A Comparison of Five Color Order Systems

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Abstract: Five color order systems (Munsell Renotations, Munsell Re-renotations, OSA-UCS, NCS, and Colorcurve) have been compared by optimizing the powers applied to individual opponent-color functions. The results indicate general similarities in that powers applied to the red and green functions tend to be closer to 1, while those applied to the blue function and the yellow function are generally smaller. Specifically, there are many individual differences that make each system unique. The results inspire confidence in the veracity of the opponent-color system methodology. © 2000 John Wiley & Sons, Inc. Col Res Appl, 25, 123–131, 2000

Key words: color order systems; color scaling; opponent-color system

INTRODUCTION

According to Wyszecki and Stiles, "A color order system is a rational method or a plan of ordering and specifying all object colors or all within a limited domain by means of a set of material standards selected and displayed so as to represent adequately the whole set of object colors under consideration."[1] Over the last 100 years, several systems have been developed and some are in regular use. It is of interest to compare some of these systems in an objective way, based on the new insight that an optimal fit between a mathematical model and the colorimetric values of the aim samples can be achieved by application of varying powers to their normalized tristimulus values.[2]

The following systems have been compared:

1. Munsell Renotations (REN): these represent the aim colors of the current *Munsell Book of Color* and are tabulated in Ref. 1. They represent improvements in hue, chroma, and lightness spacing of the Munsell colors compared to Munsell's original work and have resulted from efforts of the OSA Subcommittee on the Spacing of Munsell Colors. They were originally published in 1943. Three attributes have been scaled: hue, chroma, and lightness. The hue scale has 100 steps, forty of which have been illustrated and are listed in the Renotations. The lightness scale has ten steps and the chroma scale is open-ended. The geometrical arrangement is cylindrical. The Renotations are expressed in terms of the CIE 2° observer. The Munsell system is widely known and widely used, and its history has been described by Nickerson[3] and Berns and Billmeyer.[4]
2. Munsell Re-renotations (RERE): these presumably were considered at the time of their publication to represent an improvement in spacing over that of the Munsell Renotations. The data have been published as National Bureau of Standards Report 192693 in December of 1967.[5] They represent the results of hundreds of thousands of visual judgments to improve on the uniformity of spacing of the Renotations. The lightness has been adjusted to compensate for the Helmholtz–Kohlrausch effect. They are also expressed in terms of the CIE 2° observer. They have not been implemented as a *Book of Colors* and are not mentioned in Nickerson's history of the Munsell system.
3. Optical Society of America Uniform Color Scales (UCS): These represent the fruit of further labors of many of the people behind the Renotations and the Re-renotations, now in the OSA Committee on Uniform Color Scales. The UCS were published in 1974 and are expressed as the OSA Color System in a book of colors and as colorimetric information. The colorimetric data of the aim colors are in terms of the CIE 10° observer and are published in Ref. 1. The spacing in the UCS is based on a regular rhombohedral lattice and does not explicitly result in a hue circle at equal chroma. Lightnesses have been adjusted for the Helmholtz–Kohlrausch effect as well as for the effect of the

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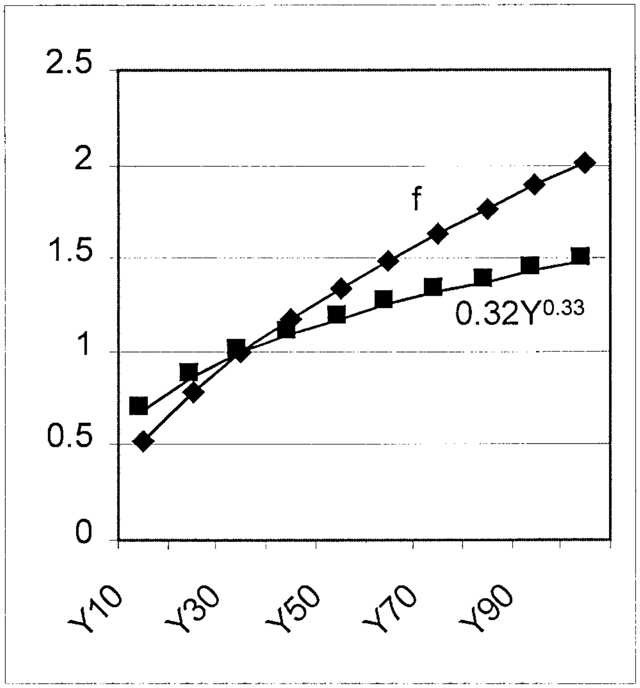


FIG. 1. Scaling factor *f* and, for comparison, cube root of *Y* as a function of *Y*.

surround lightness. The development of the UCS has been described by MacAdam.[6]

4. Natural Color System (NCS): This system has been developed as an implementation of the Hering opponent color system. It is the basis of the Swedish standard SS019100-03. It exists in form of a *Colour Atlas*, a color notation system, and colorimetric specifications of the aim colors. These have been expressed in terms of the CIE 2° observer. The fundamental scales of the NCS are blackness, chromaticness, and hue. Forty hue steps have been illustrated and defined. At their highest chromaticness level (similar to chroma), which is equal to zero blackness, they fall on a plane. The system's geometrical form is a double cone. It has been developed to have equal visual steps of hue, blackness, and chromaticness. The development of the NCS has been described by Hård, Sivik, and Tonnquist.[7]
5. Colorcurve System (CC): This system has been developed without any claims for visual uniformity. It is uniform in that equal steps between neutral gray and a color with a^* or $b^* = 60$ are based on equal percentage changes in the tristimulus values. It does not explicitly result in hue circles at equal chroma. Its geometrical arrangement is cubic. It has been implemented as a book of colors, and the colorimetric data of the aim colors are available in terms of the CIE 10° observer. The development of the system has been described by Stanziola.[8] Its inclusion in this exercise is for comparison purposes only, and a formula has been fitted as if the system were visually uniform.

