Uniform Color Appearance Model

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Abstract: In this paper, a new color appearance model, the Uniform Color Appearance Model, is proposed for color reproduction applications in graphic art. The goal of this work is to provide a solution to the limitations of the traditional color reproduction technology in color appearance technology. This new model incorporates a simplified chromatic adaptation transformation with a generalized tonal reproduction and color correction. An expanded Munsell color space is applied for color appearance definition and color correction. It is capable to account for the changes in media and viewing conditions, and to manipulate color in a perceptual uniform color manner. This new model is referred to as the Uniform Color Appearance Model

Introduction

Colorimetry based on CIE system of color measurement was and still is the core of the traditional color reproduction technology for the graphic art industry. It has become aware many years ago that the colorimetry technology can not reproduce sufficient colors across different media and viewing conditions. This is because colorimetry was designed only for fixed viewing conditions. The color appearances matching between two colors with the same CIE measurement only occur for the same viewing conditions.

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There are at least three types of effects that affect the color appearance for two colors of different viewing conditions: the differences in color between two illuminants, known as chromatic adaptation; the differences in intensity between the two illuminants; and the differences in the surrounding conditions. Much effort has been made to improve the quality of colorimetric technology for the color reproduction industry. The CIELAB and CIELUV were suggested for nearly uniform color spaces, Bartleson-Breneman (1967) proposed tonal reproduction curves for different surroundings, Hunt (1987), Holub (1987) and Viggiano and Wang (1992) suggested different color correction (gamut compression) algorithms for cross media rendering. However, perhaps the lack of the color appearance definition and non-uniform color space are the major limitations of colorimetry technology.

Recently, several color appearance models have been proposed to exhibit mathematically the relationship between the CIE measurement of colors and their appearance for a wide range of viewing conditions. Some of them have recently been tested by Luo et al. (1991, 1993). As Luo recommended, the most extensive color models are those of Hunt (1991) and Nayatani et al. (1990), in terms of their adaptation abilities for various viewing conditions. Even there is significant interest in developing and testing such color appearance models, their application in color reproductions has been developed slowly. Perhaps the main reasons are: inconsistency between test data, and complexity of implementation.

Fairchild (1991) proposed a simplified Hunt model to take account of the effect of chromatic adaptation. Then he extended his model with CIELAB to form a complete color appearance model for color reproduction (1993). It is attractive to introduce color appearance technology into colorimetric technology because the feasibility of implementation. However, the non-uniform effect of CIELAB space can not be resolved with Fairchild's model.

In this paper, a new model, the Uniform Color Appearance Model, is proposed for a solution of the limitations of colorimetry technology. Experiments to evaluate the new model as well as CIELAB and CIELUV, and other color appearance models are discussed. The focus of this research is on transparency-to-print color reproduction.

In order to accomplish our goal, the new color appearance model should satisfy the following requirements:

a) It should have a chromatic adaptation mechanism to adapt different reference white points upon the change of spectral distribution of the illuminant.

b) It should have a perceptual uniform color appearance space to support perceptual gamut mapping and color correction. It should have metrics to measure the color appearance in terms of perceived amplitude.

c) It should have a mechanism to adapt the gray scale and color correction for the change of intensity of the illuminant, particularly for transparency-to-print color reproduction procedures.

d) It should have a simple invertible relationship between CIE colors and the color-appearance space to coordinate the new model with colorimetric device calibration.

e) It should have a gamut as large as the gamut of transparency (film), because film has a larger gamut than that of other media, to support a large enough container for color exchange, gamut mapping and color correction.

This new model has four major functional parts: chromatic adaptation, color conversion, tonal reproduction and color correction. Fig. 1 shows the flowchart for calculation of color appearance coordinates of the new model proposed in this paper to accomplish all the requirements mentioned above.

