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Computational Color Harmony based on Coloroid System

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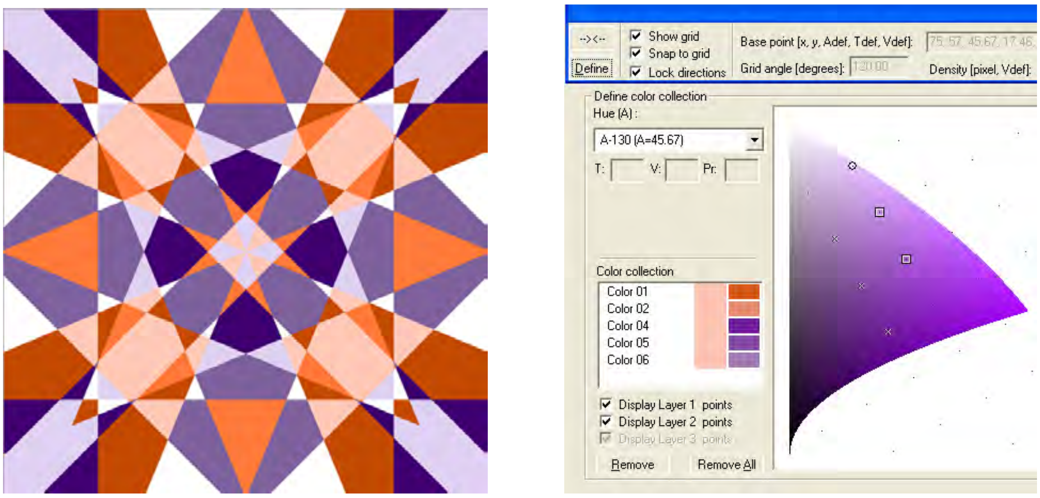

(*a*) (*b*)

Figure 1: *(a) visualization of the overall appearance of a dichromatic color set with 'caleidoscope' option of the Color Plan Designer software and (b) interactive color selection of a dichromatic color set in multi-layer mode, applying rotated regular grid.*

Abstract

This paper presents experimentally based rules and methods for the creation of harmonic color sets. First, dichromatic rules are presented which concern the harmony relationships of two hues. For an arbitrarily given hue pair, we define the just harmonic saturation values, resulting in minimally harmonic color pairs. These values express the fuzzy border between harmony and disharmony regions using a single scalar.

Second, the value of harmony is defined corresponding to the contrast of lightness, i.e. the difference of perceptual lightness values. Third, we formulate the harmony value of the saturation contrast, depending on hue and lightness. The results of these investigations form a basis for a unified, coherent dichromatic harmony formula as well as for analysis of polychromatic color harmony.

Introduced color harmony rules are based on Coloroid, which is one of the $5-6$ *main color-order systems and furthermore it is an aesthetically uniform continuous color space. Coloroid has simple closed forward and backward transformation formulas with the color space of CIE XYZ. It relies on a huge number of observations and experiments, and it is a very suitable tool of color dynamics for describing aesthetical relationships. It has been used in numerous architectural projects. The experimental data that may be retrieved from them are only partly processed and published so far. Our article utilizes a 'slice' of this database, together with additional complementary observations. This paper is the first of a planned series of articles, dealing with rules and coherences of color harmony based on the Coloroid system.*

Keywords: Coloroid Color-order System, Computational Color Harmony, Human Vision, Environmental Color Design, Color Dynamics

1. The COLOROID color-order system

1.1. Historical survey

A series of experiments were done between 1962 and 1996, mainly at the Technical University of Budapest, Hungary, in order to formulate rules of color harmony and describe aesthetic relationships. Nearly 80 *thousand* observers performed 26 *million* elementary observations and brought elementary decisions during this unique series of experiments. Observers have been classified by various points of view, covering a wide spectrum of different aspects, like gender, age, as well as socio-cultural points of view, as educational qualification, cultural identity, habitation, and also physical and mental health, and so on.

Most of the experiments investigated the perceptual attributes of hue, saturation and lightness, the role of aesthetical uniformity, the color preferences, color associations and other factors of color harmony. The results have been employed to create the aesthetically uniform Coloroid color-order system relying on dH "harmony threshold", and to create the system of the color preference indices.

