A STUDY OF COLOR APPEARANCE MODELS' PERFORMANCE USING SINGLE COLOR STIMULI IN A SIMPLE VIEWING FIELD UNDER AN AVERAGE SURROUNDING

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Key Words: Device Characterization, color appearance model, paired comparison, category judgement, color management system.

Abstract: The goal of this study is the evaluation of various color models for achieving accurate color rendition between a self-luminous reproduced color (softcopy) and a original surface color (hardcopy) in a bright room under an average surrounding. The color models tested were CIELAB, von Kries, ZLAB, LLAB, Hunt and CIECAM97 models. The whole experiment was divided into 4 phases. A set of 36 reflection single stimuli was chosen to be the original colors.

A forced-choice paired-comparison experiment was performed. Observers accessed the color-fidelity quality of each reproduced color, processed using a particular model of interest, in a simple field using a 7-point category scale. The laws of both comparative judgement and category judgement were applied to analyze the visual data. Analysis shows that the CIELAB (also CIEXYZ) system is adequate to implement color matches across media for the symmetrical viewing conditions. For asymmetric viewing conditions wherein different chromaticities were used for hardcopy and softcopy reference whites, the CIECAM97's model overall performed better than other models. Moreover, the results obtained using the category ranking method indicate that those good performing models also gave satisfactory color-fidelity quality. Successively, a set of experiments will be carried out to achieve the ultimate goal of establishing a reliable color model, capable of predicting the change of perceived appearance of colors under a wide range of media/viewing conditions.

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INTRODUCTION

"What You See Is What You Get" (WYSIWYG), the essence of accurate reproduction color images across a wide variety of media and applications, has already become an urgent demand and recently been substantially researched on in the color imaging industry. It is one of the main concerns in both desktop and pre-press environments.

From a detailed retrospective examination of color-encoding problems, three underlying obstacles however are often encountered in achieving WYSIWYG. These are device dependency, color gamut mismatch among dissimilar color imaging devices, and variations of color appearance under different media/viewing conditions. The practical solution in the process of a state-of-the-art cross-media color image production, dealing with these problems, is to provide software known as a color management system (CMS). Three essential elements, device characterization, color appearance modeling, and gamut mapping should be therefore included in a CMS.

In a practical sense, traditional CIE colorimetry alone, basically only dealing with quantities derived from physical properties of individual stimuli, does not represent color appearance unambiguously. The same color stimulus in terms of CIE XYZ tristimulus or CIELAB L*a*b* values could have entirely different appearances under disparate media/viewing environments. As far as the global conditions under which a color is viewed are concerned, some critical factors affecting its appearance include the medium type, the white point, the background, the surround, the adapting stimulus, the luminance level, and cognitive discounting the illuminant etc. This is a critical issue needed concerned due to limitless possible sets of media/viewing conditions involved in practical situations. To deal with these complications just mentioned, the internationally practical solution is to derive appearance-based color-encoding models. Thus, the perceptual color appearance attributes of stimuli of interest can be predicted by taking into account the influence of the environment under which they are viewed.

Recently, CIE TC1-31 has completed a series of tests to investigate the performance of various previously published color appearance models and data sets. A new model, based on the results of tests, was formulated by incorporating the best features from these existing color models and announced at the 1997 CIE Division 1 meeting in Kyoto, Japan (Hunt 1997). Two versions of this model were derived due to practical and effective needs. These are simple and comprehensive versions of CIECAM97 designated as CIECAM97s and CIECAM97c models respectively. In this study, a work involving color appearance modeling was encompassed. A set of experiments was conducted under an average surrounding using single stimuli in a simple field. The CIECAM97s was compared with a variety of existing color models for achieving high color fidelity between a reproduced self-luminous color (softcopy) and the original surface color (hardcopy). The test of color models' performances using single stimuli in a simple field will be also extended to conduct under a dim surrounding in a darkened room in a near future. Successively, a more advanced study will be performed using complex images, which are practically often used in areas of such as graphic arts and desktop publishing. Based on the findings obtained using both single stimuli and complex images, the best performing color model found (assuming CIECAM97s) will be verified. These works are consecutively conducted closely to link to the task of CIE TC1-34, Testing Color Appearance Models, established to test various models for the prediction of the color appearance, under various media/viewing conditions and phenomena, of object colors (Fairchild 1997). The ultimate goal of this research, as expected by CIE TC1-34, is that, at some future day, *a more accurate and/or theoretical-based model might be evolved.*

COLOR APPEARANCE MODELS TESTED

In this study, color models tested were classified into three categories as follows.