SYSTEM UNIVERSALS

Common to all five systems is that they can be seen as based on various interpretations of an opponent-color system. This is not explicit in REN and RERE because of Munsell's choice of five fundamental hues. However, new analyses have shown that REN (and presumably RERE) can be well and completely described in terms of four fundamental hues.[9] This also becomes apparent, if one plots chromatic data of a REN or RERE hue circle at equal chroma and lightness in an *a, b* diagram.

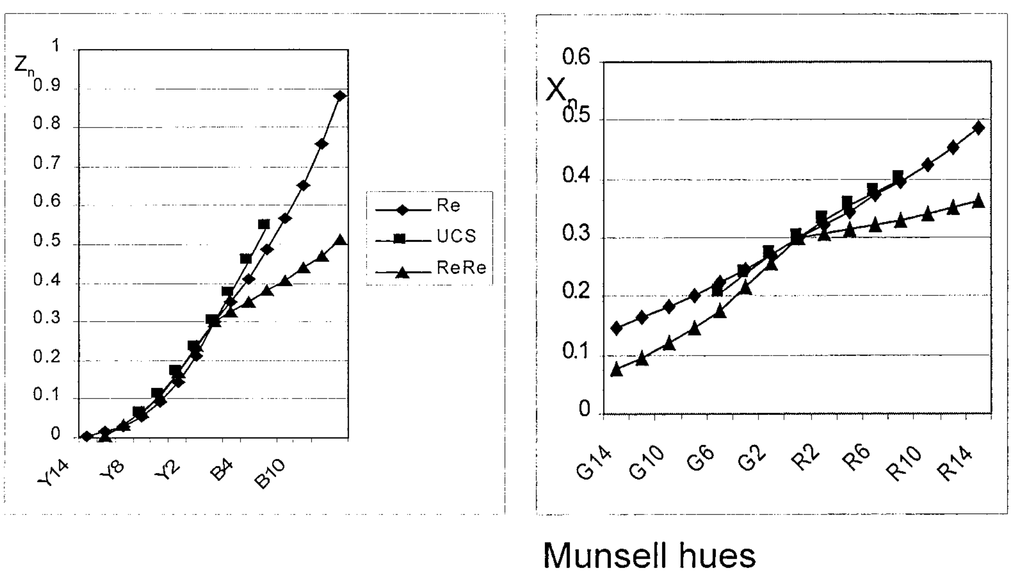
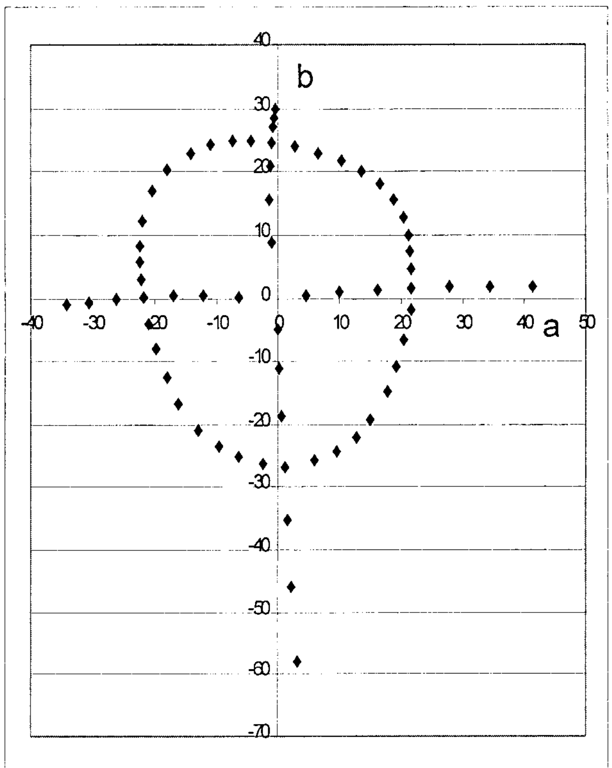


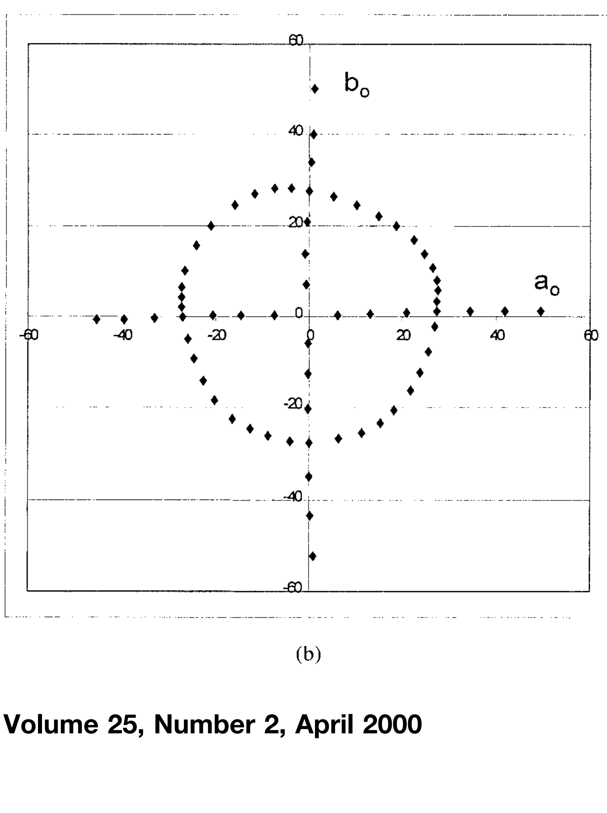
FIG. 2. Change in the normalized tristimulus values *Z* and *X* as a function of chroma of near unique hues at value 6 in the REN and RERE systems, as well as at $L = 0$ in the UCS system. Left half: Z_n as a function of yellowness-blueness from yellow chroma 14 via neutral to blue chroma 14. Right half: X_n as a function of greenness-redness from green chroma 14 to red chroma 14. Chroma steps in REN and UCS are similar in size.

