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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

SPECIFICATION OF COLOUR APPEARANCE FOR REFLECTIVE MEDIA AND SELF-LUMINOUS DISPLAY COMPARISONS

Background Information Relating to the Development of the
CIECAM02 Colour Appearance Model

CIE 195:2011

UDC: 159.937.51
535.66
612.843.31

Descriptor: Perception of colour
Colours of objects
Colour vision

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This Technical Report has been prepared by CIE Technical Committee 1-27 of Division 1 "Vision and Colour" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-27 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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CONTENTS

SUMMARY	V
RESUME	V
ZUSAMMENFASSUNG	V
1 INTRODUCTION	1
2 PUBLICATION OF THE GUIDELINES IN 1994	1
3 EXPERIMENTAL RESULTS OF SIX RESEARCHERS RESPONDING TO THE PUBLISHED GUIDELINES IN 1996	1
4 EXPERIMENTS FEATURING UNEQUAL WHITE POINT CHROMATICITY AND EQUAL LUMINANCE LEVEL CONDITIONS ACROSS MEDIA	4
5 EVALUATION OF NINE DIFFERENT COLOUR APPEARANCE MODELS FEATURING UNEQUAL WHITE POINT CHROMATICITY AND EQUAL LUMINANCE LEVEL CONDITIONS ACROSS VIEWING CONDITIONS	5
5.1 Print Generation	7
5.2 Matching Softcopy Image Generation	8
5.3 Pilot Experiment to Determine Proper Surround for Each Colour Appearance Model	9
5.4 Experiment to Evaluate Nine Colour Appearance Models	12
5.5 Data Analysis and Results for Experiment	13
5.5.1 Multi-Dimensional Scaling Analysis	13
5.5.2 Frequency Matrices for Pairs Data	15
5.5.3 Duncan's Test of Statistical Significance	16
5.5.4 Results from Observer's Raw Scoring of Hardcopy/Softcopy Match Integrity	19
5.5.5 Summary of Results from Experiments Conducted at Derby Featuring Different White Point Chromaticity and Equal Luminance Across Hardcopy/Softcopy Media	22
5.5.6 Conclusions from Experiment Featuring Different White Point Chromaticity and Equal Luminance Across Hardcopy/Softcopy Media	22
6 EVALUATION OF NINE DIFFERENT COLOUR APPEARANCE MODELS FEATURING UNEQUAL WHITE POINT CHROMATICITY AND UNEQUAL LUMINANCE LEVEL CONDITIONS ACROSS VIEWING CONDITIONS	22
6.1 Pilot Experiment to Determine Proper Surround for Each Colour Appearance Model	25
6.2 Psychophysical Experiment Featuring Different White Point Chromaticity and Luminance Across Media	26
6.3 Data Analysis and Results for Experiments	26
6.3.1 Multidimensional Scaling Analysis	26
6.3.2 Duncan's Test of Statistical Significance	26
6.3.3 Comrey Constant Sum Rating	30
6.3.4 Possible Reasons for Why Different Models Performed Better for Different Scenes	33
6.4 Conclusions from Experiment Featuring Different White Point Chromaticity and Luminance Across Hardcopy/Softcopy Media	34
7 CONCLUSIONS FOR BOTH HARDCOPY/SOFTCOPY EXPERIMENTS	34
8 RECOMMENDATIONS FOR FUTURE WORK	34
ANNEX A INSTRUCTIONS FOR PSYCHOPHYSICAL COLOUR MATCHING EXPERIMENT – PILOT WITH EQUAL WHITE POINT CHROMATICITY ACROSS MEDIA	35
ANNEX B INPUT DATA FOR PILOT EXPERIMENT	36
ANNEX C INSTRUCTIONS FOR PSYCHOPHYSICAL COLOUR MATCHING EXPERIMENT	38
REFERENCES	39

SPECIFICATION OF COLOUR APPEARANCE FOR REFLECTIVE MEDIA AND SELF-LUMINOUS DISPLAY COMPARISONS

Background Information Relating to the Development of the CIECAM02 Colour Appearance Model