- Uniform Color System: CIELAB (CIE 1986)
- Chromatic-Adaptation-Transforms: von Kries (Helson et al. 1952)
- Color Appearance Models: ZLAB (Fairchild 1997b), LLAB (1996), Hunt (1994), CIECAM97s.

EXPERIMENTAL PREPARATION

Device Characterization

A Barco monitor was used to display screen colors under an average surrounding. The Barco monitor, internally set white point to the color temperature tested in each particular phase in this study, was characterized using the 3^{rd}_SVD (3^{rd} polynomial) characterization model derived by Lo et al. (1998). Two characterization data sets of 729 (cube) and 54 color patches were created for each white point of interest. The latter was composed of 18 sample patches produced for each of red, green, and blue channels in terms of 15 DAC interval ranging from 0 to 255 values. Based on perceptually equal step-to-step differences, the cube data set was rendered using 9×9×9 matrix. The measurement equipment used was a PR650 SpectraColorimeter, manufactured by Photo Research.

Image Preparation and Processing

A set of 36 single color patches, in terms of 3 variations in lightness and chroma approximately at 12 different hues in CIELAB color space (shown in Fig.1), was chosen from Pantone Color Selector to be the original surface colors (hardcopies). Those covered a wide color space and had Y values ranging from 5 to 95. The spectral reflectance values, ranging across 360-740 nm with a 20-nm interval, of each color were measured using a Macbeth Color-Eye 3100 Spectrophotometer. Tristimulus values were then calculated, against the real light source used in viewing those hardcopies in each corresponding experimental phase considered.

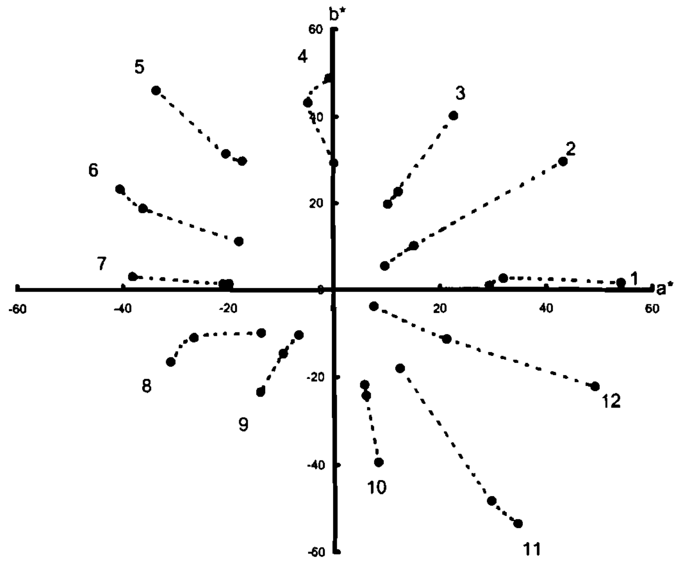

Fig. 1 The (a*, b*) coordinates of 36 single color patches tested, chosen in terms of 3 variations in lightness and chroma approximately at 12 different hues in CIELAB color space.

Image processing software was developed to correlate the hardcopy's XYZ values (in the reference field) to the monitor's RGB intensities (i.e. DACs) (in the test field) for a particular color model tested on a pixel by pixel basis. The computational process is illustrated in Fig. 2. The XYZ and X′Y′Z′ tristimulus values specifically form a set of corresponding colors, having the same color appearance when viewed under adapting fields of hardcopy (reference) and softcopy (test) viewing conditions respectively. The monitor characterization model described earlier were applied to convert X′Y′Z′ to RGB intensities.