Figure 2: *The aesthetically uniform 48 limit-colors of the Coloroid system built 7 hue groups with the non-uniform numbering: 10,...16, 20,...26, 30,...35, 40,...46, 50,...56, 60,...66, 70,...76, according the yellow, orange, red, purple, blue, cold-green, warm-green intervals*

Data are already processed, partly processed and raw. Catalogs of circumstances of the experiments have been documented in the Library of Technical University of Budapest

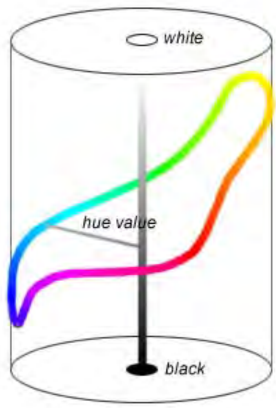

Figure 3: *A cylindrical projection of the continuous limit-color curve of the Coloroid*

and a survey of experiments is in a recently written report [Nem05]. This data set, only part of which is digitally stored, promises answers and formulas on several further questions. Some complementary experiments have been performed in the last years, similar to ones in this article.

1.2. Basics of the Coloroid

Conditions of observations and basic concept of the Coloroid differ from other color order systems. "*The aim is to provide a system in which the colors are spaced evenly in terms of their aesthetic effects, rather than of color differences as in the Munsell system, or perceptual content as in the NCS.*" [Hun92]. In typical Coloroid experiments, the observer is given a wide field of view to observe a large set of often unneighboring color samples, and must give their responses relative quickly. These conditions make it similar to an observation of a complex image in the real life. Under this viewing conditions the human vision system can distinguish few colors, especially in the darker regions. Thereby the dH esthetical threshold in Coloroid is one to four times greater than the ds line element, which is the "*unit*" of just noticeable difference in other systems [Nem95]. A rotating Maxwell wheel was applied in a great number of experiments, ensuring an arbitrary additive mixture of the black, white and the limit-color, by ratios s, w, and p, respectively, where $s+w+p=1$. The limit-colors were the available most saturated solid-colors instead of spectral colors.

Due to the very great number of observations and also to the obtained good correlations, we consider the basic concepts of Coloroid to be "*axioms*", which are valid for the above mentioned view-conditions:

1. Surfaces of a constant Hue (A) form a plane, containing the neutral axis and a hue dependent limit-color, unlike

Figure 4: *The continuous version of a yellowish-orange constant hue page*

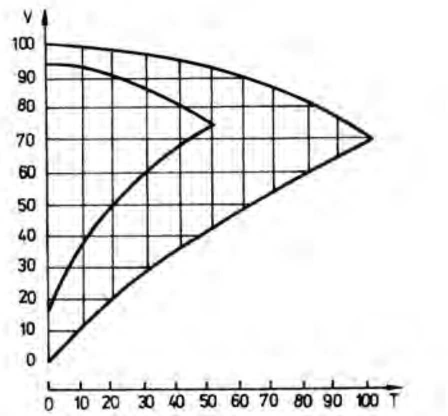

Figure 5: *A hue plane of the Coloroid with the greater and smaller gamut according to the limit-colors, using spectral and solid-color, respectively*

most of the other systems having curved hue-surfaces, like e.g. the Munsell system.

2. Saturation $T = const \cdot ratio$ of the limit-color, where the constant depends on the hue.
3. Lightness $V = 10 \cdot \sqrt{Y}$. It does not contain a 3^{rd} root or logarithmic formula, like the ds line-element based spaces contain them.

Every hue plane's perceptual metric is Euclidean, but it fulfills just within hue planes. Color difference formulas between two different hues are not so simple, and hues are equidistant only in a general sense [NN95].

Fine structure of perceptual metrics in the 3D Coloroid space is under investigation, but the preliminary results are very interesting. We obtained not only color differences for

Figure 6: *An artwork of Antal Nemcsics about 3D arrangement of the Coloroid space*

local and large scales, but also geodetic lines or shortest paths. Latter ones have deep and practical aesthetical meaning.

Details of the Coloroid will not be presented in this paper. Only definitions of hue, saturation and lightness, signed by A, T, V respectively, have been recalled. The basic arrangement is similar to other color-order systems. Fig 2 shows the circle of 48 limit-colors, while fig 3 shows the continuous 3D limit-color line. Fig 4 illustrates a yellowish orange hue page of Coloroid, where the horizontal axis is the psychometrical saturation, which in near to the 'chroma' of several systems, and the vertical axis depicts the lightness. Fig 5 demonstrates the typical shape of the Coloroid gamut at a fixed hue value. The two Coloroid gamuts represent the limit-color selections. The larger one corresponds to the spectrum and purple limit-colors and smaller to the most saturated solid-colors.

