A Structural Comparison of the Munsell Renotation and the OSA–UCS Uniform Color Systems

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Abstract: A structural comparison has been made of the lightness, chroma, and hue scales of the Munsell system, as expressed in the Munsell Renotations, and of the OSA-UCS system. While the lightness scales are similar (except for the adjustment for the Helmholtz–Kohlrausch effect and the inclusion of a "crispening" effect in OSA–UCS), there are significant differences in the chroma scales along the major chromatic axes. Unlike in CIELAB, the increments in X *and* Z *along these axes for equal chroma steps in both systems do not fall on a continuous function. In the two systems, as well as in CIELAB lines connecting colors of equal chroma differences at different* Y *values point to nonreal origins. These differ among the three systems. A major difference between Munsell and OSA–UCS is the size of the first chroma step away from gray. An experiment has been performed with the result that the OSA–UCS system is in much better agreement with the average observer in this respect than the Munsell system. OSA–UCS exhibits considerably more internal uniformity in terms of* X *and* Z *increments between steps than the Munsell system.* © 2000 John Wiley & Sons, Inc. Col Res Appl, 25, 186–192, 2000

Key words: uniform color space; Munsell system; OSA–UCS system; CIELAB formula

INTRODUCTION

The Munsell system and the OSA–UCS system represent two different attempts at a uniform color space. In the former case, separate scales of hue, chroma, and lightness (value) have been developed by visual evaluation. In the latter, color differences in a triangle have been adjusted until all three differences appeared to be of the same size. Adjoining triangles were added until a volume of space was filled with realizable, visually equidistant colors. It was of interest to compare the two systems in terms of increments between visually equidistant colors in X, Y, and Z tristimulus values, to the extent that such comparisons can be made. The Munsell system as represented by the Munsell renotations (REN) and the OSA–UCS system (UCS) as represented by the corresponding aim color tables were used. Both tables as well as descriptions of the systems can be found in Ref. 1 (see Ref. 2 for the original description of UCS). A complication is that REN is expressed in terms of the CIE 2° observer and Illuminant C, while UCS is expressed in terms of the 10° observer and Illuminant D65. In both cases, the data have been adjusted to an equal energy illuminant by dividing the tristimulus values, or the corresponding tristimulus values of the illuminant.

SENSITIVITY REGULATION IN THE VISUAL SYSTEM

For a perceptual criterion response in terms of lightness, hue, or chroma difference to occur (i.e., a lightness, hue, or chroma step large enough to be seen), visual signals have to change by a certain magnitude. The model used for this comparison is an opponent-color model in which the input is three magnitudes designated X, Y, and Z (the CIE tristimulus values) from three putative cone responses L, M, and S as discussed in a previous article.[3] Two of the three tristimulus values have direct neurophysiological correlates in the retina. The correlate for X has not yet been located. We assume that, in order to obtain a perceptual criterion along axes where only either X or Y or Z changes, the value of the magnitude has to change by a certain increment or decrement. The magnitude of this increment/decrement has been of considerable interest in color science since the 19th century. Conceptually, one might assume that, at any given value of a detector response, to obtain a perceptual criterion response would take a given and equal percentage of the basis response. This, in fact, is the assumption made by

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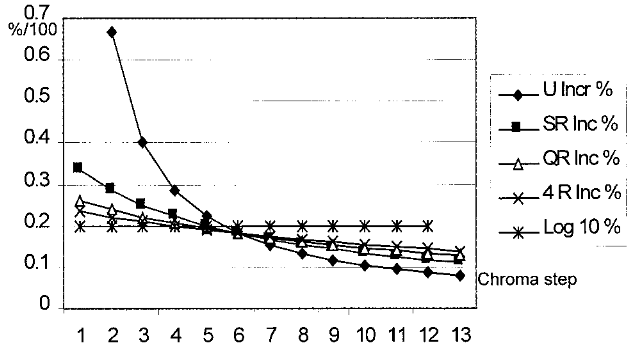


FIG. 1. Percent increment/decrement in X or Z required to produce uniform scales according to five different models: U uniform increments; SR square root; QR cube root; 4R fourth root; Log logarithmic (Weber–Fechner law).