TABLE I. Constants for the basic formula optimized for the five color order systems.

	a					b			
	M(R)	Power *m*	M(G)	Power *n*	*f(Z)*	M(Y)	Power *p*	M(B)	Power *q*
RE	600	0.5	500	0.5	0.02	210	0.333	245	0.5
RERE	600	0.75	1380	0.333	0.05	315	0.75	270	1
OSA-UCS	600	1	640	1	0.075	480	0.5	530	0.5
NCS	600	0.333	200	1	0.03	160	0.333	275	0.333
CC (R)	600	1	867	1	0	568	1	188	1



(a)



(b)

FIG. 3. REN hue circle at value 6/chroma 8 and near unique hue colors at chroma steps from 2–14 (a) in the linear *a, b* diagram and (b) in the optimized diagram.

If there are four fundamental color processes, as has been claimed by Hering, and as neurophysiological data appear to confirm, then, if one scales the four processes on the four semi-axes appropriately, one presumably also has correctly scaled the intermediary colors on a hue circle that are combinations of the two fundamental colors involved in their creation. There are two aspects to "appropriate" scaling. One has to do with the unresolved question of whether visual hue scaling is based on equal changes in a polar coordinate or a Cartesian coordinate system. The former imposes a slightly sinusoidal nonlinearity on the scales of the two fundamental hues. The latter imposes this nonlinearity on the hue angle differences between adjacent hues when illustrated in a polar system.[2] The other is a system-related nonlinearity imposed by the operation of the opponent-color system.

The general facts of our standard visual color space can be surprisingly well approximated with an opponent-color system based on subtractions of normalized tristimulus values. When the differences are adjusted to reflect equal areas under the opponent function curves, reasonable hue circles are obtained, at least at lower chromas. The mentioned system-related nonlinearity emerges most strongly at higher chromas.

An additional issue involves the agreement, or lack thereof, between the psychological fundamental colors as expressed by the unique hues and the model fundamental colors. Ideally, the two sets of axes would be identical. The 2° observer system axes colors are in good agreement with the unique hues experimentally determined by the author.[2] The unique hues of the NCS system are generally noticeably different from the model axes. The yellow-blue model axis, as determined by subtraction of the 10° observer color matching functions, is significantly different from the psychological yellow and blue unique hues, as can be seen in UCS. This issue requires further clarification.

The current standard model for the visual color space is the CIELAB space. In a previous article, I have shown that application of cube roots to the normalized tristimulus values does not describe color order systems optimally.[2]

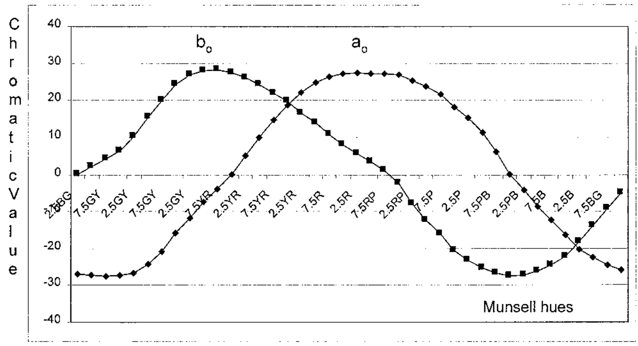


FIG. 4. Progression of optimized *a* and *b* values through the REN hue circle at value 6/chroma 8.

a AND *b* ADJUSTMENT AS A FUNCTION OF LUMINOUS REFLECTANCE

As mentioned in the previous article, an advantage of the CIELAB formula is that through the application of cube roots to all three normalized tristimulus values the a^* and b^* values are automatically appropriately spaced to result in equal hue and chroma differences at different lightness levels, i.e., the conical *a, b, Y* space is efficiently converted to a cylindrical a^*, b^*, L^* space. A new formula has been found that achieves the required adjustment of the properly scaled *a* and *b* values. It is illustrated in Fig. 1 in comparison with the cube root of *Y*. It has been empirically found in the fitting of an optimized formula to REN, as described in the previous article. It has since been confirmed to apply also to optimizations for RERE and UCS. The different structures of NCS and CC makes those data unsuitable for testing of the formula.

FITTING OPTIMAL FORMULAS

The fitted formulas are optimal to the extent that is achievable with different weighting factors and powers applied to simple differences in the normalized tristimulus values. (These are defined as $N_n = N/N_0$, where N is a tristimulus value for one of the two standard observers and a given illuminant, and N_0 is the corresponding tristimulus value for that illuminant.)

The basic formula used is:

If $X_n > Y_n$,

$$a_o = \frac{M_R}{p}[((1 + f_z)\, X_n^m Y_n^{1\text{-}n}) - Y_n - (f_z Z_n)];$$

if $Y_n > X_n$,

$$a_o = \frac{M_G}{p}[((1 + f_z)\, X_n^n Y_n^{1\text{-}n}) - Y_n - (f_z Z_n)];$$

$$\text{if } Y_n > Z_n, \quad b_o = \frac{M_Y}{p}[Y_n - (Z_n^p Y_n^{1-p})];$$

$$\text{if } Z_n > Y_n, \quad b_o = \frac{M_B}{p}[Y_n - (Z_n^q Y_n^{1-q})], \tag{1}$$

where a_o, b_o are the optimized *a* and *b* values, the normalized tristimulus values N_n have been defined earlier, p has a value of $0.133Y^{0.59}$, $M_{R,G,Y,B}$ are scaling multipliers for the corresponding system semi-axes, *m, n, p, q* are powers, f_Z is a factor that adjusts the balance between the short wave lobe and the long wave lobe of the $\bar{x}$ color-matching function (see Ref. 2).

The optimizations were done, where possible, using data at a *Y* value near 30 (Munsell value 6). Arbitrarily, in these optimizations the value of M_R has been set at 600 in all cases. The object of the optimizations was to have as uniform as possible, and equal, spacing of the colors along

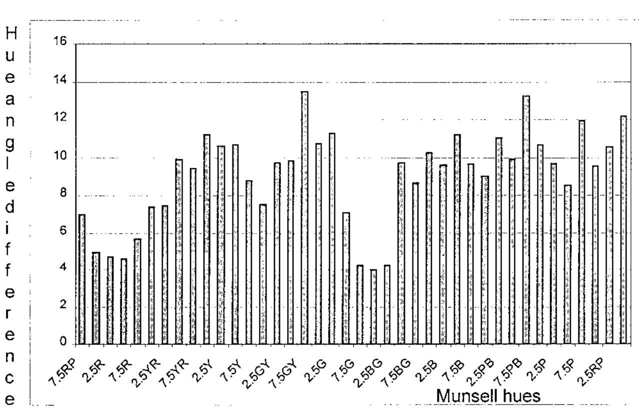


FIG. 5. Hue angle differences between adjacent REN hues at value 6/chroma 8 as a function of Munsell Hue.