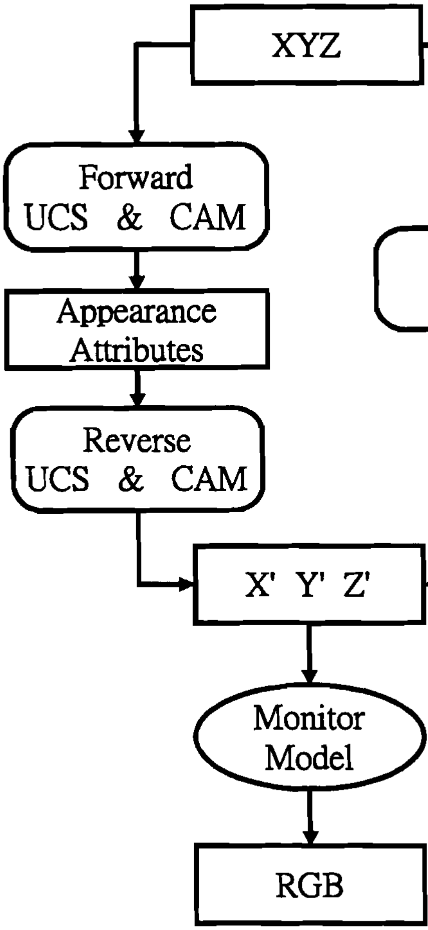

Fig. 2 Computational procedures of image processing correlating the hardcopy's XYZ values to the monitor's RGB intensities for each particular color model tested. The UCS, CAM and CAT processes represent uniform color space, color appearance model and chromatic adaptation transform respectively.

For different categories of color models, the computational procedures are varied. For chromatic adaptation transforms, the XYZ values were directly transformed to X′Y′Z′. As for each uniform color space or color appearance model, the predicted lightness, chroma, and hue are first calculated via its forward model and followed by computing its corresponding X′Y′Z′ using the model's reverse.

EXPERIMENT

Viewing Conditions

The experiment was divided into two categories and 4 phases according to different light sources and white points used in the viewing reflection hardcopies (single patches in the reference field) and screen softcopies (single patches in the test field). Table 1 summaries the differences among all phases. A panel of 5 observers attended and repeatedly made the assessments twice in each of 4 phases. In total, 21, 600 comparisons were made.

The correlated color temperatures (CCTs), luminances and colorimetric data used for both hardcopy (reference) and softcopy (test) fields in each phase under an average surround are tabulated in Table 2. The luminance level of white points used for both screen display and viewing hardcopy was approximately set to 70 cd/m^2 for all Phases 1 to 4.

Table 1 Summary of experimental phases.

Phase	Hard -copy	Soft -copy	VT[a]	MD[b]	No. of observers	Repetition	Pairs	No. of comparisons
Category 1								
1	D65	D65	BSM	SS	5	2	1,080	5,400
Category 2								
2	D65	D93	BMM	SS	5	2	1,080	5,400
3	A	D65	BMM	SS	5	2	1,080	5,400
4	A	D93	BMM	SS	5	2	1,080	5,400
Total					5		4,320	21,600

VT: viewing technique; MD: monitor display; [a]BSM : binocular simultaneous matching
[b]SS : simultaneous display; BMM : binocular memory matching.

Table 2 Colorimetric data and luminances used for both hardcopy (reference) and softcopy (test) fields in each phase under an average surround.

Phase	1	2	3	4
Hardcopy field				
White point	D65	D65	A	A
CCT	6154K	6154K	2758K	2758K
L (cd/m^2)	71.54	71.54	71.87	71.87
X	92.24	92.24	110.91	110.91
Y	100.00	100.00	100.00	100.00
Z	98.00	98.00	32.24	32.24
x	0.3178	0.3178	0.4561	0.4561
y	0.3445	0.3445	0.4113	0.4113
u'	0.1956	0.1956	0.2598	0.2598
v'	0.4771	0.4771	0.5270	0.5270
Softcopy field				
White point	D65	D93	D65	D93
CCT	6394K	8884K	5854K	8011K
L (cd/m^2)	71.29	70.44	73.42	72.58
X	94.32	92.24	95.80	95.69
Y	100.00	100.00	100.00	100.00
Z	105.92	136.24	99.29	129.68
x	0.3141	0.2851	0.3247	0.2940
y	0.3331	0.3026	0.3389	0.3073
u'	0.1973	0.1882	0.2024	0.1929
v'	0.4707	0.4493	0.4753	0.4535