Weber in the law that is now known as the Weber–Fechner law. Accordingly:

$$\frac{\Delta x}{x + x_0} = k, \tag{1}$$

where x is a detector response, x_0 is the internal noise of the system, Δx is the change in response required for a perceptual criterion response, and k is the proportionality constant called the Weber fraction (for a discussion of these issues, see Ref. 1, p 488). Alternatively, one might assume that the required signal increment is the same in magnitude regardless of the size of the basis response, or the required response might be intermediate to these two cases. In the former case, the result is a log scale:

$$s(x) = a + b \log(x + x_0), \tag{2}$$

where $s(x)$ is the increment required to obtain a criterion response, and a and b are constants. In the second case, it is linear. If the required percentage change at lower basis value is somewhat higher than at higher basis value, as one might expect from a somewhat less than perfect detector system, the required change can be mathematically modeled by a power function. The meaning of the power function is not that the output of opponent-color cells is nonlinear, but simply that the required increments for a criterion response vary according to a power function. The lower the value of the power, the closer the scale approaches the log scale, as illustrated in Fig. 1. In Fig. 2, theoretical equal chroma increments at various levels of Y are shown along one of the two opponent-color axes, using the log scale model. The line marked 0 represents neutral gray, and the colors left and right of it, for example, are green and red at increasing chroma. It is evident that in this model all lines of equal chroma end at the origin. If the increment is of the same size at all levels of Y, then all equal chroma lines would run parallel to the zero line. Power law models have lines of equal chroma between the two extremes, with an unreal origin, such as is shown in Fig. 3 for the cube root scale (in a view that plots Z vs. Y).

In theory, there could be other situations, for example, that the increment needs to increase as a constant percentage until a certain level is reached after which it remains uniform, i.e., the percentage the change represents from that point on is smaller and smaller. If all three dimensions have the same increment mechanism, then all increments along the major axes fall on common curves (as expressed, for example, in the CIELAB formula).

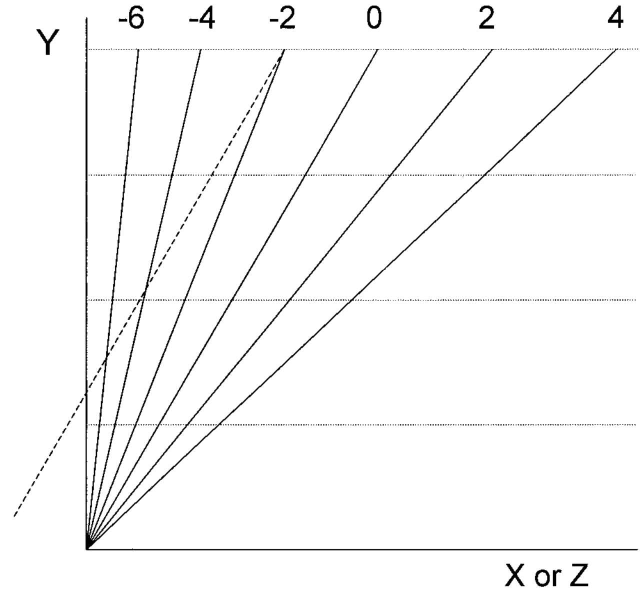


FIG. 2. Schematic representation of chroma steps at different levels of Y that represent a logarithmic scale. The 0 line represents the gray scale. The numbers refer to chroma steps. The dashed line indicates the extreme case of identical increments at all levels of Y.

Another possible variable is that the increment function applicable to X, Y, and Z is not identical. I have presented evidence for this in the Munsell and OSA–UCS system elsewhere.[4, 5] This could be due to intrinsic differences in the response properties of the putative X, Y, and Z detectors. (In reality, we can expect it to be the sum of the performance characteristics of the cone cells and the opponent-color cells.) If different X and Z increments and perhaps different multipliers are required for best fit, an additional power

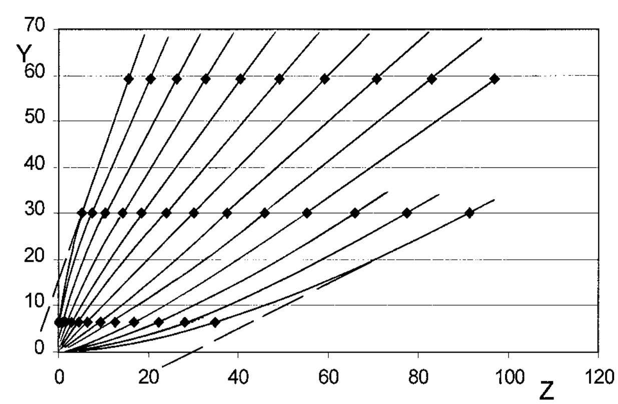


FIG. 3. Comparable to Fig. 2, but calculated using the CIELAB formula; chroma steps at 10 unit intervals to 50 (where possible). Straight line extensions point to negative origin.