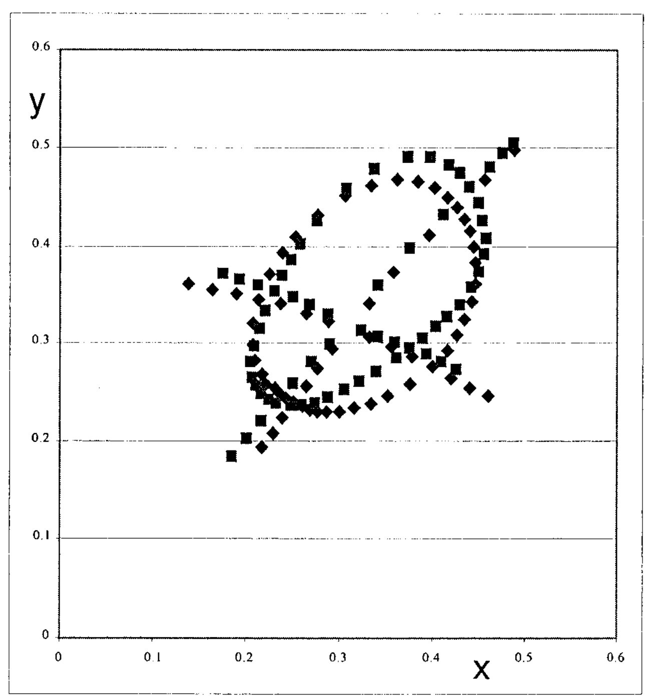
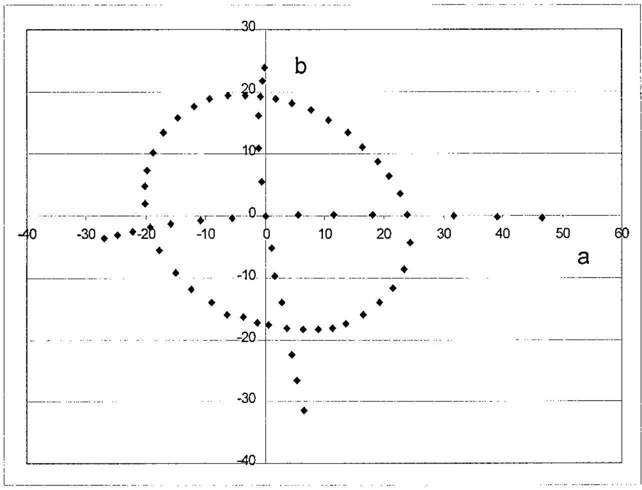
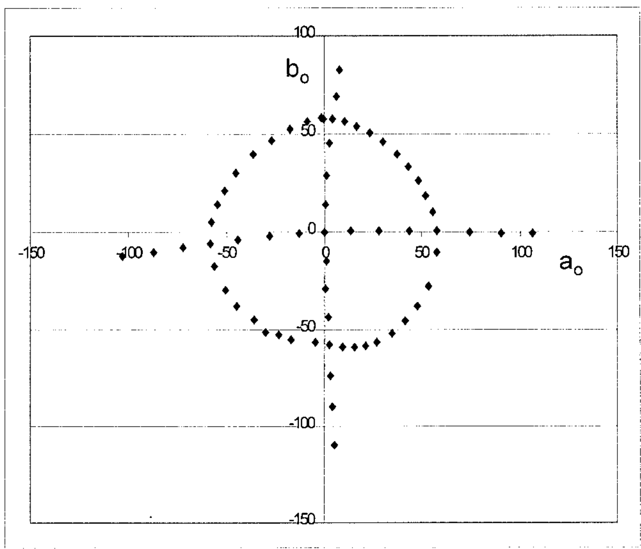


FIG. 6. Comparison of the chromaticities of (■) REN and (♦) RERE colors in a portion of the CIE 1931 chromaticity diagram. Near unique hues at chroma 2–14 and hue circles at value 6/chroma 8.



(a)



(b)

FIG. 7. RERE hue circle at chroma 8 and near unique hue colors at chroma steps 2–14 at value 6 (a) in the linear *a, b* diagram and (b) in the optimized diagram.

the two main system axes. This requires the linearization of the change in Z_n values for colors on or close to the *b* axis, and correspondingly for X_n values along the *a* axis. The changes in these values for REN, RERE, and UCS are shown in Fig. 2 for colors between neutral and chroma 14. It is apparent that the three systems show more or less significant differences in this respect. It is also apparent that a much larger portion of the available scale is used up in the Yellow-Blue (*b*) system than in the Green-Red system (*a*).

The results of the optimizations are listed in Table I. The results are shown graphically by plotting the colors nearest the system axes at various chroma steps (as data are available) and, where possible, those of a complete hue circle. The effects of the scaling multipliers, the applied powers, and the f_Z factors are shown by comparison with a plot of the same colors in a linear *a, b* diagram where $a = 227\ (X_n - Y_n)$ and $b = 100(Y_n - Z_n)$, (equal areas under the opponent-color functions).

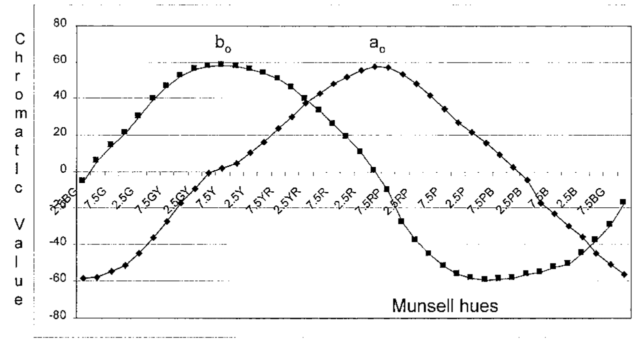


FIG. 8. Progression of optimized *a* and *b* values through the RERE hue circle at value 6/chroma 8.