SUMMARY

This Technical Report summarizes the body of work conducted by CIE Technical Committee 1-27 "Specification of Colour Appearance for Reflective Media and Self-Luminous Display Comparisons" from 1990 until 2001. After compiling data from researchers around the world and studying various forms of colour appearance models to predict results from hardcopy/softcopy matching experiments under a variety of viewing conditions, it was discovered that the same colour appearance model would not consistently or adequately predict the visual results. In 2001, all CIE TC 1-27 results were passed along to CIE TC 8-01, Colour Appearance Modeling for Colour Management Systems. This Technical Committee within Division 8 formulated an effective colour appearance model by combining the best features of the colour appearance models that were studied by CIE TC 1-27. The result was the development of the CIECAM02 colour appearance model.

SPECIFICATION DE L'APPARENCE CHROMATIQUE POUR DES COMPARAISONS ENTRE MATERIAUX REFLECHISSANTS ET AFFICHEURS AUTO-LUMINEUX

Informations supplémentaires au développement du modèle d'apparence colorée CIECAM02

RESUME

Ce rapport technique résume l'ensemble du travail conduit par le CIE TC 1-27 "Spécification de l'apparence chromatique pour des comparaisons entre matériaux réfléchissants et afficheurs auto-lumineux" de 1990 jusqu'à 2001. Après la compilation des données des chercheurs au niveau mondial et l'étude de divers types de modèles d'apparence chromatique pour prédire les résultats expérimentaux d'égalisations entre copies papier et écrans d'affichage pour une variété de conditions d'observation, il a été conclut qu'un modèle unique d'apparence chromatique était incapable de prédire les résultats visuels de manière consistante ou adéquate. En 2001 tous les résultats du comité CIE TC 1-27 furent transmis au comité CIE TC 8-01, Modélisation de l'apparence chromatique pour les systèmes de gestion de la couleur. Ce Comité technique de la Division 8 formula un modèle opérationnel d'apparence chromatique en incorporant les meilleurs éléments des modèles d'apparence chromatique étudiés par le comité CIE TC 1-27. Le développement du modèle d'apparence chromatique CIECAM02 en fut le résultat.

SPEZIFIKATION DER FARBERSCHEINUNG FÜR VERGLEICHE VON REFLEKTIERENDEN MEDIEN UND SELBSTLEUCHTENDEN DISPLAYS

Hintergrundinformation zur Entwicklung des CIECAM02-Farberscheinungsmodells

ZUSAMMENFASSUNG

Dieser Technische Report fasst den Hauptteil der vom CIE TC 1-27 „Spezifikation der Farberscheinung für Vergleiche von reflektierenden Medien und selbstleuchtenden Displays“ von 1990 bis 2001 durchgeführten Arbeiten zusammen. Nach Zusammenstellung von weltweiten Forschungsergebnissen und Untersuchung verschiedener Arten von Farberscheinungsmodellen zur Vorhersage von Ergebnissen aus Experimenten zur Ermittlung der Übereinstimmung zwischen Drucker- und Bildschirmausgabe unter verschiedenen Beobachtungsbedingungen, wurde festgestellt, dass dasselbe Farberscheinungsmodell nicht widerspruchsfrei oder hinreichend die visuellen Ergebnisse vorhersagen würde. 2001 wurden alle CIE TC 1-27 Ergebnisse an das CIE TC 8-01,

Farberscheinungs-Modellbildung für Farbmanagementsysteme, übergeben. Dieses Technische Komitee innerhalb Division 8 formulierte ein effektives Farberscheinungsmodell durch Kombination der besten Eigenschaften der Farberscheinungsmodelle, die von CIE TC 1-27 untersucht wurden. Das Ergebnis war die Entwicklung des CIECAM02-Farberscheinungsmodells.

1 INTRODUCTION

CIE TC 1-27 developed the knowledge of hardcopy/softcopy colour appearance matching to the point where a wealth of information was learned, as it was discovered that no one colour appearance model could make a perfect hardcopy/softcopy match under a variety of different viewing conditions. In 2001, the work was passed along to CIE Division 8, where it was embraced by CIE TC 8-01, Colour Appearance Modeling for Colour Management Systems, and led to the development of CIECAM02 [1].