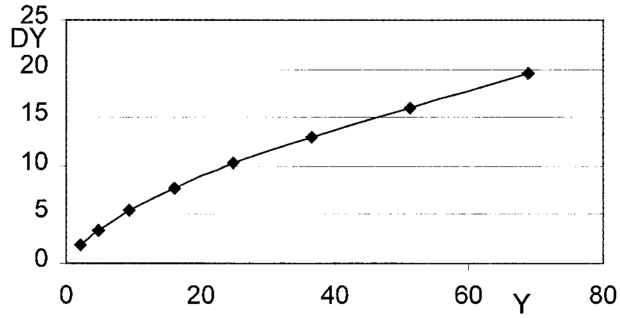


FIG. 4. Increment in Y (DY) vs. Y for visually equal steps of the Munsell gray scale.

adjustment for a and b values is required to make their values identical at different levels of Y for equal perceptual steps. It has not been resolved whether such a situation is due to experimental conditions or error.

LIGHTNESS SCALE

The relationship between luminous reflectance (Y) and lightness for REN is modeled well with a cube root relationship. The UCS system also uses a cube root relationship. However, in the colorimetric version, Y is adjusted for the Helmholtz–Kohlrausch effect for chromatic colors, and the system contains a Semmelroth-type adjustment for "crispening" of lightness differences.[1, 2] In terms of increments in Y, for neutral grays double steps from L-6 to L4 in UCS are very similar to double steps in REN. The increments in Y for a value step are not linearly related to Y, as is shown in Fig. 4 for the Munsell value scale. They are modeled well with the following relationship:

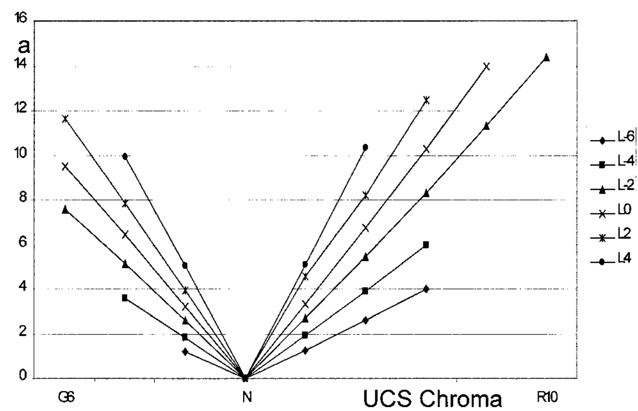
$$\Delta Y = 1.155 Y^{0.667}. \qquad (3)$$

Lightness differences of object colors as viewed under the conditions used in establishing the Munsell system do not follow the Weber–Fechner law, but require increments that are a somewhat higher percentage at lower Y values, and the reverse for higher Y values. It is well known that the experimental conditions have a considerable effect on the required increments. A log scale has been used as the basis of the gray scale in the 1944 *Color Harmony Manual*.[6]

CHROMA SCALE

Along the system axes in the opponent color system at equal Y values and for the equal energy illuminant, only either the X tristimuls value or the Z tristimulus value changes with a change in chroma. For colors at equal Y away from the axes, both X and Z (and, therefore, a and b) change, and chroma is determined by the square root of the sum of the squares of the a and b values. Figures 5 and 6 show graphically the relationship among chroma steps and Z and X increments or decrements from the neutral point at different lightness levels in both REN and UCS. It is evident that REN has stronger curvatures in all four semi-axes than UCS, indicating that lower powers are required to linearize the scales in REN compared to UCS. For REN, separate (nonlinear) scales apply to blueness and yellowness. In an earlier publication, I have shown that a cube-root relationship applies to the REN yellowness scale, while a square root relationship applies to the blueness scale.[4] Previously, I have applied a 0.5 power scale to the complete REN greenness–redness scale, but closer analysis shows that here also separate scales (at least at higher Y values) apply. We also see that changes away from neutral in both directions in UCS are similar in tristimulus increment size, while in REN they differ significantly. In UCS along the yellowness–blueness scale [Fig. 6(a)], the steps toward blue are always somewhat larger than those toward yellow. In REN [Fig. 6(b)], the first steps toward yellow are much larger than the first steps toward blue. This reverses rapidly as value increases. A similar situation applies to the greenness–redness scale, where in REN the first step toward green is significantly larger than the first step toward red.

