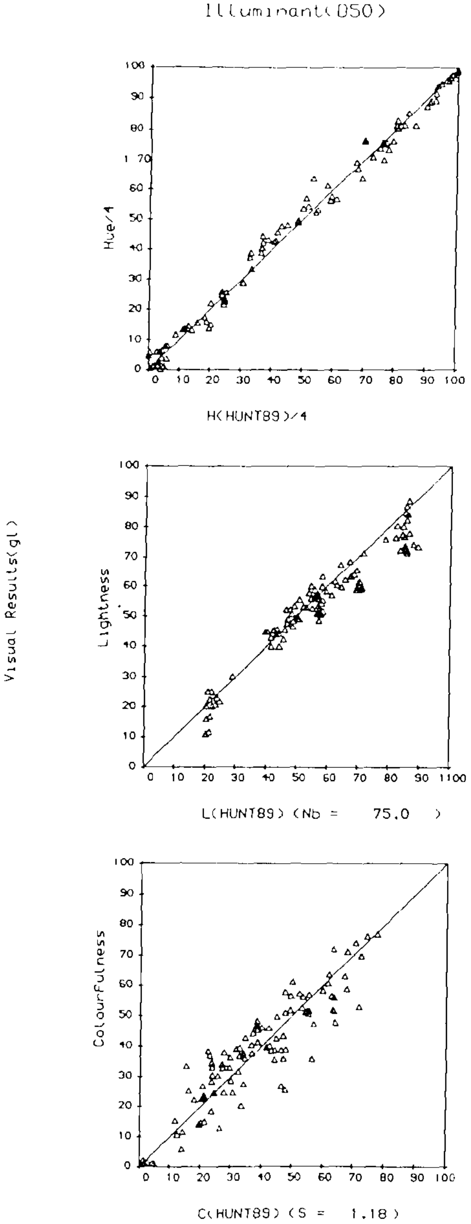


Figure 3 - Comparing visual scaling data against Hunt-Acam predictions

(Luminous samples - Low illumination level (44.5 cd/m^2)

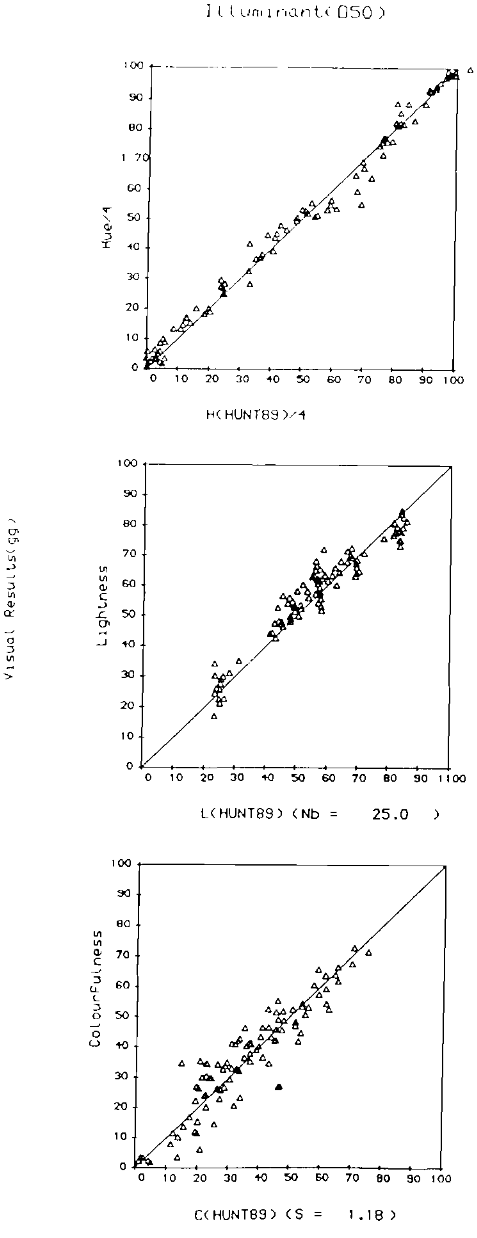


Figure 4 - Comparing visual scaling data against Hunt-Acam predictions

(Luminous samples - Low illumination level (44.5 cd/m²)- White border)

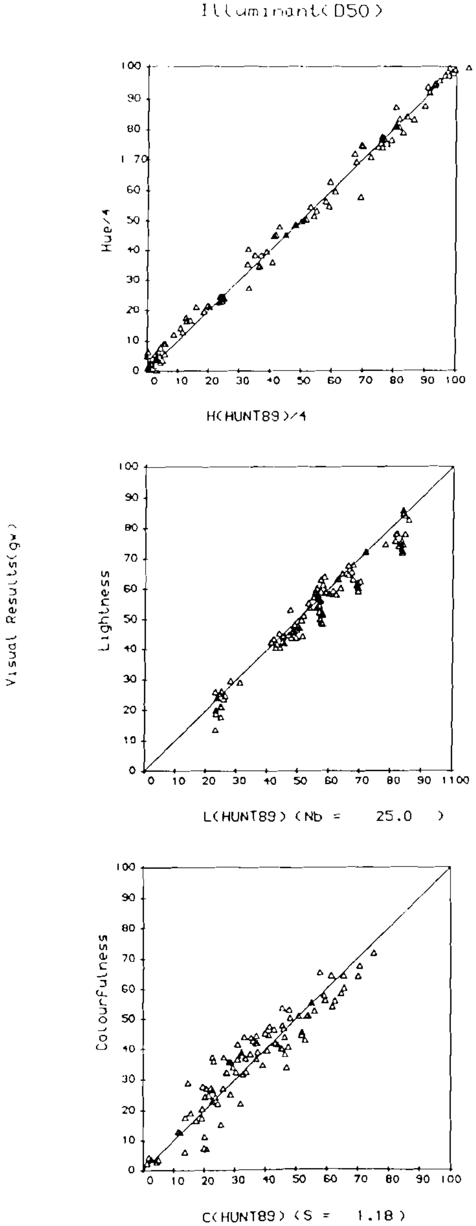
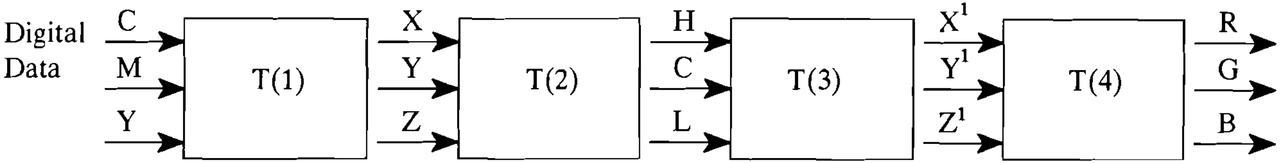


Figure 5 - Transforming CMY to RGB whilst maintaining appearance matching



T(1) = Transform from CMY -> XYZ (D50)

T(2) = Hunt-ACAM Colour Appearance Model

T(3) = Inverse Hunt-ACAM Model

T(4) = Transform from XYZ -> RGB