Note: CCT: correlated color temperature

View Configuration and View Techniques

Fig. 3 illustrates the display arrangements configured in the experiment. The experimental viewing pattern basically included a test color being surrounded by 11 color patches, which were randomly selected from the Pantone Color Paper Selector, along with the "reference white". Two reproduced viewing patterns of softcopies in the test field were displayed side by side. Each reproduced pattern had equal size to that of the original hardcopies diffusely illuminated in the reference field.

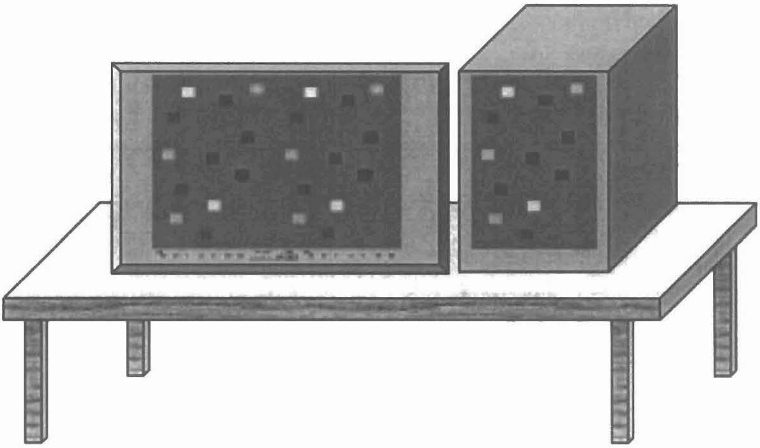

Fig. 3 Experimental viewing configurations.

Table 3 Colorimetric data, luminance of gray background used in the reference (hardcopy) field.

Phase	Source	x	y	L	X	Y	Z
Phases 1 & 2	D65	0.3194	0.3506	16.27	20.72	22.74	21.40
Phases 3 & 4	A	0.4593	0.4095	18.00	28.09	25.05	8.02

In Category 1 experiment, the chromaticities and luminances of both the white points and the gray backgrounds used in the test field were similar to those in the reference field (Table 3). Therefore the binocular simultaneous matching (BSM) technique was applied. Only one light source, D_{65}, was investigated (i.e. Phase 1). Each observer sat in a bright room under an average surrounding, at approximately 100 cm from the monitor and original considered. Two viewing patterns of test patches on monitor were arranged approximately co-planar. Each observer was instructed to use both eyes to look at either the test or the reference fields at a time, but could switch between two fields at any time.

In Category 2 experiments, the binocular memory matching (BMM) viewing technique was adopted due to different sets of chromaticities and luminances of white points used for both fields. A comprehensive study was carried out by Braun et al. (1996) to investigate methods for scaling the color fidelity of color images. It was found that the BMM technique, among 5 viewing techniques, gave the most reliable results when hardcopy and softcopy white points had different colorimetric values. Three phases included in Category 2 experiment. For instance, in Phase 3 the reference field was illuminated by a source A, whereas the white point in the test field (monitor) was set close to the chromaticities of the D_{65} illuminant. To avoid incomplete adaptation when comparing two simultaneously displayed softcopies, only one background color was rendered on the Barco monitor in each phase of Category 2 (Table 3). It was profiled in terms of the mean RGB DAC values obtained by averaging those of the background colors predicted from all the models in each particular phase. The reference and test fields were arranged to ensure that observers could not view both fields at the same time. Table 4 lists the parameters used in each of color appearance models tested, accounting for effects of such as cognitive or sensory chromatic mechanism, surroundings etc.