In Figs. 7 and 8, the relationship of X vs. Y and Z vs. Y for chroma steps at various luminous reflectances for colors on or near the system axes are shown for both UCS and REN. In UCS along the greenness–redness axis [Fig. 7(a)],



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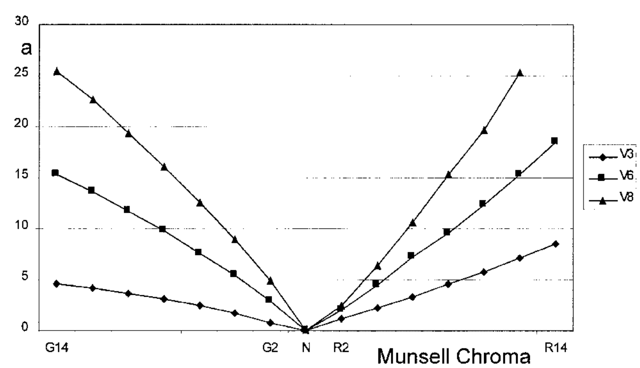
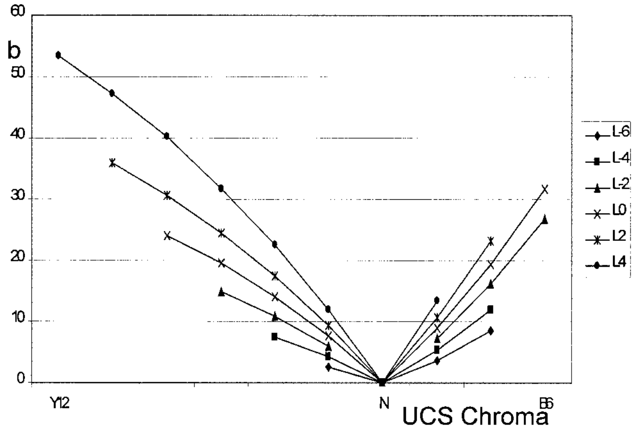


(b)

FIG. 5. (a) Increments or decrements in X along the greenness–redness axis as a function of UCS chroma from G6 to R10 at different levels of lightness (colors j0g6 to j0g-10). (b) Comparable figure for Munsell chroma from G14 to R14 (colors 2.5BGx/2-14 and 7.5RPx/2-14).



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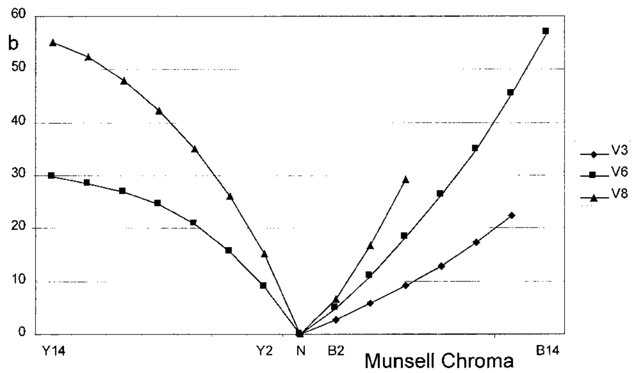
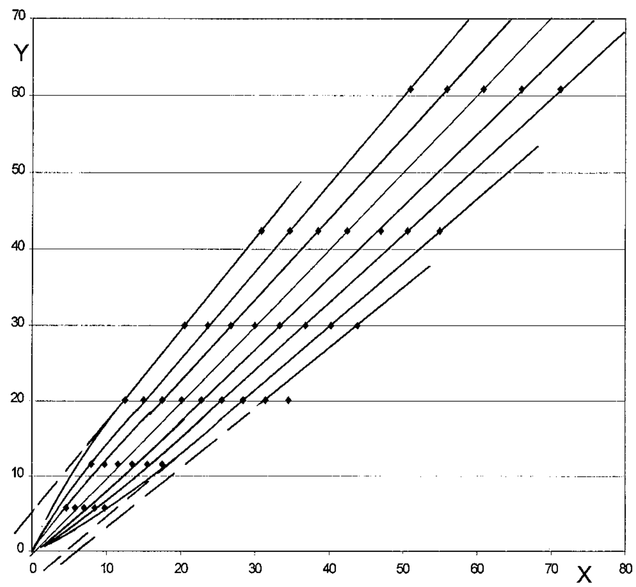


(b)

FIG. 6. (a) Increments or decrements in Z along the yellowness–blueness axis as a function of UCS chroma from Y12 to B6 at different levels of lightness (colors j12g0 to j-6g0). (b) Comparable figure for Munsell chroma from Y14 to B14 (colors 5Yx/2-14 and 5PBx/2-14).

chroma steps in an equi-Y plane differ by equal increments at a given level of Y. The increments are linearly related as a function of Y. The connecting lines of higher chroma colors, if extended (dashed lines), point to an origin beyond the origin of the diagram. We have seen that this is the case, when the increments do not follow a log scale. As a result, at lower Y values the incremental changes are no longer linearly related. This is particularly evident in Fig. 8(a) for the Z vs. Y relationship. Here the increments between chroma steps at a given Y level are not equal, but have a square root relationship at each level. At higher Y values, the changes from one level of Y to the next are still linearly related.