The chromatic adaptation part considers the white points change due to the color change of the illuminant and the color effect of the illuminance intensity change (requirement a). A simplified chromatic adaptation transformation of Hunt's model (1991) (Fairchild 1993) is applied. This transformation can be formulated as shown in equations (1) through (3).

$$\rho_a = C_\rho \bullet \rho / \rho_w,$$
$$\gamma_a = C_\gamma \bullet \gamma / \gamma_w,$$
$$\beta_a = C_\beta \bullet \beta / \beta_w. \qquad (1)$$

Here C_ρ, C_γ and C_β are chromatic adaptation factors. They can be calculated by the following formulae (Hunt 1991).

$$C_\rho = (1 + L_a^{1/3} + h_\rho) / (1 + L_a^{1/3} + 1/h_\rho),$$
$$C_\gamma = (1 + L_a^{1/3} + h_\gamma) / (1 + L_a^{1/3} + 1/h_\gamma),$$
$$C_\beta = (1 + L_a^{1/3} + h_\beta) / (1 + L_a^{1/3} + 1/h_\beta), \qquad (2)$$

Where L_a is the luminance of the adapting field,

$$h_\rho = \rho / (\rho + \gamma + \beta),\ h_\gamma = \gamma / (\rho + \gamma + \beta),\ h_\beta = \beta / (\rho + \gamma + \beta). \qquad (3)$$