This Technical Report will focus on the following stages of evolutionary development for TC 1-27:

- Publication of the Guidelines in 1994 [2];
- Experimental results of six researchers responding to the published guidelines in 1996 [3];
- Work to sort out why two research groups reporting on hardcopy/softcopy experiments featuring unequal white point chromaticity and equal luminance level conditions across media in 1996 and 1997 [4, 5] led to two different performance rankings for the same colour appearance models [6];
- Work done to study nine different colour appearance models solving the shortcomings of the previous two studies. This work featured unequal white point chromaticity and equal luminance level conditions across viewing conditions;
- Work done to study nine different colour appearance models solving the shortcomings of the previous two studies. This work featured unequal white point chromaticity and unequal luminance level conditions across viewing conditions;
- Final recommendation to hand off the work to CIE Division 8 for completion.

2 PUBLICATION OF THE GUIDELINES IN 1994

The purpose of the publication of the guidelines for coordinated research was to gather as much data from as many different sources as possible for the evaluation of colorimetric and colour appearance models. These colour appearance models were used to create visual matches for self-luminous display (softcopy) and reflection print (hardcopy) image comparisons. Visual results were to be compared to predicted results expressed in terms of CIELAB and CIELUV [7] equations, modifications of CIELAB and CIELUV equations, and the more current colour appearance models proposed by Hunt [8] and Nayatani et al. [9] (Please note that the models of Hunt and Nayatani were the most current publications as of the writing of these guidelines. They and others have published other colour appearance models throughout the evolution of CIE TC 1-27. References for those newer models will be cited when necessary.) The hope was to determine which approach, i.e. a standard colorimetric one, a modified colorimetric one, or a colour appearance one, would be best for predicting perceptual results of image comparisons between hardcopy reflective and softcopy self-luminous media.

The guidelines for coordinated research outlined experimental set-up procedures, controlled viewing condition specifications, psychophysical experimental measurement methods for visual assessments, instrumental colour measurement procedures, and data analysis techniques for correlating the results from visual experiments with computational results from colorimetric spaces or colour appearance models for illuminated reflection print and self-luminous display comparisons. The experimental design defined the reflection print image as the reference colour original. The self-luminous display image must be designed to visually match that reflection print original. Researchers from around the world were encouraged to perform experiments as prescribed by these coordinated research guidelines and submit their results as input to the CIE TC 1-27 evaluation of various colour science models for these hardcopy/softcopy applications.

3 EXPERIMENTAL RESULTS OF SIX RESEARCHERS RESPONDING TO THE PUBLISHED GUIDELINES IN 1996

Six research groups from around the world responded to the published guidelines with experimental results. Two research groups performed image-matching experiments with colour patch patterns. The first was Masato Abe from Ciba University Faculty of Education

(Japan), whose experiments featured successive binocular hardcopy/softcopy matching across media. The second was Peter Bodrogi from the University of Veszprem, Informatics, Department of Image Processing and Neural Computers (Hungary), whose experiments featured hardcopy/softcopy memory matching techniques across media. Three research groups performed paired comparison experiments on complex images. The first was Karen Braun studying under Mark Fairchild from the Munsell Colour Science Lab at the Center for Imaging Science at the Rochester Institute of Technology (USA), whose experiments featured hardcopy/softcopy memory matching techniques across media [5]. The second was Mei-Chun Lo from the Department of Computer Studies at Loughborough University of Technology, M. Ronnier Luo, and Peter A. Rhodes from the Design Research Centre at the University of Derby (England), whose experiments featured simultaneous binocular hardcopy/softcopy matching across media and hardcopy/softcopy memory matching across media [4]. The third was Dr. Robert Wei and Professor James Shyu from the Industrial Technology Research Bureau (ITRI) of Taiwan, whose experiments featured simultaneous binocular hardcopy/softcopy matching across media. Finally, Raimondo Schettini and B. Barolo from the Istituto Tecnologie Informatiche Multimediali (ITIM) and Paola Campadelli from the University of Milan (Italy) used a computational feed-forward neural network approach with training of the neural network with a back propagation algorithm to approximate the Hunt '94 model [9].