Concepts and formulas of Coloroid can be found in several basic publications [Nem80], [Nem87], [Hun92] and [Nem95]. Fig 6 artwork shows the spatial arrangement of the colors, while fig 7 shows the borderlines of the Coloroid space and its cylindrical arrangement. A deep survey of application areas can be found in [Nem04], which is a revised and significantly extended edition. Article [NN04] contains a concise introduction to the basics of the Coloroid, connecting to a gamut mapping method. The Coloroid has been already successful also in practice by designing new buildings and by contributing in restoration of old parts of cities, e.g. the historical part of Budapest which is declared as world heritage. Numerous architectural applications of Coloroid are known, and it is an official standard

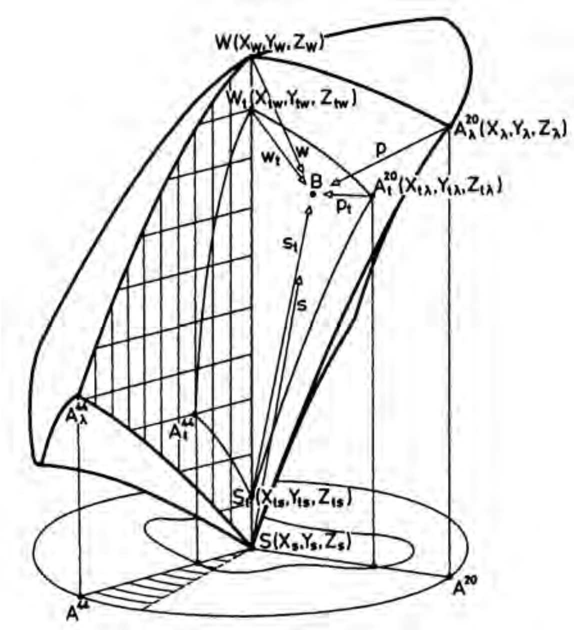

Figure 7: *The color space of the Coloroid illustrated by its cylindrical projection: the inner gamut is defined by solid-colors, while the large, theoretical gamut is defined by spectral and purple colors*

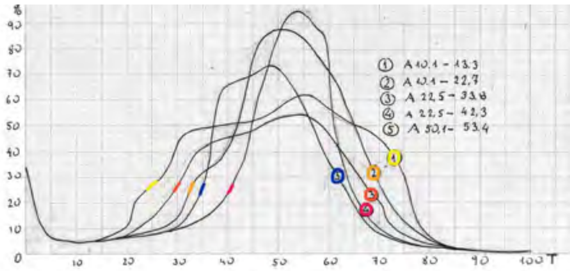

Figure 8: *Distribution of saturations of the most preferred colors for five randomly selected hue-pairs. Results of the experiments form a* 24 × 24 *distribution matrix*

in Hungary [Nem02]. A Coloroid-based color planning tool is available already as easy-to-use software [Col04]. However, international publicity of the Coloroid does not mirror yet wide practical possibilities of the unique amount of its experimental data or even its already known results. This article endeavors to fill a little gap in this area.

2. Just harmonic hue-saturation pairs

2.1. Background of the Experiments

We use terminology of *just harmonic* in this paper, similarly to the *just visible* or *just noticeable* in the color difference field, where also does not exist a sharp borderline, but a transition with a fuzzy nature.

Experiments of preferred and not accepted $hue-saturation$ pairs, respectively, have been performed between 1989 and 1992 by 357 observers, being students of $18-24$ years, roughly $50-50\%$ male and female. Total number of elementary observations and judgments has been about 189.000, each observer made 529 experiments on the average. The observations performed under not fully typical Coloroid view-conditions. The measuring apparatus, the *Colorimeter* with a 2° viewing field [NB] has been developed just for these experiments. Every highly saturated Coloroid limit-colors have been displayed in the one half of the viewing field, while in the other half of the viewing field, the most preferred, i.e. mostly harmonic color to the first selected one had to be mixed by black, white and some limit-color, from a set of 24 hue planes, being uniformly preselected by the user. These experiments have been resulted in a set of harmonic color pairs, and finally each of the hues has been ordered to one of 24 fixed hue intervals. This final simplification has classified the experiments into 24 × 24 classes, and each color has been represented by one of the 24 hue values and their original saturation and lightness values. Each class of above 24 × 24 contains a set of saturation values, which has defined a distribution or density function of T. We focus in this paper on the saturation T, but of course, lightness V, or T and V together could be investigated as well.