DISCUSSION

Excluding CC, in two of the four cases a different power is required for the yellow half of the *b* axis compared to the blue half, and in both cases the power *p* has a lower value than the power *q*. The powers *m* and *n* are identical in two cases and differ in opposite direction in the other two.

The required adjustment of the $\bar{x}$ function is smaller for the 2° observer than for the 10° observer. For REN (2° data) f_Z has a slight dependence on *Y*. This has not been included in the above optimization equation. No such dependence was found for the UCS data (10° data).

Munsell Renotations

Further analysis has indicated that, unlike given in a previous article,[2] the optimum power for a_o is 0.5. Figures 3(a) and (b) show the hue circle and axes colors at V6 in the linear and the optimized diagrams. While there is much improvement in the optimized plot along the *b* axis, the yellow colors are still unevenly spaced. The changes in the a_o and b_o values for the hue circle are shown in Fig. 4. This figure can be compared to similar figures in Ref. 2. There is considerable unevenness in hue spacing, a situation that is

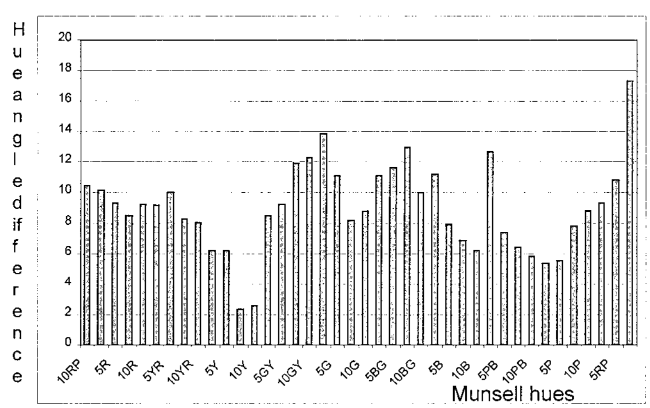
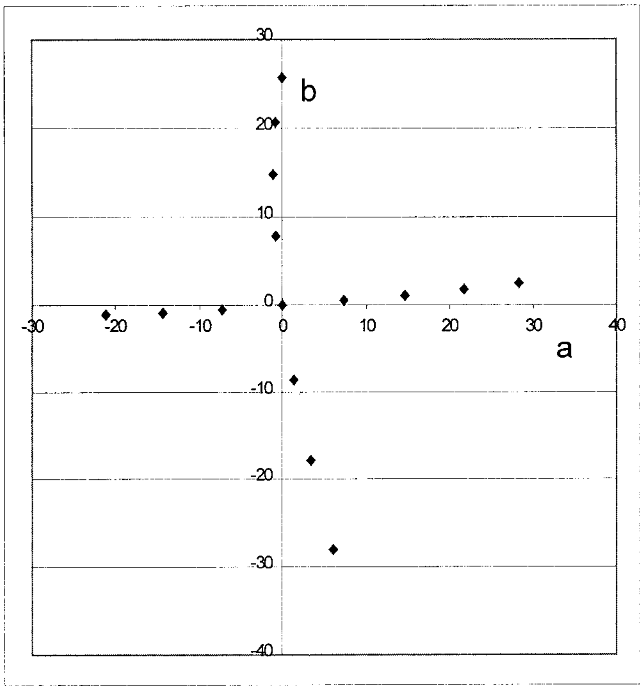
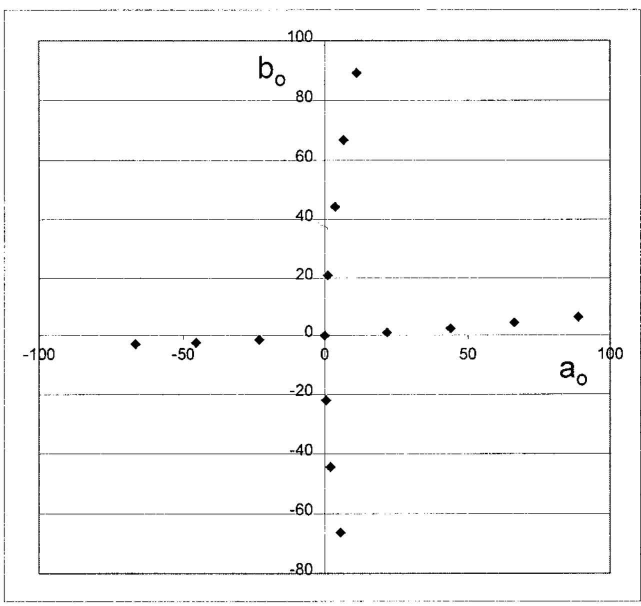


FIG. 9. Hue angle differences between adjacent RERE hues at value 6/chroma 8 as a function of Munsell Hue.



(a)



(b)

FIG. 10. UCS unique hue colors at L = 0 and various chroma levels (a) in the linear *a, b* diagram and (b) the optimized diagram.

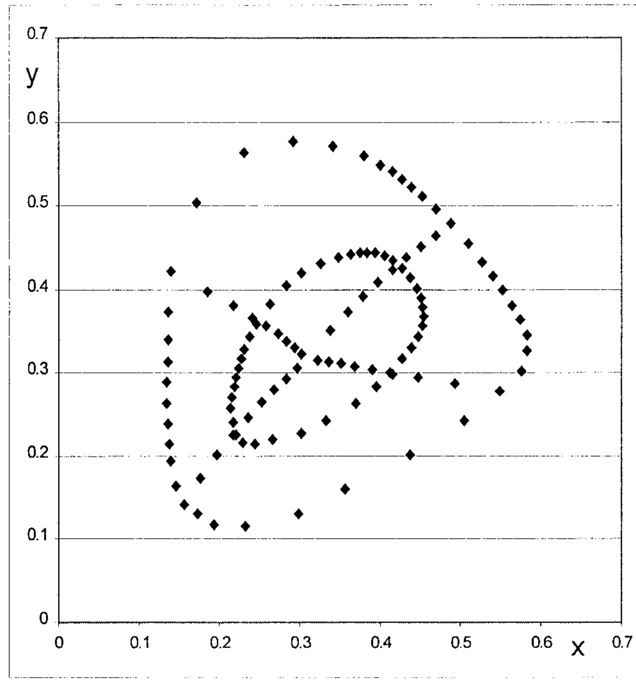


FIG. 11. Chromaticities of NCS colors at (outer ring) 0090, and 2050 and near-unique hues from 0090 in 5 unit blackness steps to 4510 in a portion of the CIE 1931 chromaticity diagram.