Each research group studied different colour models (i.e. uniform colour spaces, chromatic adaptation or colour appearance) and used a different number of observers. Table 1 provides a summary of these differences.

Table 1. Summary of Models Studied and Number of Observers.

Research Group	Experiment Type	Colour Models	Number of Observers
Abe (JP)	Image Matching – Colour Patch Patterns	CIELAB and CIELUV	5
Bodrogi (HU)	Image Matching – Colour Patch Patterns	CIELAB, Hunt 1991 [8], Hunt 1994 [9], Nayatani 1990 [10], Nayatani 1995 [11], RLAB [12]	12
Braun et al. (US)	Paired Comparison – Complex Images	CIELAB, von Kries [13], Hunt 1994, Nayatani 1990, RLAB	14-24
Lo et al.(GB)	Paired Comparison – Complex Images	CIELUV, CIELAB, BFD [14], von Kries, Hunt 1994, Nayatani 1995, RLAB	9
Wei et al. (TW)	Paired Comparison – Complex Images	Two versions of CIELAB, von Kries, RLAB	12
Schettini et al. (IT)	Feed-Forward Neural Networks	Hunt 1994, RLAB 1996 [15], LLAB [16]	0

Table 2 summarizes the parameters that differed across hardcopy and softcopy media for each research group's experiments.

Table 2. Different Parameters Varied Across Media by Each Research Group.

Parameter that Varied Across Media	Research Group
Equal white point chromaticity and luminance	Abe (equal white point chromaticity only) and Lo et al.
Equal white point chromaticity and unequal luminance	Braun et al.
Unequal white point chromaticity and equal luminance	Bodrogi, Braun et al., Lo et al., Wei et al., and Schettini
Unequal white point chromaticity and luminance	Braun et al.
Different self-luminous display reference white point chromaticities	Wei et al.
Different surrounds (ambient lighting)	Braun et al. And Wei et al.
Different backgrounds	Braun et al.

It is instructive to summarize results from each research group.

Abe Results: A hardcopy/softcopy visual match does not equal a colorimetric match for viewing conditions that are equal in white point chromaticity. The most likely probable cause is a luminance mismatch across media and an observer task limitation in their use of the joystick to obtain the softcopy match.

Bodrogi Results: The RLAB and Hunt '94 models were better predictors of the observers hardcopy/softcopy matches than the Nayatani '95 model.

Wei et al. Results: The von Kries chromatic adaptation model, CIELAB and the RLAB colour appearance model all performed similarly for a D50 print compared to a D65 self-luminous display and a self luminous display with the white reference at the average of the print and self-luminous display white points. Use of a mixed adaptation white reference for the self-luminous display white point gave worse model performance results than use of the D65 white point set-up for the self-luminous display. An ambient surround difference of 700 lx did not influence model performance.

Lo et al. Results: For identical white point chromaticities and luminance across media, a visual match is a colorimetric match. For different white point chromaticities at equal luminance across media, the model ranking was:

CIELUV < CIELAB < von Kries, Hunt '94, Nayatani '95, RLAB, and BFD

Thus the two uniform colour spaces performed worse than the chromatic adaptation and colour appearance models. One notable exception was that BFD significantly outperformed all other models for the viewing condition that featured the print being illuminated by a simulator of CIE Standard Illuminant A and the self-luminous display being set to a D65 white point. Other important results from these experiments were that CIELUV and BFD showed the best image independence. Paired comparison and category scaling results were very similar. Also similar results were obtained regardless of whether the self-luminous display pairs were toggled or shown simultaneously. Finally, observer precision was highest when the white point chromaticity differences across media were largest.

Braun et al. Results: Table 3 summarizes the results from the Braun et al. experiments.

Table 3. Summary of Results from Braun et al. Experiments.