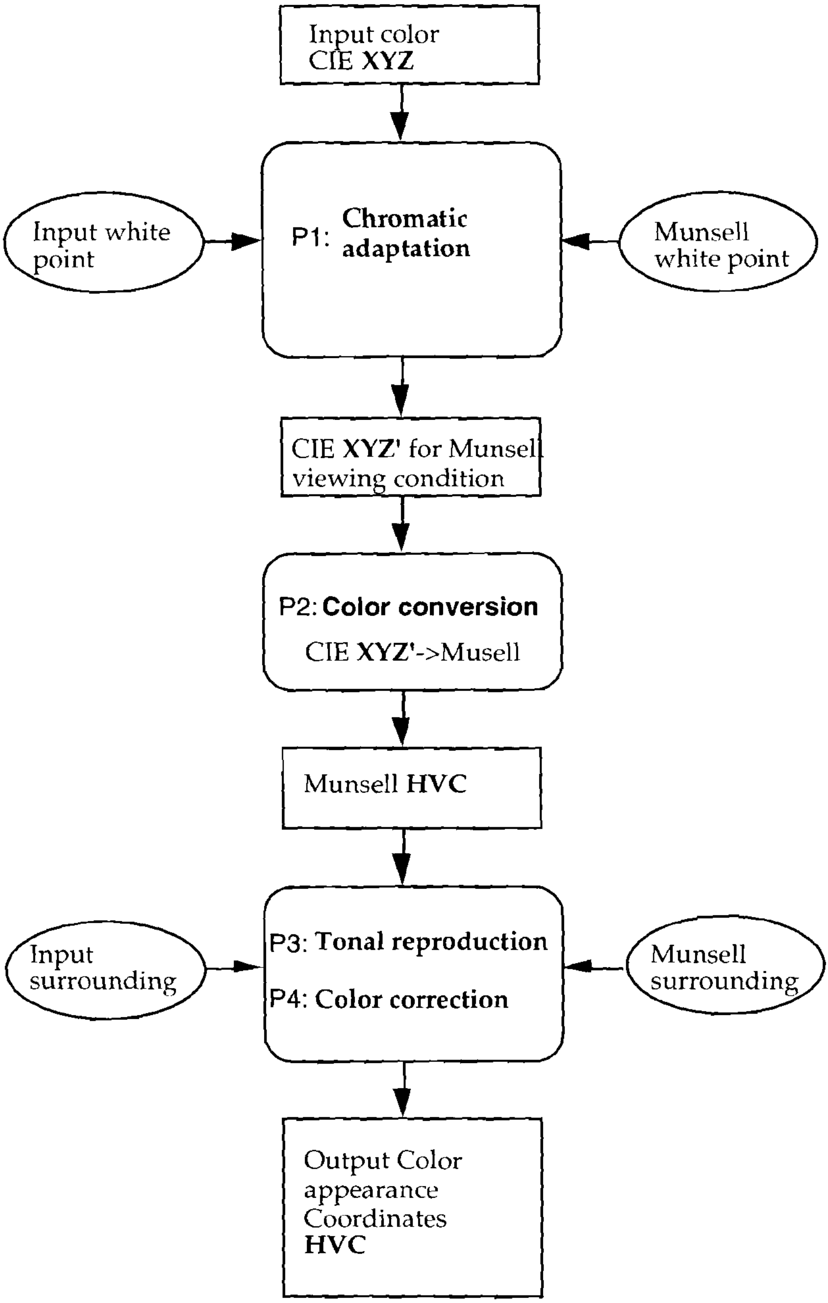


Fig. 1 Flowchart for calculation of color appearance coordinates of the new model

The tonal reproduction and color correction parts compensate the gray level and chroma for different surroundings (requirement c). A linear compressed Bartleson-Breneman equation (1967) is used for tonal reproduction. Constant gamut compression (color correction) ratio optimized from our experiment (reference to the model performance section) is used.

An expanded Munsell color space is applied as the color appearance space (requirement b). A quadrilateral interpolation algorithm (will be discussed in another paper in late 1996) is developed to convert colors between the color appearance space and CIE colors (requirement d). Requirement e) has been accomplished by using a polynomial extrapolation method to expand the existing Munsell gamut.

Model performance

Three experiments have been conducted to evaluate the new model. They were chromatic adaptation, hue reproduction and visual comparison experiments. Two sets of corresponding color pairs were chosen in the chromatic adaptation experiment to quantify the ability of chromatic adaptation. The hue reproduction experiment tests the uniform effect of the new model. Finally, the visual comparison gives the general subjective judgment of the new model.

In the chromatic adaptation experiment, the Hunt, Nayatani, and Fairchild color appearance models as well as CIELAB and CIELUV spaces were tested on selected corresponding colors. The two sets of corresponding colors were selected from the results of Breneman's experiment (1987). The first data set we chose presented five groups of 60 pairs of the matched colors with five different fixed illuminance levels for illuminant A to D6500 chromaticities. While the second set of data presented three groups of 36 pairs of the matched colors for different illuminance levels with constant illuminant D5500 chromaticities.

The results of testing the models with the two test data sets are presented in $\Delta u'v'$ and ΔE of CIELAB as shown in Table 1. Column 1 of Table 1 (with constant adapting illuminance level) shows a similar result of Fairchild's experiment (1991). The new model, Hunt's and Fairchild's models perform significantly better than other models. The significant level is determined by $\alpha >= 0.05$ from a statistical T-test. The CIELAB and CIELUV models produce the worst results than all the other test models.

The second and third columns in Table 1 show the test result of constant illuminant chromaticity (d5500) with various adapting illuminance levels. The new model performs better than all of other models in Δu'v' measurement but significantly better than others in ΔE measurements. Fairchild's model has a good Δu'v' measurement but ΔE measurement. Further data analysis indicates that the C matrix of the Fairchild's model produces large L* errors. Hunt's and Nayatani's models produce less accurate in both Δu'v' and ΔE measurement than the new model. Examination of the data shows the C matrix in Fairchild model over compensated the lightness. The CIELAB and CIELUV models produced still the least accurate results compared to other test models. But if suitable compression ratio is chosen to compress the chroma as 0.79 and 0.84 are used in this experiment, the CIELAB and CIELUV can provide much better results for the data set 2 as shown in the fourth column in table 1. These ratios were derived in the best fit of the test data set 2.