The peaks of maximum values of the distributions are within $20-30$ long T-intervals. The curves decrease before and after this interval quickly, but depending on the hue-pair, as it can be seen on an original manually drawn fig 8. Three most important values can be derived from each curve. The most harmonic saturation values of the most harmonic dichromatic color pairs have been defined by averaging the top 20% part of the distributions. In average an upper 13% clipping of cumulated distributions, corresponding to the locus of the high angle of slope of curves. This place represents the just harmonic saturation by one value in the best way. This border is not a sharp, but has a fuzzy-like region and transition between the harmonic and disharmonic fields.

Values of just harmonic saturations for different firstly selected highly saturated colors form a curve. These just harmonic curves (fig 9) have a high importance in this paper. We will use only these conclusions of the above described experiments. The lower 13% clipping expresses the *boring* limit of saturations. For very low saturation ($T < 5$), the preference increases once again (fig 8), in according to the widely known fact, that the neutral axis, containing the black, grey and white colors, has a special aesthetical value in the color harmony.

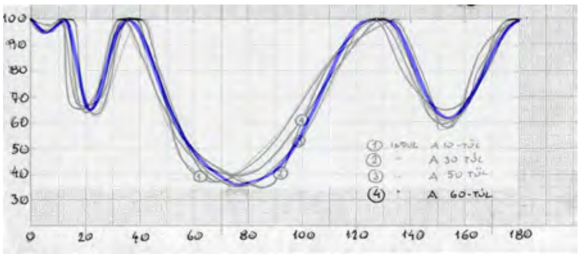

Figure 9: *The best approximation of a universal 'just harmonic' saturation curve, depending only on the relative angular hue-degreet*

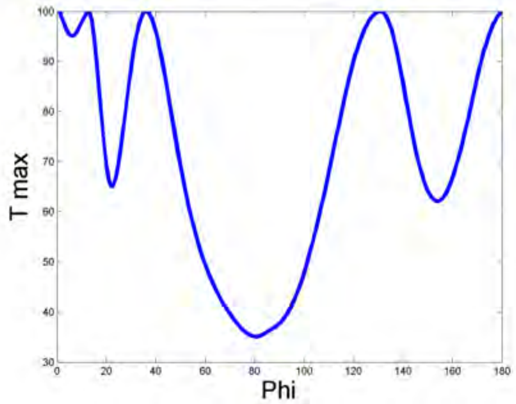

Figure 10: *Shapes of the just harmonic saturation values for different starting hues are very similar. The model can be simplified by using only one appropriate curve*

2.2. Curve of the Just Harmonic Saturation

The Coloroid hue value, beyond his notation A, can be expressed also by the angular value φ around the $D65$ white point in the *CIE xy* system. Let us recognize, that curves in the fig 9, depending on φ of the second color, and parameterized by their first color's φ. These curves have similar profiles, with a good correlation, for all of the firstly selected 24 hue classes. This fact made it possible to build a single hue-independent $T_{max}(\Delta_\varphi)$ function. This function is defined over relative angular values, which expresses the difference of hue angles, regardless to the hue value of the first color. It is sufficient to demonstrate this function over the interval $[0,180]$ degrees (fig 10) instead of $[-180,180]$, since it is symmetric to the selected saturated color, identified by zero degree. Some highly preferred hue-differences can be recognized by analyzing this curve, ensuring maximal harmony at ± 12, 35, 130, and 180 degrees, latter corresponds to the complementary color.

Selected intervals around these high value peaks, fitting roughly to $T_2 > 95$ range in the domain of Δ_φ, are

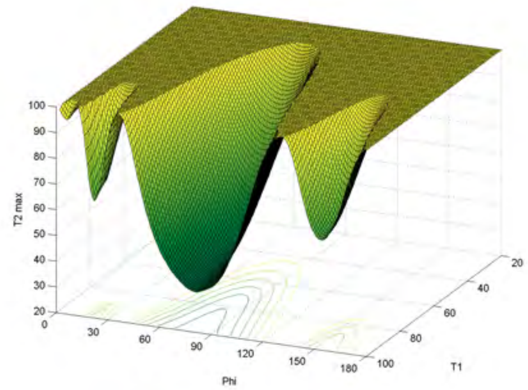

Figure 11: *A 2D generalization: the just harmonic saturation surface, using relative hue angles. It describes the harmonic and disharmonic regions for arbitrary hue saturation pairs*

used in *Coloroid Color Wheel* [Nem04] and similarly in the earlier publications since the late 70's. There are also *forbidden intervals*, containing the worst loci in their middle, namely the ± 21, 80 and 153 degrees. The worst case looks 80 degrees of difference, when a saturated color with the other hue can build a harmonic pair at last with saturation $T = 35,1$.