Parameter that Varied Across Media	Model Rankings
Unequal white point chromaticity and equal luminance	Nayatani '90 < Hunt '94 < von Kries < CIELAB < RLAB
Equal white point chromaticity and unequal luminance	All models = except Nayatani '90 significantly worse
Unequal white point chromaticity and luminance	Nayatani '90 < Hunt '94 < CIELAB < von Kries = RLAB
Different surrounds (ambient lighting)	RLAB < Hunt '94 < Nayatani '90 = von Kries = CIELAB
Different backgrounds	All models = except Hunt '94 significantly worse

One notable exception was that the von Kries chromatic adaptation model tied with RLAB in performance for the viewing conditions featuring a print illuminated with a CIE Standard Illuminant D50 simulator and a self-luminous display set to a 9 300 K white point. Other important results from these experiments were that the category scaling results were in good agreement with the paired comparison results as was found by Lo et al. Finally, RLAB and von Kries showed the best image independence.

Schettini et al. results: Any of the colour appearance models (i.e. Hunt '94, LLAB, or RLAB) can be adequately approximated by a feed-forward neural network trained by a back propagation algorithm that computes neural weights. For cross media colour reproduction experiments, results given by the network cannot be distinguished from those given by any of the colour appearance models. The use a network for these hardcopy/softcopy image matching experiments reduces the computational complexity associated with some of these colour appearance models.

Unfortunately, after examining all results obtained from the six research groups, it was difficult to find one model that would always support the visual colour appearance image matching results across media for all viewing conditions. The six research groups followed the published guidelines, but there was not always common ground among experiments, which made it difficult to tie their results together. Common ground was found among research groups who showed that a visual match is a colorimetric match for identical viewing conditions. Encouraging results were found for various models under different viewing conditions across media. For the two research groups that studied different white point chromaticities at equal luminance levels (i.e. Lo et al. and Braun et al.), the model rankings were different for the same sets of viewing conditions across media. The next task for TC 1-27 was to understand the source of these differences among research groups.

4 EXPERIMENTS FEATURING UNEQUAL WHITE POINT CHROMATICITY AND EQUAL LUMINANCE LEVEL CONDITIONS ACROSS MEDIA

The most studied experimental condition among all research groups was the unequal white point chromaticity and equal luminance level condition across media. The results, based on a z-score analysis of paired comparison data, showed differences in model rankings among the Braun et al. and the Lo et al. research groups. Factors that could have contributed to the inconsistent results were input model parameters, data analysis procedures, experimental design (i.e. numbers of models and/or observers and use of different pictorial image), image processing paths, and gamut mapping techniques.

A careful check was made between both research groups regarding input model parameters for the five common models and the four common viewing conditions across media. Agreement on all input model parameters was found between the Braun et al. and the Lo et al. research groups. Thus input model parameters could be eliminated from the list of factors contributing to the inconsistent results.

Both research groups kindly sent their raw data from all forced choice paired comparison experiments. A common data analysis was performed on the raw data sets consisting of two statistical tests: multi-dimensional scaling and a Duncan test of statistical significance. The multi-dimensional scaling analysis allowed identification of outliers in each data set and general observer preference trends on a scene/viewing condition basis. Multi-dimensional scaling analysis was also used to examine the extent of dimensionality present in the observer model ranking data. This dimensionality analysis showed that on average, two dimensions explained 82,5 % of the total variance for each data set received from each research group. With models as different as uniform chromaticity spaces, chromatic adaptation models, and colour appearance models, there is something two dimensional describing the observer preferences for both research groups. The challenge was to determine exactly what those two dimensions might be. After removing the outliers and running the Duncan test of statistical significance on only the common models, the model rankings for the two research groups were still inconsistent as shown in Table 4.

Table 4. Duncan Test Results for Two Research Groups.