Model	DataSet1 (Δu'v')	DataSet2 (Δu'v')	DataSet2 (ΔE)	
New model	0.0174	0.0114	5.32*	
Fairchild	0.0174	0.0134	11.1	
Hunt	0.0187	0.0223	17.1	
Nayatani	0.0211	0.0199	12.8	
von Kries	0.0211	0.0235	11.5	
CIELAB	0.0282	0.0237	15.6	7.34**
CIELUV	0.0367	0.0237	15.6	8.02***

* a constant ratio 0.77 is used
** a constant ratio 0.79 is used
*** a constant ratio 0.84 is used

For the hue reproduction experiment, the six color bars on AGFA IT8.7/1 target have been selected as the test data. The IT8.7/1 target is a transparent medium calibration standard recommended by the Technical Committee of Accredited Standards Committee IT8. The new model has been tested as well as CIELAB and CIELUV. The same Bartleson-Breneman tonal reproduction algorithm and three constant color compression ratios (0.77, 0.79, 0.84) used for the tested models respectfully. In this way, all tested models have the same tone curve and about the same colorfulness. The results and their original colors are plotted in Fig. 2 (2-d a*b* space of CIELAB), Fig. 3 (2-d u*v* space of CIELUV) and Fig. 4 (2-d t m of the Munsell color space).

In general, the three figures show the blue bars have the largest reproduced hue difference, red bars have the second largest hue difference, and the yellow bars are the third. The interesting thing is that CIELAB, CIELUV and the new model match their reproduced color bars to their original in the corresponding color space (the compressed colors have the same hues as its originals). The loci of color bars are different from one model to another that reveal the difference of uniformity for particular hue area of the color space. Measuring the hue difference in degree, CIELAB has a larger difference for the blue bar (5.21 in average) with a maximum difference of 13.57, while CIELUV has a larger difference for red (4.4 in average) and blue (3.89 in average) in Fig. 4. In this case, the hue difference is zero for the new model result.

Finally, a visual experiment has been conducted to test the new model, and CIELAB and CIELUV. Three natural images, "Models" with much skin tone, "Scene" with green grass and blue sky, and "Desktop" with some saturated color objects on cut-sheet films (4x5 in), were compared with their reproduced prints for the tested models. One light booth and one light viewer were used as the test fields. The light viewer was put in the light booth to do side-by-side comparison as suggested by ANSI PH2.30-1989. All backgrounds were covered with N8 gray (Munsell N/8). The original transparencies were mounted with 1 inch gray border on the light viewer. Both the light booth and the light viewer were illuminated with Tc=5000k fluorescent lamps. Eleven observers participated in this experiment, and the paired comparison method was used to calculate the statistic results.

Three results are shown in Fig. 5, Fig. 6 and Fig. 7. The new model produces closer reproductions than CIELAB and CIELUV in general. Particularly, the new model provides better color quality for saturated colors as shown in Fig. 7.

Conclusions

In this paper, a new color appearance model, the Uniform Color Appearance Model is developed and tested. The experiment results show that the new model fits the chromatic adaptation test data better than other tested models. The new model provides better hue reproductions particularly for saturated colors such as blue and red. With these advantages, this new model may lead to practicable applications with better color quality for color reproduction industry.