DATA ANALYSIS

A forced-choice paired comparison method was employed in this experiment. It was based on the judgements made for the color-fidelity quality of test colors reproduced by color models of interest. A panel of 5 observers viewed a paired of reproduced softcopies, and judged which of the two gave a better match (i.e. color fidelity) to the original hardcopy (as shown in Fig. 3). In addition, they also accessed the degree of match of the softcopy against the hardcopy using a predetermined equi-interval of 7-point category scale for overall color fidelity. Each observe entered visual results via radio buttons numbered from 1 to 7, which were located underneath each corresponding viewing pattern. The resulted visual data were then analyzed using the laws of both category judgement (Togerson 1958) and comparative judgement (Thurstone 1927, Bartleson and Grum 1984).

Table 4 Parameters used for Hunt, LLAB, ZLAB and CIECAM97s color appearance models in the experiment.

Phase	1	2	3	4
Hunt				
Hardcopy Field				
L_A	17.42	16.72	6.77	6.77
Flas	1.056	1.073	0.600	0.600
N_c	1.0	1.0	1.0	1.0
N_b	75	75	75	75
Soft Field				
L_A	17.42	16.72	6.77	6.77
Flas	1.062	1.221	1.042	1.195
N_c	1.0	1.0	1.0	1.0
N_b	75	75	75	75

L_A : Photopic luminance of adapting field
Flas : Scotopic luminance level conversion factor
N_c : Chromatic surround induction factor
N_b : Brightness surround induction factor

Phase	1	2	3	4
LLAB				
Hardcopy Field				
D	1.0	1.0	1.0	1.0
F_S	3.0	3.0	3.0	3.0
F_L	1.0	1.0	1.0	1.0
F_C	1.0	1.0	1.0	1.0
Soft Field				
D	1.0	1.0	1.0	1.0
F_S	3.0	3.0	3.0	3.0
F_L	1.0	1.0	1.0	1.0
F_C	1.0	1.0	1.0	1.0

D : Discounting-the-illuminant factor
F_S : Surround induction factor
F_L : Lightness induction factor
F_C : Chroma induction factor

Table 4 Parameters used for Hunt, LLAB, ZLAB and CIECAM97s color appearance models in the experiment. (Continued)

Phase	1	2	3	4
ZLAB				
Hardcopy Field				
L_A	17.42	16.72	6.767	6.767
F	1.0	1.0	1.0	1.0
D	1.0	1.0	1.0	1.0
$1/2\sigma$	0.345	0.345	0.345	0.345
Soft Field				
L_A	17.42	16.72	6.767	6.767
F	1.0	1.0	1.0	1.0
D	1.0	1.0	1.0	1.0
$1/2\sigma$	0.345	0.345	0.345	0.345
CIECAM97s				
Hardcopy Field				
L_A	17.42	16.72	6.767	6.767
F	1.0	1.0	1.0	1.0
c	0.69	0.69	0.69	0.69
F_{LL}	1.0	1.0	1.0	1.0
N_c	1.0	1.0	1.0	1.0
D	1.0	1.0	1.0	1.0
Soft Field				
L_A	17.42	16.72	6.767	6.767
F	1.0	1.0	1.0	1.0
c	0.69	0.69	0.69	0.69
F_{LL}	1.0	1.0	1.0	1.0
N_c	1.0	1.0	1.0	1.0
D	1.0	1.0	1.0	1.0

L_A : Luminance of adapting field
F : Factor for degree of adaptation
c : Impact of surround
F_{LL} : Lightness contrast factor
N_c : Chromatic-induction factor
D : Degree of adaptation
σ : Impact of surround

The ranking method of the category judgement yields ordinal data. Theoretically, an ordinal scale involves assigning stimuli on a limited usually numerical scale correlating with their magnitude for a specified attribute. The rule for assigning number on an ordinal scale is that the ordinal position (rank order) of numbers on the scale must represent the rank order of psychological attributes of the stimuli of interest. In this study, the 7-point category scale for color fidelity is defined from 1 (exact match), through 4 (acceptable match) to 7 (awful match) as below.

Category Rank	1	2	3	4	5	6	7
Word Category Scale	Exact Match	Good Match	Moderate Match	Acceptable Match	Poor Match	Bad Match	Awful Match

Note that the law of categorical judgement relates the relative position of a specified attribute, of the stimuli considered with respect to category boundaries on the psychological continuum rather than with respect to one another as Thurstone's law of comparative judgement does. The results obtained using this approach would, hence, serve as a basis to locate the models tested on the absolute scales of color-fidelity quality. The models tested are considered to have similar performances if they were located on the same category of color fidelity. Therefore an identical category rank number would designate these models.