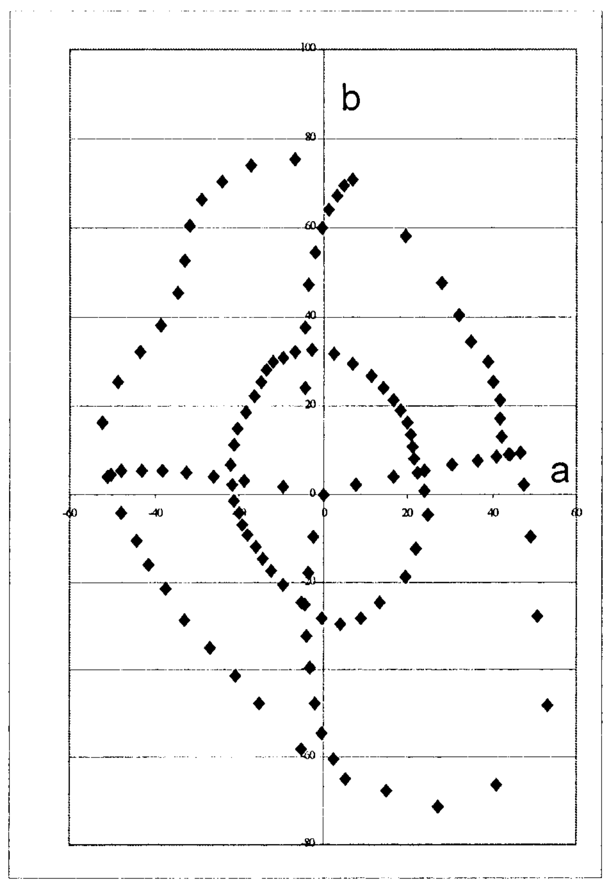


FIG. 12. NCS colors of Fig. 11 in the linear *a, b* diagram.

further illustrated by showing the differences in hue angles between adjacent colors on the hue circle in Fig. 5. Ideally (based on a polar coordinate system), all the differences should be identical (9°).

Munsell Re-renotations

It was of interest to see what changes have been made in RERE compared to REN. Some of the changes have already

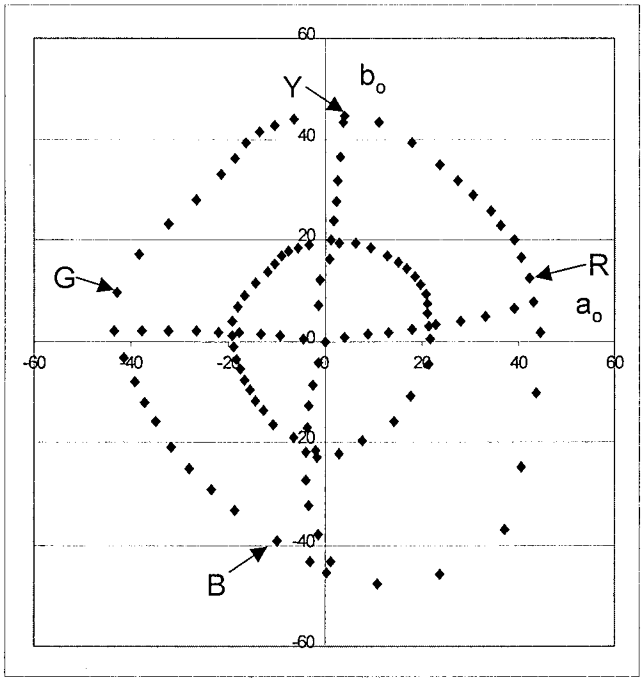


FIG. 13. NCS colors of Fig. 11 in the optimized diagram. *Y*, *R*, *B*, *G* identify the visually determined unique hues of NCS.

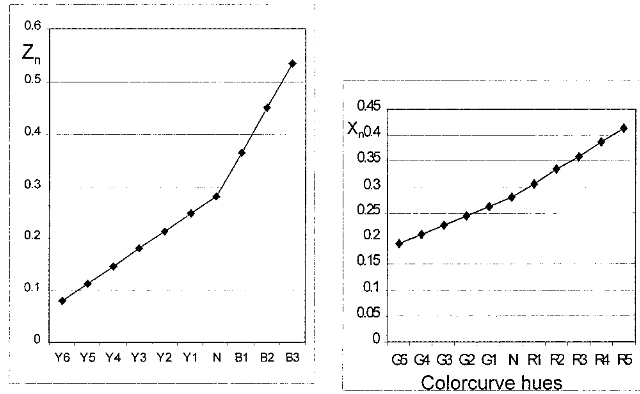


FIG. 15. Changes in the normalized Z and X tristimulus values of CC axes colors at different chroma steps at $L = 60$. Left hand: Z_n as a function of yellowness-blueness; Right hand: X_n as a function of greenness-redness.

become evident in Fig. 2. Figure 6 illustrates the V6/C8 hue circle and near-axes colors at different chroma levels in the CIE chromaticity diagram. While in REN an unequal number of hue steps exists in each quadrant, in RERE there are 10 hue steps in each quadrant. RERE is also unusual in that it requires significantly different powers along the *a* axis (see Table I). On the other hand, the powers along the *b* axis are significantly smaller than those required in REN. Figures 7(a) and (b) illustrate the selected colors in the linear and the optimized diagram. The effect of f_Z is clearly visible. Hues are more evenly spaced, particularly in the yellow half of the diagram. There are some irregularities in the optimized diagram along the *b* axis, indicating that the relatively simple optimization of the *a* axis is not fully adequate for the RERE data. The changes in *a* and *b* as a function of hue are shown in Fig. 8 and the hue angle differences in Fig. 9. In total, RERE is a quite radical change from REN, particularly in the green scale.