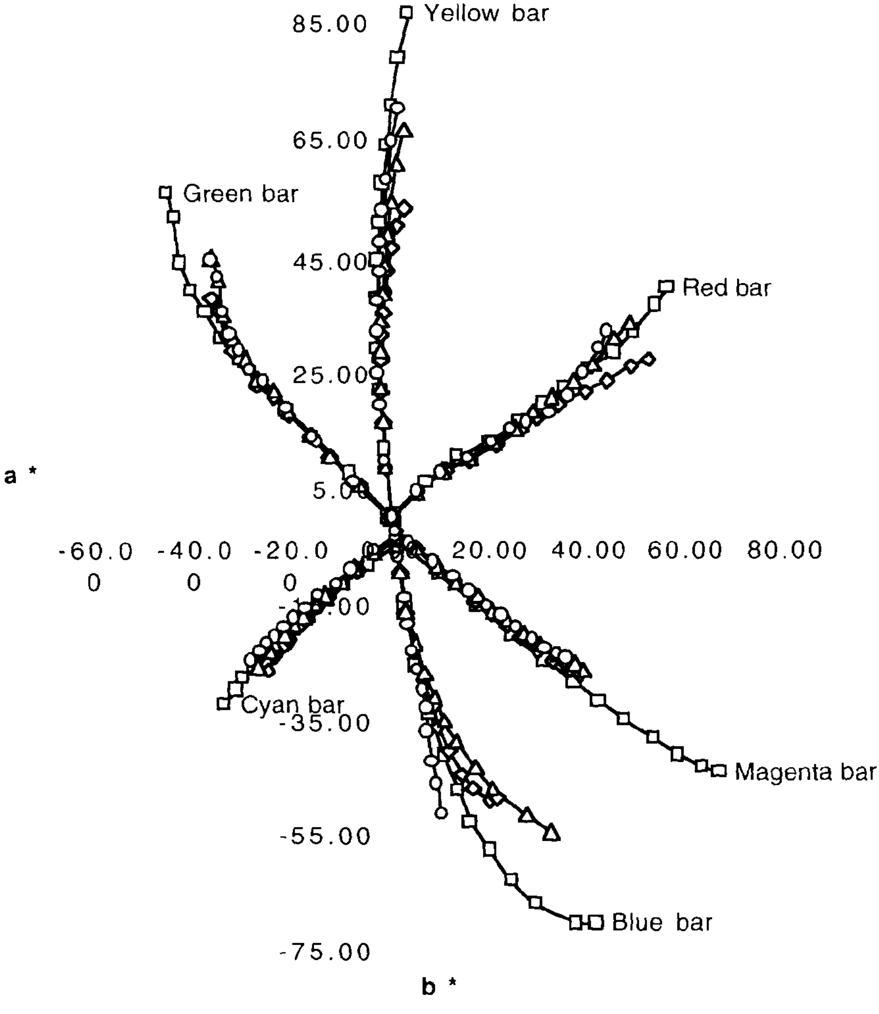


Fig. 2 Hue reproduction plot on the a*b* plane of CIELAB
Legend: Square -- original color bar, diamond -- CIELAB, triangle -- CIELUV and circle -- the New model.