RESULTS AND DISCUSSION

The results in terms of z score obtained using the law of comparative judgement are summarized in Table 5. A model tested is considered not to be significantly different from another if its z score is within the 95% confidence limit (CL, i.e. ±2 units of standard deviations) of the other. Hence, these would be ranked in the same order. The overall results are also depicted in Fig. 4 for Phases 1 to 4. Each point in these figures represents the z score of a model of interest, and a line drawn indicates its 95% confidence limit (CL).

From the overall results shown in both Table 5 and Fig. 4, it can be clearly seen that there are insignificant differences among all 4 models tested in Phase 1 wherein the similar viewing conditions were used for both the reference and the test viewing fields. This indicates that identical colorimetric data in terms of XYZ or L*a*b* values should enough provide a satisfactory visual match of images between the reference and test fields. This agrees with what has been found in an earlier experiment conducted by Lo et al. (1996).

Table 5 Paired comparison results in terms of z-score scale based on the judgements made for the overall color-fidelity accuracy obtained from all 36 test colors combined. (95% CL = ±0.4383 for all phases)

Phase	Hard -copy	Soft -copy	z-score scales					
			von Kries	CIELAB	ZLAB	LLAB	Hunt	CIECAM97s
1	D65	D65	-0.2792	0.0349	-0.0418	*0.2652*	0.0418	-0.0209
		Rank	2	1	1	1	1	1
2	D65	D93	-0.5767	-0.8950	0.3882	0.4413	-0.5481	*1.1903*
		Rank	4	4	2	2	4	1
3	A	D65	-0.7030	-1.4930	0.9709	0.7577	-0.5921	*1.0595*
		Rank	4	6	1	1	4	1
4	A	D93	-1.4387	-1.6252	0.7837	0.6924	-0.5658	*2.1536*
		Rank	5	5	2	2	4	1

Note: The underlined figure indicates the best performing model in a particular phase, and CL represents confidence limit.

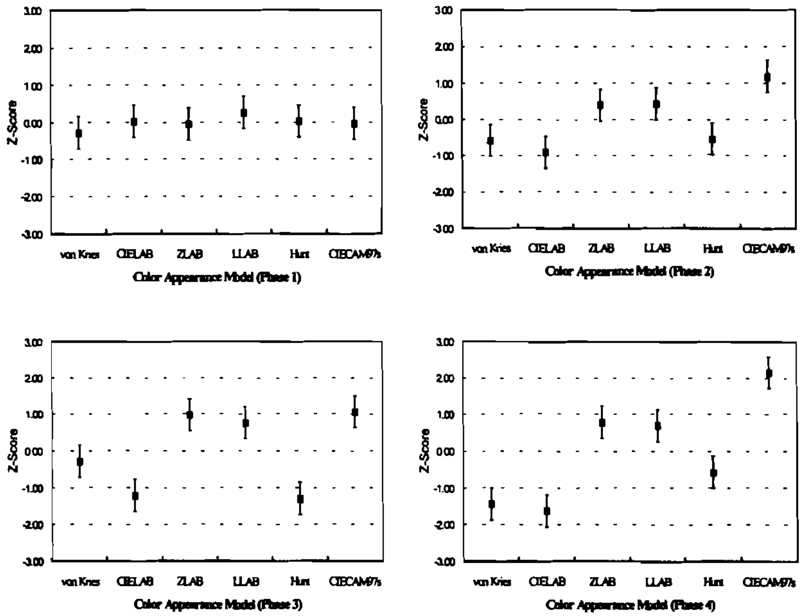

Fig. 4 Color models' performance evaluated using the law of comparative judgement for the overall color-fidelity accuracy of all 36 test colors from Phases 1 to 4 (including 95% confidence limit).

Table 6 Category ranking results, including both boundary estimates and category scales, based on the judgements made for the degree of match obtained from all 36 test colors combined.