The diagonals in these graphs connect the neutral colors. It is evident that any given Z value can represent either a yellow or a blue color, depending on the Y value. If the Z value is higher than the Y value, the color is blue, otherwise yellow. This applies in a comparable fashion to the greenness–redness scale. The two views of the tristimulus space offered for the Munsell system by Figs. 7(b) and 8(b) also indicate the natural limitations of color perceptions as the space is filled out. It is evident from the figures that yellowness–blueness scales in REN and UCS fill out a greater portion of the available tristimulus space than the greenness–redness scales. There should be more chroma steps possible along the green–red axis than along the yellow–blue axis. What can be achieved depends on the availability of suitable colorants. It is also apparent why at high Y values many chroma steps are possible for yellow colors and few for blue, and vice versa at low Y values. In the same way, in theory many chroma steps are possible for green colors (few for red) at high Y values and the reverse at low Y values.



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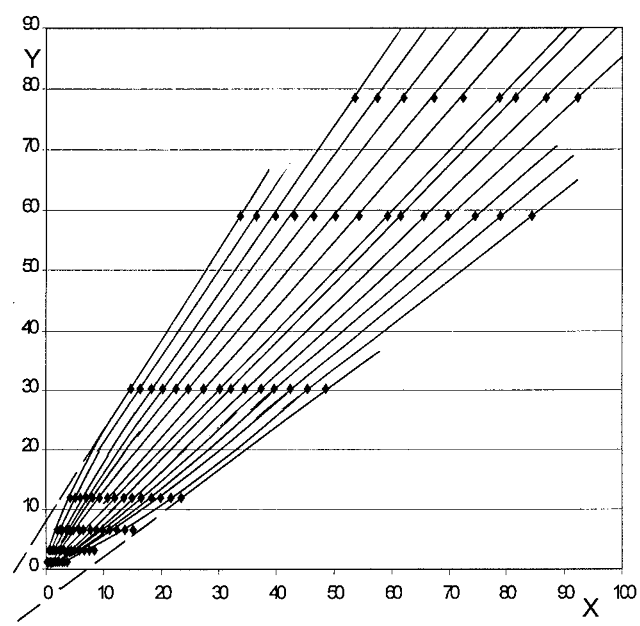
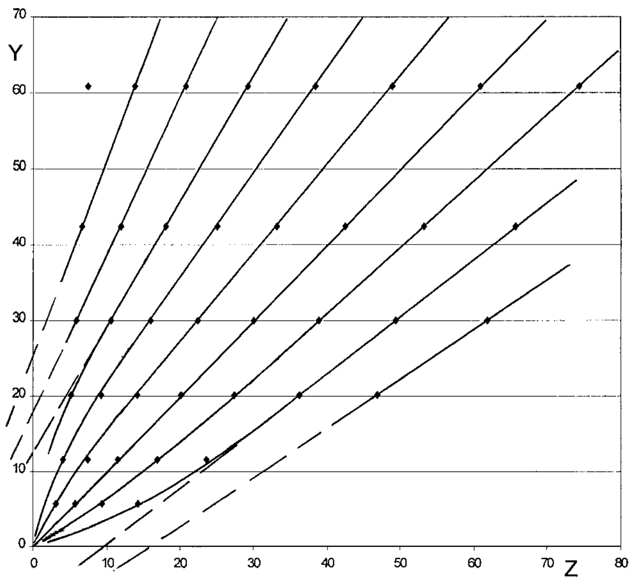


(b)

FIG 7. (a) Plots of X vs. Y of colors along the greenness–redness axis at different chroma levels (connected by lines) and different lightness levels for UCS. The dashed lines point towards the negative origin. (b) Comparable figure for the Munsell system.



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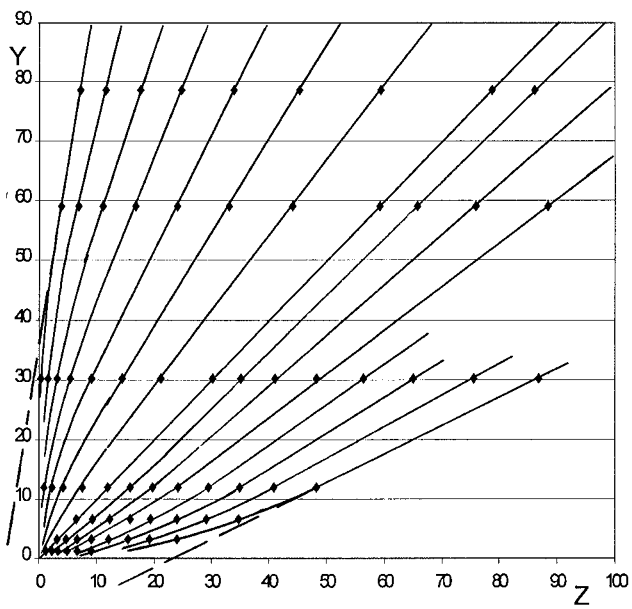