Research Group	Model Rankings after Duncan Test for Common Models and No Outliers
Lo et al.	CIELAB < Nayatani '95 < von Kries < RLAB = Hunt '94
Braun et al.	Nayatani '90 < CIELAB < Hunt '94 < RLAB < von Kries

It was determined after a careful examination of the image processing paths that the reflection print generation stage and the reverse video model stage were different. If the device characterizations from *RGB* (Braun et al.) or *CMYK* (Lo et al.) to print *XYZ* and both reverse video models were accurate and robust, these differences should not be large contributors to the inconsistent model ranking results. In spite of the fact that there was a difference in the treatment of surround, each research group was consistent in the surround condition across media. The treatment of surround should not have contributed to the different model rankings. Finally, the treatment of the image grey background was different enough to have contributed to inconsistent model rankings. The Braun et al. colour appearance model-independent image grey background and the Lo et al. model-dependent grey background were most likely contributors to the different model ranking results among both research groups.

The gamut mapping techniques among the two research groups were different. The Braun et al. research group compressed the print gamut of each image until it fit within the video gamut for all models to be studied for each condition. The Lo et al. group clipped the video pixels that were out of the print gamut for each model. This technique resulted in an average of 3 % of the pixels per image being clipped; however, some images had as many as 10 % of the pixels clipped. After some supporting tests of the two gamut mapping techniques, it was determined that the gamut mapping technique differences were a contributing factor to the different model rankings among both research groups.

Thus we learned that input model parameters and data analysis did not contribute to the discrepancies among research groups. Obviously, the experimental design featuring different images and number of observers played some role in differences among research group results. The other two most likely factors contributing to different model rankings among research groups were image processing paths and gamut mapping techniques.

5 EVALUATION OF NINE DIFFERENT COLOUR APPEARANCE MODELS FEATURING UNEQUAL WHITE POINT CHROMATICITY AND EQUAL LUMINANCE LEVEL CONDITIONS ACROSS VIEWING CONDITIONS

The final phase of TC 1-27's work involved experiments featuring prints made at one location (i.e. Eastman Kodak Company) and evaluations done at two different laboratories: Eastman Kodak Company and Dr. Luo's lab at Derby University. Consistency among both groups was achieved wherever possible. The results from Derby University were completed after most of

the work for this Technical Committee was completed. Thus the Derby work was published at a separate time [17].

The viewing condition to be studied featured the print under CIE D50 Simulators at $70 \text{ cd}\cdot\text{m}^{-2}$ and self-luminous display at 9 300 K and $70 \text{ cd}\cdot\text{m}^{-2}$. The print sizes were either $20,32 \text{ cm} \times 20,32 \text{ cm}$ ($8'' \times 8''$) or $20,32 \text{ cm} \times 25,4 \text{ cm}$ ($8'' \times 10''$). At Eastman Kodak Company, the print was viewed in a room equipped with CIE D50 Simulators overhead, whereas at Derby University, the prints were viewed in a viewing cabinet lined with a 20 % grey reflector and equipped with the CIE D50 simulators. Thus the surround condition for print viewing was average. The print viewing angle was 70° and the print viewing distance was 50 cm. The self-luminous display was set to a white point of 9 300 K also at $70 \text{ cd}\cdot\text{m}^{-2}$. The self-luminous display viewing angle was 90° and the self-luminous display viewing distance was 50 cm. When the self-luminous display images were viewed, the room lights were turned off. Thus the surround condition for self-luminous display viewing was dark.

The models being studied were CIELAB, von Kries, Bradford (BFD), RLAB, LLAB, Nayatani '97 [18], Hunt '96 [19, 20], and CIECAM97s. The scenes being used for images were Barn, U-chart, Musicians, and Golfer. These scenes were chosen to be as representative of overall colour space as possible.



Barn



U-Chart



Musicians



Golfer

Figure 1. Scenes Used for the Study of Different Models.

Each hardcopy and softcopy image had a background. The prints were mounted with an 18 % non-selective grey border in such a way that 0,64 cm ($\frac{1}{4}''$) of paper base was left showing all around the image. The self-luminous display images had a 0,64 cm ($\frac{1}{4}''$) white border surrounded by an 18 % grey border that filled out the entire 48,26 cm (19") screen.

5.1 Print Generation

The first step in the process was print generation. The prints were made on a large format cathode ray tube (LFCRT) printer using photographic paper.