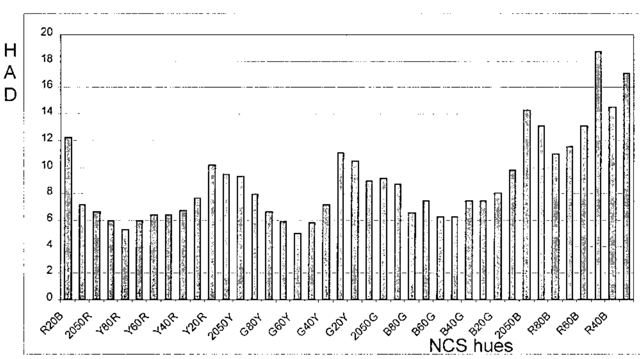


FIG. 14. Hue angle differences between adjacent NCS colors of the 2050 hue circle as a function of NCS hue.

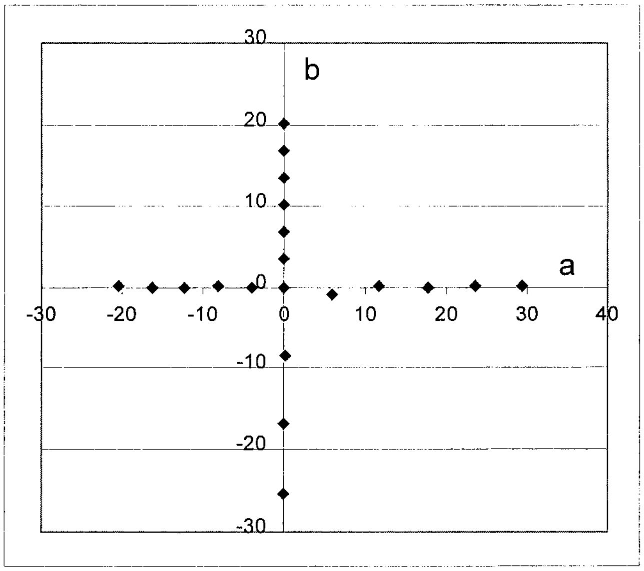
OSA-UCS

Historically, OSA-UCS is the successor to RERE. Aside from the change from a polar coordinate system, it represents a significant reversal of the dramatic changes between REN and RERE. The required power for the *a* axis is 1. Further analysis of the *b* scale for UCS has shown that the optimum power for the complete yellowness-blueness scale is 0.5. However, slightly different multipliers are required for the yellow and the blue side. UCS requires the strongest adjustment of $\bar{x}$. This may be due to the fact that the 10° observer applies. The factor 0.075 is a compromise based on its effect on yellow and blue colors (compare Figs. 10 and 11). The effect of the optimization on a larger number of UCS colors can be seen in Ref. 2.

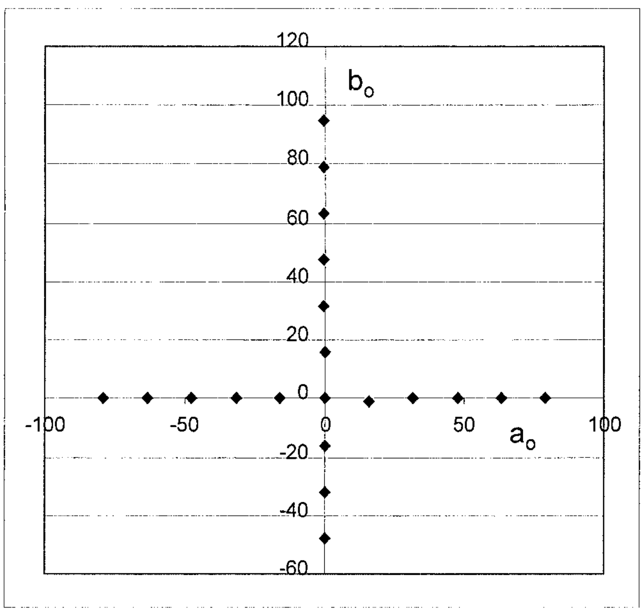
NCS

Analysis of the NCS system in terms of an *a*, *b* opponent-color system is difficult because of its structure. Aim color data have been selected that represent the forty 0090 hues, those closest to the perfect most highly chromatic colors (which are at location 00100 and have not been specified). An additional hue circle was selected at 2050. Chroma steps of near-system axis colors (the closest possible based on the fact that the full chromaticness scale is specified at only every other hue step) have been selected at 5 blackness steps intervals: 0090, 0580, 1070 . . . 4510. These lie on a horizontal line perpendicular to the white-black axis, a fact that has no easily definable meaning. They are not of equal lightness. The selected colors are shown in the CIE chromaticity diagram Fig. 11. They show that the 2050 circle has a general resemblance to the Munsell hue circle at 6/8 (see Fig. 6), while the 0090 circle does not. Implicit in the optimization is the assumption that *p*, which was found to apply to REN, RERE, and UCS, also applies to NCS. Also here a more detailed analysis has resulted in powers somewhat different from those reported earlier.[2]

While in REN the apparent visual unique hues fall very nearly onto the system axes, in NCS they are quite different,



(a)



(b)

FIG. 16. CC system axes colors at $L = 60$ (a) in the linear *a, b* diagram and (b) the optimized diagram.

as seen in Fig. 13. This results in different numbers of NCS hue steps in the four quadrants of the *a, b* system. Figure 14 shows the differences in hue angle between adjacent colors of the 2050 hue circle. The figure is much different from Fig. 5, showing the differences for REN.

It is evident that the 0090 colors have significantly varying Munsell chroma, while by definition having the same NCS chromaticness. By the time one gets to the 2050 hue circle (about half way towards neutral), these differences have been smoothed out so that the 2050 hue circle is close in form to a Munsell constant chroma circle.