Phase	Hard -copy	Soft -copy	Boundary estimates (T_i)					
			T_1	T_2	T_3	T_4	T_5	T_6
1	D65	D65	0.0000	0.7027	1.1839	1.7390	2.3883	3.0760
2	D65	D93	0.0000	0.8771	1.4263	1.8648	2.5533	3.4500
3	A	D65	0.0000	0.6754	1.1539	1.6470	2.3416	3.1501
4	A	D93	0.0000	0.6699	1.1787	1.6829	2.2922	3.1244

Phase	Hard -copy	Soft -copy	Category scales					
			von Kries	CIELAB	ZLAB	LLAB	Hunt	CIECAM97s
1	D65	D65	1.5548	1.5872	1.5673	*1.6104*	1.5787	1.5605
		Category Rank	4	4	4	4	4	4
2	D65	D93	1.6981	1.6154	1.7534	1.7553	1.7320	*1.7967*
		Category Rank	4	4	4	4	4	4
3	A	D65	1.1126	1.0267	1.2219	1.2039	1.1256	*1.2504*
		Category Rank	5	5	4	4	5	4
4	A	D93	0.9552	0.8888	1.2117	1.1944	0.9598	*1.4120*
		Category Rank	5	5	4	4	5	4

Note: The underlined figure indicates the best performing model in a particular phase.

Overall, the CIECAM97s model outperformed the others in Phases 2-4, wherein different chromaticities were used for the hardcopy and softcopy white points. Both the LLAB and the ZLAB models performed similar to the CIECAM97s in Phase 3, whereas they gave average level of predictions for Phases 2 and 4. However the Hunt model didn't give satisfactory predictions for Phase 2-4. The von Kries performed slight better than both the CIELAB and the Hunt models in Phase 3. The CIE model together with the von Kries model was consistently judged worse than other models for Phases 2 and 4.

As mentioned earlier, the raw visual data from this experiment were also transformed to an interval scale using a method described by Torgerson (1958). Empirical estimates of both the scale values of the color models tested and category boundaries of 7-point scale were obtained and summarized in Table 6. The data for category scales are not normally distributed as those are obtained on an ordinal scale as mentioned above. Nevertheless, it is assumed that the data would be forced to fit the statistical normal distribution, accomplished by dealing with the cumulated, if they were transformed in Torgenson's method.

It is encouraging to see that the model, performing the best found in the results obtained using the law of comparative judgement, also had top rank in those obtained using the law of category judgement for each of 4 phases tested. Moreover, all models outperforming or giving average predictions, were located on the category scale of "acceptable match".

CONCLUSION

This study closely followed up the task of CIE TC1-34, Testing Color Appearance Models, established to test various models for the prediction of the color appearance of object colors. The experiment was divided into 4 phases according to different light sources and white points used in the viewing reflection hardcopies and screen softcopies. Both the paired comparison and the category ranking techniques were applied to analyze the raw visual results, obtained by a 7-point category scale for color-fidelity. The evaluation of results shows that all models tested gave satisfactory predictions for the D_{65} used in both the reference and the test fields. It suggests that the CIELAB (also CIEXYZ) system should be accurate enough to fulfill color matches across media for the symmetrical viewing conditions (e.g. showing in Phase 1 in this study). In other words, a simple colorimetric match among media is practically adequate for the majority of color imaging applications wherein similar viewing conditions are used. For asymmetric viewing conditions wherein different chromaticities were used for the hardcopy's and the softcopy's reference whites, the CIECAM97's model overall performed better than other models. Moreover, the color fidelity of colors produced using the best performing model found in each of 4 phases was all at least on the category scale of acceptable match.

The work in the test of color appearance models' performance will be further extended to carry out using also single color stimuli in a simple viewing field in a darkened room under a dim surround. An advanced testing using complex images practically often used will be successively proceeded. The findings obtained will be compared and/or conformed to those found using single stimuli and based on to further verify the best performing color model (assuming CIECAM97s). These anticipated scientific insights will, at some time in the future as expected by CIE TC1-34, allow the derivation of more theoretically correct models, capable of predicting the change of perceived attributes of color appearance under various media/viewing conditions and phenomena.

ACKNOWLEDGMENTS

This research has been mainly financed by the Industrial Technology Research Institute, Taiwan, R. O. C.

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