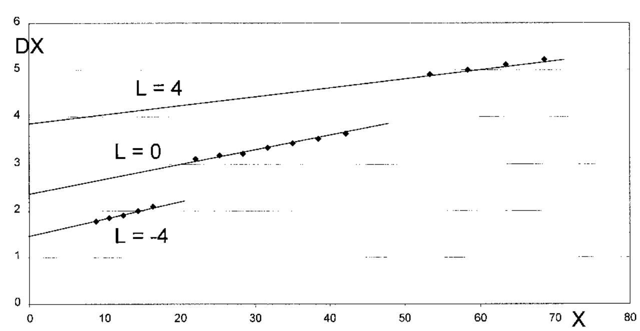
(b)

FIG. 8. (a) Plots of Z vs. Y for colors along the yellowness–blueness axis at different lightness levels and chromas for UCS. (b) Comparable figure for the Munsell system.

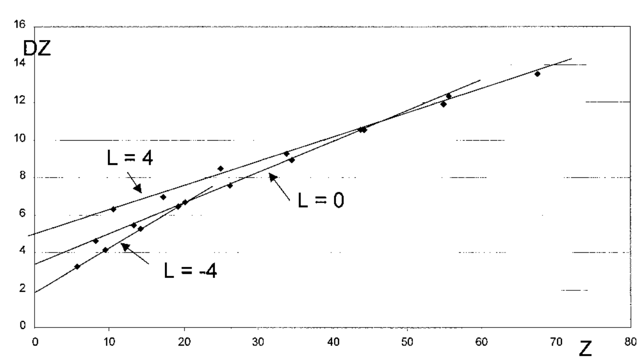
As remarked earlier, in UCS the changes in Z as a function of chroma at different luminous reflectances change in a consistent manner across the complete yellowness–blueness scale. The situation in REN is different. The changes in Z required for a chroma step at a given Y level are not consistent. There are independent scales with different Z increments for chroma steps in yellowness and blueness. A similar situation applies to the redness–greenness dimension, where in UCS the increments of X are uniform throughout that dimension, while in REN they change in different ways on the red side and on the green side. The differences are most dramatic in the first steps away from gray. The resolution of this discrepancy is of interest. It is not possible that in a direct comparison both scales are correct. An experiment, described in detail in the Appendix, has been performed to make such a comparison. The results indicate that the average observer is in much better agreement with the UCS first steps from gray than those of REN. Thus, the true power function applicable to a uniform chroma scale appears to be continuous throughout the full opponent scale.

There is a remarkable consistency in the changes in X and Z values over the range of Y. This is not too surprising in UCS, as colors at lightness levels other than from $L = 1$ to from $L = -1$ have been extrapolated from those levels evaluated experimentally. The consistency of the chroma scales over the Y range is more surprising in REN, particularly the sizes of the first steps away from gray. This (inaccurate, as we have seen) consistency is better than that of hue angles of intermediate hues at different levels of lightness, as is shown later.

At a given lightness plane in UCS for both the yellowness–blueness and the greenness–redness scale, the tristimulus increments for chroma steps increase linearly. The slope depends on the lightness, as illustrated in Fig. 9(a) and (b). In Table I, the equations that describe the slopes are listed. All six equations have nonzero constants. The constants themselves change in nonlinear fashion with Y. The



(a)



(b)

FIG. 9. (a) Plots of increments in X (DX) vs. X at three different lightness levels for colors along the greenness–redness axis in UCS. The increments are not on a continuous function. (b) Comparable figure for increments in Z vs. Z for colors along the yellowness–blueness axis in UCS.

TABLE I. Increments in X or Z as a function of X or Z for chroma steps along the axes in UCS at three levels of lightness.

Lightness	DX =	DZ =
L − 4	1.40 + 0.042X	1.88 + 0.234Z
L0	2.40 + 0.031X	3.30 + 0.162Z
L + 4	3.86 + 0.020X	5.00 + 0.130Z

incremental multipliers increase linearly in case of X and nonlinearly in case of Z. In REN, the corresponding relationships are nonlinear in all respects.