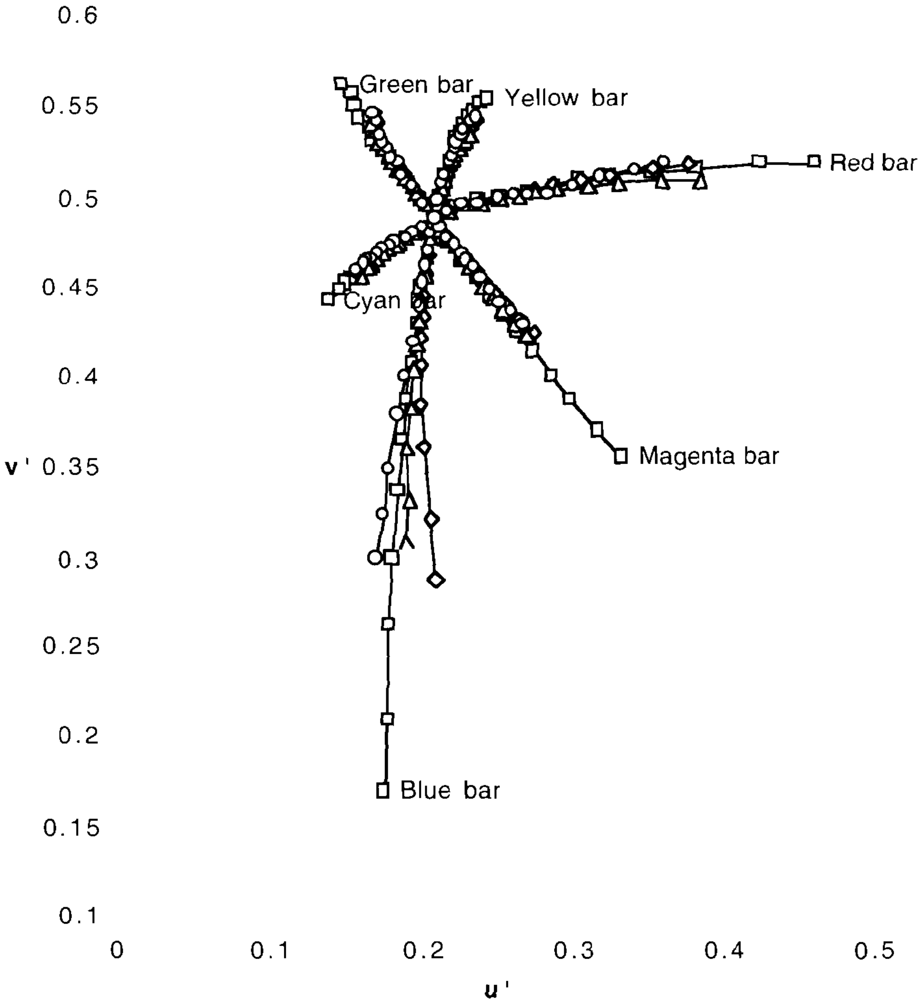


Fig. 3 Hue reproduction plot on the u*v* plane of CIELUV Legend: Square -- original color bar, diamond -- CIELAB, Triangle - CIELUV and circle -- the New model.

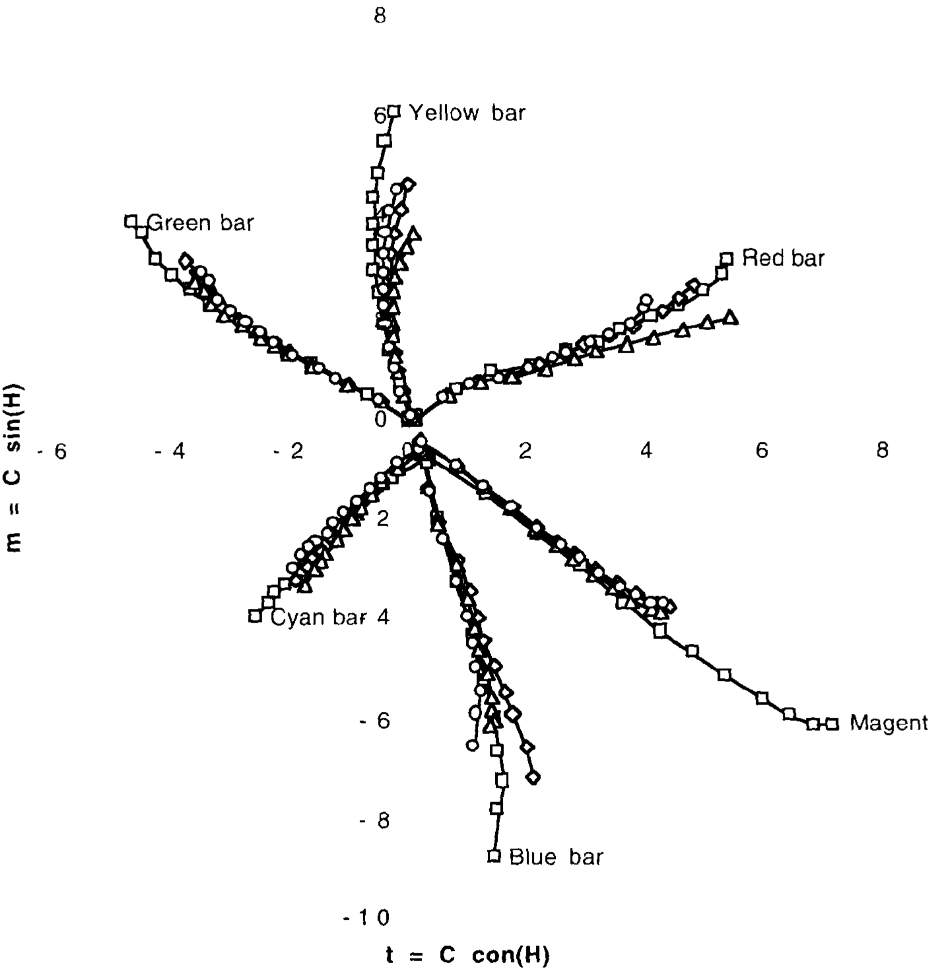


Fig. 4 Hue reproduction plot on the t m plane of the new model
Legend: Square -- original color bar, diamond -- CIELAB,
triangle -- CIELUV and circle -- the New model.