Since the purpose of this experiment was to study colour appearance models, there was a desire to eliminate mismatches between the hardcopy and softcopy gamuts. Thus the first step was to manipulate the print gamut until all pixels for each scene were within the self-luminous display gamut for all colour appearance models.

Since all colour appearance models work from XYZ tristimulus values, it was necessary to first convert from the scene input data metric, Photo YCC , to XYZ . A von Kries chromatic adaptation transformation was performed to convert the resulting tristimulus values from Standard CIE D50 to their corresponding values for the simulated CIE D50 print viewing illuminant.

The image-processing algorithm that was used to achieve the gamut mapping started from the print XYZ tristimulus values as shown in Figure 2.

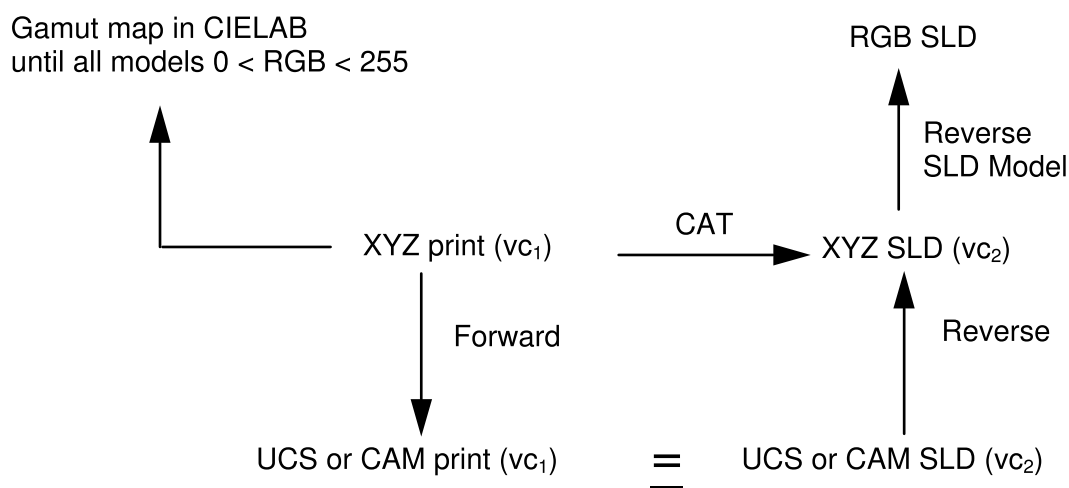


Figure 2. Image Processing Model for Hardcopy Print Generation.

Each pixel's print XYZ values for viewing condition one, (vc_1) , were either translated into self-luminous display (SLD) XYZ for viewing condition two, (vc_2) , by a chromatic adaptation transform (CAT) like von Kries or Bradford (BFD) or converted to a Uniform Colour Space (UCS) like CIELAB or a Colour Appearance Model (CAM) like RLAB, LLAB, Hunt '96, Nayatani '97 or CIECAM97s. If the UCS or CAM was perfect, then the data for the print under viewing condition one (vc_1) would be equivalent to the data for the SLD at viewing condition two (vc_2) . Then a reverse transform was done to get SLD XYZ values from the Uniform Colour Space or the Colour Appearance Model. Next the SLD XYZ values from a UCS or CAM or a chromatic adaptation model (CAT) were translated into red, green and blue code values for the self-luminous display (RGB SLD). If any of the red, green or blue code values were greater than 255 or less than 0, they would be out of the SLD gamut, which meant that the XYZ values of the print had to be manipulated by some gamut mapping strategy until all pixels resulted in SLD RGB code values between 0 and 255 for all UCS, CAT, and CAM.

The gamut mapping strategy was performed in the CIELAB Uniform Colour Space. It had to be fast since it was operating on multiple pixels over multiple models for a $2K \times 3K$ image. It involved mapping only out-of-gamut pixels, preserving the original print colour hue angle and mapping L^* and C^* to the closest point on the gamut boundary by aiming towards $L^* = 50$ and $C^* = 0$.