As is evident from Fig. 9, the increments in UCS are not located on one continuous function. The same applies to REN. In CIELAB, all DZ increments at different levels of lightness are located on a continuous, nonlinear function. The increments in CIELAB are modeled well with the following equation:

$$DZ = 0.7Z^{0.667}. \tag{4}$$

A similar situation applies to the X increments. CIELAB differs from UCS and REN in this respect.

A comparison has been made of the size of the average Z and X increments for chroma steps at $Y = 30$ for the two systems. They are for UCS $DZ = 8.0$ and $DX = 3.3$, with a ratio of 2.4. For REN they are $DZ = 5.8$ and $DX = 2.4$, also with a ratio of 2.4. The ratio is the same, but the average chroma step in UCS requires a 30% larger increment than the average step in REN.

HUE

Hue changes are the result of changes in the ratio of a and b. As discussed in a previous article,[4] equal hue changes are either the result of equal percentage changes in a and b or equal changes in hue angle. Which of these models applies is currently being investigated experimentally.

If equality of hue means equality of ratio b/a and if the chroma increments along the two system axes are different, then in the linear a, b diagram lines of equal hue are curved, with a different curvature in each quadrant. They are straight, if the a and b scales are appropriately adjusted with the correct power function.

The degree to which a given Munsell hue is represented by a given hue angle, regardless of its Y value, has been investigated. The linear a, b values have for this purpose been recalculated as optimized $a\hat{}$, $b\hat{}$ values by applying the powers and multipliers described in Ref. 3. Figure 10 illustrates the hue angle differences in this diagram between adjacent Munsell hues around the 40 hue circle (beginning with 7.5RP and going counterclockwise), at three value levels. Note that not all hues are available at all three levels. If REN were uniform in terms of the optimized opponent-color system, all hue angle differences would be identical in size (9°). The agreement of the hue angles at the three value levels has been assessed numerically by calculating for all cases where it is possible the percentage of average deviation in hue angle of the lower and higher value compared to the middle value. In the case of REN, this value is 10.5%, with a standard deviation of 9.2%. The actual deviations can be seen in the figure. A pattern is not discernible, and the changes are either due to experimental inconsistencies in the Munsell system or complex nonlinearities not understood at this time.

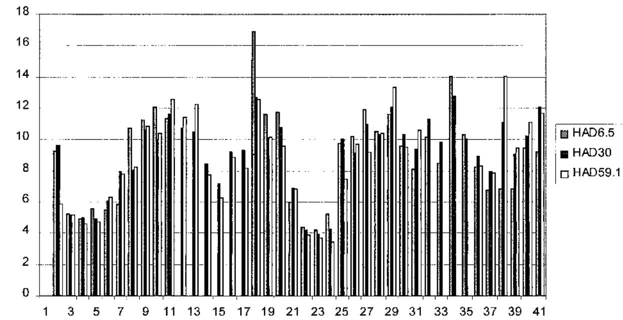


FIG. 10. Plot of differences in hue angle between adjacent hues on the Munsell 40 hue scale, starting at 7.5RP and going counterclockwise, calculated at chroma 8 at Y values of 6.5, 30, and 59. HAD30 means hue angle difference at $Y =$ 30. No data are available for certain colors at certain Y values.

UCS does not have a hue circle. For this reason, a comparable analysis has not been made.

CONCLUSIONS

Aside from their obvious macro structure differences based on the two different construction principles of the two

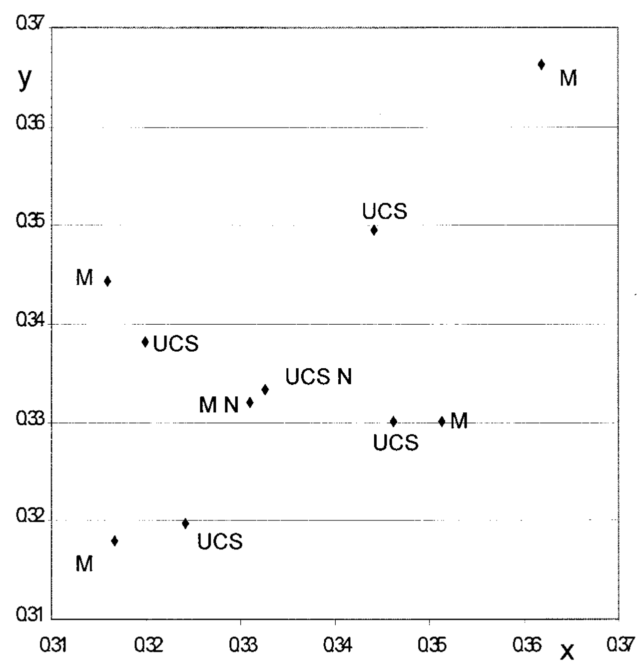


FIG. 11. Plot of chromaticities in a portion of the CIE 1931 chromaticity diagram of color samples used in the experiment described in the Appendix. M means Munsell; N means neutral gray.