Fig. 5 Visual test result on "Models" image

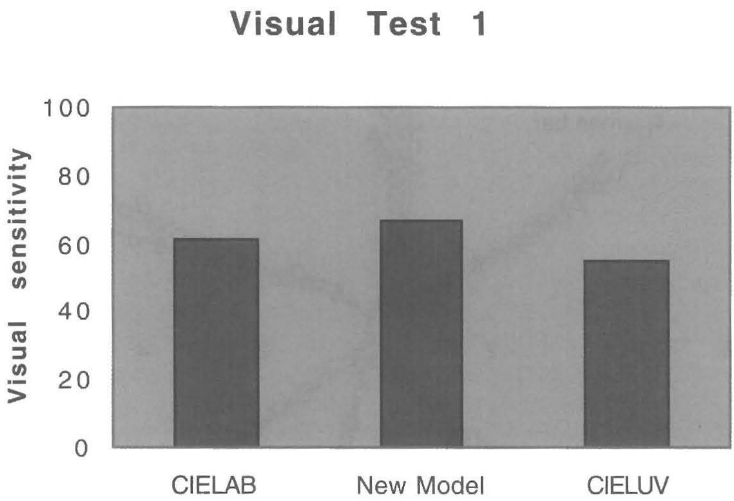


Fig. 6 Visual test result on "Scene" image

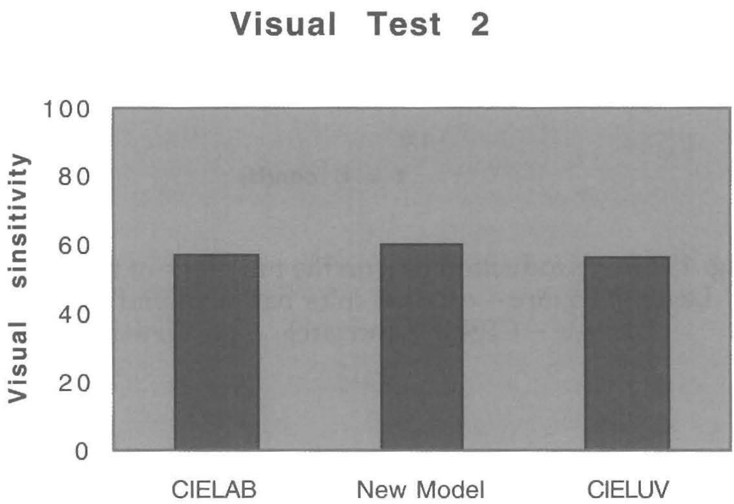
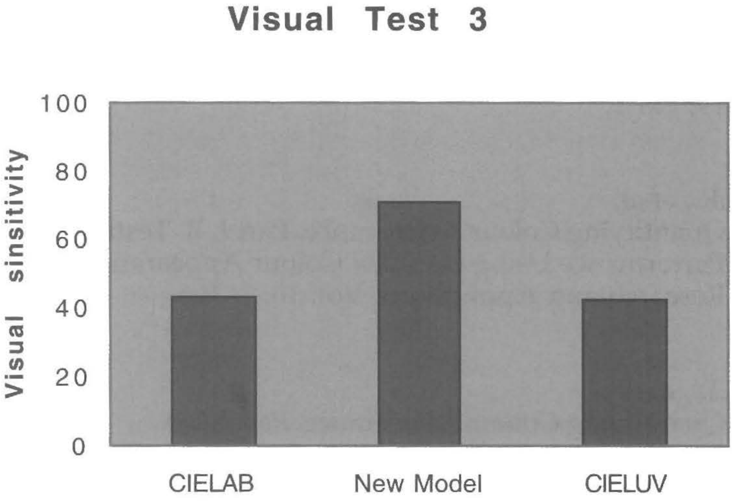


Fig. 7 Visual test result on "Desktop" image



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