Colorcurve

CC is not based on a set of visual evaluations, but rather represents a particular sampling plan in the *a**, *b** diagram. The distance between the high chroma points on the four system axes and the neutral point has been scaled linearly in equal increments of tristimulus values. This makes for a peculiarly hybrid system. The changes in Z_n and X_n as a function of color steps along the *a* and *b* axes (comparable to Fig. 2) are illustrated in Fig. 15. They indicate significant differences in Z_n along the *b* axis, with Z_n changing slower for yellow colors and faster for blue colors. There seem to be two yellow steps for every blue step. An examination of the book of colors provides visual confirmation. The *a* scale is in reasonably good agreement with the REN *a* scale. Figures 16 (a) and (b) show the system axes colors at different “chroma” steps in the linear and the “optimized” diagram. The latter, as do the factors in Table I, assumes that the system is visually uniform.

The results obtained with the four systems that are based on visual scaling lead to a number of questions that appear to be answerable only with additional visual experiments. In regard to hue scaling, a comparison has been made of the hue angle differences in the three systems where this is possible (REN, RERE, NCS). The result is shown in Fig. 17. The average hue angle difference of 9° has been subtracted from the actual hue angle differences starting with the color nearest to unique red and going counterclockwise. The result appears to be quite random except that there is a slight trend towards larger hue angle differences around the hue circle. The standard deviation around the mean of 9 is 2.85. On the basis of Fig. 17, there seems little reason not to believe that equal hue steps are caused by equal changes in hue angle.

Regarding the increments in *X* and *Z* that are required to obtain uniform chroma spacing, I am not aware of experimental data indicating how chroma spacing depends on experimental conditions. When considering the four visually established scales, it is perhaps not unreasonable to conclude that square root is the applicable power to equalize chroma increments for all four semi axes. Clearly, it would be desirable to do visual chroma scaling experiments along the major axes under different experimental conditions to learn how these impact the chroma scales.

CONCLUSION

Five different color order systems can be modeled remarkably well with a simple basic idea: an opponent-color system based on subtractions of CIE tristimulus values (with the $\bar{x}$ function appearing to require slight rebalancing, a matter that has been commented on repeatedly in the past, see, e.g., Ref. 10). To model visual chroma relationships in the investigated systems, different powers need to be applied to the tristimulus values depending on the fundamental color vector involved. Depending on the power function, different multipliers must be applied to balance the vectors. The comparison of REN, RERE, and UCS shows that

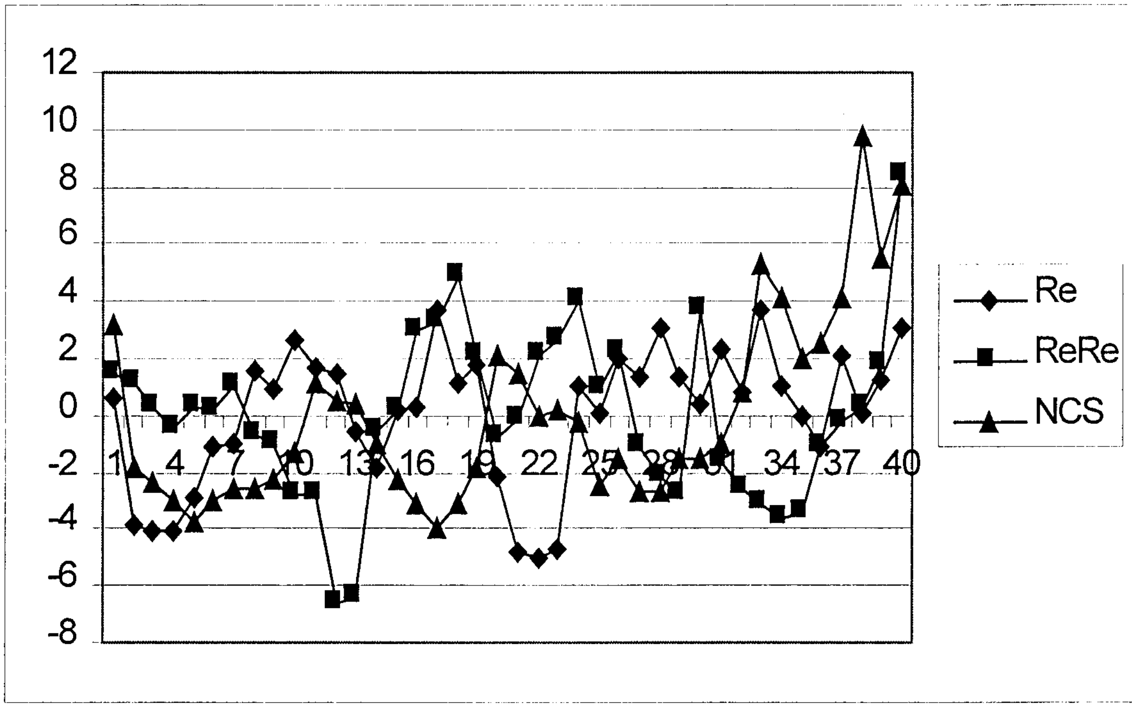


FIG. 17. Comparison of the differences between hue steps of REN, RERE, and NCS. The result of the subtraction of the mean of 9 from the difference in hue angle between adjacent hues is illustrated, starting with the near-unique red hue and going counter clockwise around the hue circle.

largely the same group of researchers has struggled over decades to determine the correct chroma scales.[3,5,6]

A comparison of REN, RERE, and NCS indicates that the hue angle differences across a hue circle in the three color order systems are of similar magnitude, but in detail significantly different. This is an apparent indicator of the difficulty in visually scaling differences equally in a quadrant. It also raises the question of whether other factors, aside from equal changes of some sort in a and b, might affect hue scaling. As a result, we have a degree of visual uncertainty both in the chroma and the hue scales.

The fact that color order systems of various design can all be modeled well with a simple opponent-color system based on color-matching functions, with the only variables being different powers and multipliers applied to the individual opponent-color functions, inspires considerable confidence in the intrinsic veracity of the opponent-color system.

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