TABLE II. Results of visual experiment.

	Difference neutral to		CV (%)	Ratio	Difference neutral to		CV (%)	Ratio
	Blue	Yellow			Green	Red		
Munsell, visual	1	2.75	51.0	2.75	1	0.9	37.8	0.90
CIELAB*	5.9	13.8		2.37	9.5	8.0		0.84
OSA-UCS, visual	1	1.19	43.8	1.19	1	1.04	41.5	1.04
CIELAB	5.3	6.4		1.21	6.1	6.0		0.98

systems compared, they also show significant differences in the internal structure. These relate primarily to the arrangement of the chroma scales fundamental to the system.

Chroma steps along the redness–greenness axis in UCS are based on uniform incements in *X*, the size of which depends on *Y*, and along the yellowness–blueness axis on equal percentage (but not uniform) changes in *Z*, the percentage depending on *Y*. Changes in *Z* required for a chroma step are 2.4 times the size of the changes required in *X* (as approximately expressed by the two factors 500 and 200 in the CIELAB formula). Chroma steps in REN are based on nonlinear changes in both *Z* and *X*. Different scales apply for each of the four semi-axes. The average chroma step in UCS is about 30% larger than in REN. The biggest differences between the two systems are in the first steps away from neutral gray. An experiment performed to show which of the two systems is in better agreement with visual judgments resulted in much better agreement for UCS. Both UCS and REN differ noticeably from CIELAB in how the chroma scales are structured. By requiring different powers, both systems appear to indicate somewhat different functioning of the greenness–redness and the yellowness–blueness system. As a result, in both visual systems the perceived equal chroma steps along the principal axes at different *Y* values do not fall on a continuous function when plotted in terms of *X* or *Z* increments against the value of *X* or *Z*, unlike in CIELAB.

In total, the internal structure of UCS as expressed in the tristimulus space is considerably more uniform than that of REN.

APPENDIX: VISUAL COMPARISON OF THE FIRST STEPS FROM GRAY AT $Y = 30$ IN UCS AND REN

Samples: Munsell (1976 glossy edition): N6, 5Y6/2, 5PB6/2, 2.5BG6/2, and 10RP6/2; UCS: N0, L0j+1, L0j−1, L0g+1, L0g−1.

The diffuse reflectances of these samples have been measured and tristimulus values were calculated for the CIE 1931 2° observer and Illuminant D65. The chromaticities of the samples are plotted in the chromaticity diagram in Fig. 11. CIELAB chromatic differences (DE-DL) were calculated for the differences between the achromatic and the chromatic samples.

Visual evaluation: the samples were displayed, three at a time, on a neutral gray background of 8.5 × 11 in of L≈80 in a Macbeth light booth with a general surround also of L≈80 and illuminated with artificial D65 light. The Munsell chips are of standard size 17 × 20 mm. The white ID handles of the chips were hidden behind a gray skirt of L≈80. The UCS chips were of approximate size 14 × 25 mm, without an ID handle. Three chips were displayed side by side, with the neutral chip in the center, with a 5 mm distance between the chips. First, the bluish chip was on the left and the yellowish chip on the right. Then the reddish chip was placed on the left and the greenish chip on the right. The observer was asked to apply a value of 1 to the color difference between the center and the left colors, and then to estimate the magnitude of the difference between center and right samples in comparison. The Munsell samples were displayed first, followed by the UCS samples.

Observers: 35 observers participated (19F/16M) with age ranging from 20–61 years.

The results of the experiment are listed in Table II. The relatively high coefficient of variation values indicate considerable variation in judgment. In the Munsell samples, the average observer saw the first step toward yellow to be 2.75 times the size of the first step toward blue, and the first step toward red 0.9 times the size of the first step toward green. The corresponding CIELAB differences have comparable ratios. In UCS, the average observer saw the first step toward yellow to be 20% larger than the first step toward blue. CIELAB provides the same ratio. The steps toward green and red were seen nearly identical in size, and the CIELAB ratio is also nearly identical. The conclusion can be drawn that the average observer in this experiment judges the first steps away from gray toward yellow and blue to be much more equal in UCS than in Munsell. The same, but to a lesser extent, applies to the first steps toward green and red.

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