The rule sounds by other words as follows: there are not fully forbidden hue pairs, since arbitrary two hues can be harmonic, but one of the two saturations has to be strongly suppressed for that in some cases. Remark, that this rule is concerning the *just harmonic colors*. However, the numerical value of the color harmony is a different question. Latter depends on hue, saturation and lightness values at the same time.

2.3. Surface of the Just Harmonic Saturation

We have supposed in section 2.1, that the firstly selected color has the maximal $T_1 = 100$ saturation. The $(\varphi_1, 100)$ is harmonic with (φ_2, T_2) at arbitrary L_1 and L_2 luminances $iff\ T_2 \leq T_{max}(|\ \varphi_1 - \varphi_2\ |) = T_{max}(\Delta_\varphi)$. In other cases the color-pair is disharmonic. The T_{max} function is demonstrated on fig 10.

However, it is a typical situation, when both of the considered colors can have arbitrary saturations. Let us select firstly the $(\varphi_1,\ T_1)$ values, and another hue, defined by φ_2. What is the maximal accepted T_2 saturation, that pair (φ_2, T_2) is harmonic with the first one? This answer defines a 2-variable function, with independent variables Δ_φ and T_1 , and a dependent variable T_2. This function can be represented by a surface (fig 11), and its intersection by the plane, being defined by $T_1 = 100$, is obviously identical to the aforementioned $limit - curve$. Let T_2 notate the the maximal harmonic saturation to the firstly given T_1. For every $\Delta_\varphi > 0$ it has to be hold that: if $T_2 = S(\Delta_\varphi, T_1)$, than $T_1 = S(\Delta_\varphi, T_2)$. Similarly to the curve T_{max}, S notates the surface of the maximum saturation value, which can build a harmonic pair with the first color (fig 11). In the following derivation we assume that $\Delta_\varphi > 0$, namely case $\Delta_\varphi > 0$ refers to the monochromatic case, having only one hue plane and being always harmonic. In the dichromatic case, which is interesting for us, Δ_φ is in the $(0, 180]$ interval.

Also, the whole surface can be derived from the curve of *just harmonic saturation*, completed by some additional experiments, and by using a reciprocity rule, which is described as follows. If $T_2 = T$ saturation is accepted for a starting $T_1 = 100$ saturation at hue difference Δ_φ (fig 10), then $T_2 = 100$ is also allowed for starting $T_1 = T$ at the same Δ_φ, obviously. This is the simple but powerful reciprocity rule, which corresponds to the following geometric rule of the aforementioned surface: a mirroring on a 45° plane, going across the line defined by $T_1 = T_2 = 100$, brings the surface onto itself, corresponding to the vertical aforementioned completion of the surface. Thereby a part of this surface belonging to the loci $T = 100$, forming a horizontal plateau, limited by the mirrored *just harmonic saturation curve*.

We have processed some additional observations for some points in the remaining unknown areas. E.g. at the 'unfriendly' $\Delta_\varphi = 80$, for $T_1 = 75$ $T_2 = 44$ has proven for the just harmonic saturation. And from the reciprocity rule, at $\Delta_\varphi = 80$ for $T_1 = 44$, $T_2 = 75$. Having just about a dozen additional experimental points of the unknown surface, the curve of fig 10 and the aforementioned plateau, symmetric smooth valleys have been defined, which join to the horizontal and vertical planes not smoothly. Fig 10 and fig 11 have been computed with conjugate gradient method.

Note, that the harmony L-independently hold or not hold, in according to the experimental results, but the value of the lightness influence the intensity or value of harmony. Fig 10 and fig 11 define the fuzzy Harmony-Disharmony borderline or border-surface. The knowledge of the numerical harmony values beyond the quantitative values of these borders requires further investigations.

3. Harmony values of the lightness and saturation contrasts

3.1. Relative harmony value of lightness contrast

Experiments have been performed in 1984-86 by 1220 students with 198.000 elementary experiments. Viewing conditions are: 45° north sky light, $1600 - 1800$ *lux*, 1 *meter* viewing distance, $Y = 30$ gray background, 18 pieces of 15×18 *cm* size color samples from the whole gamut. Observers have ordered sample-pairs in according to the harmony preference. Results have been absolute frequencies

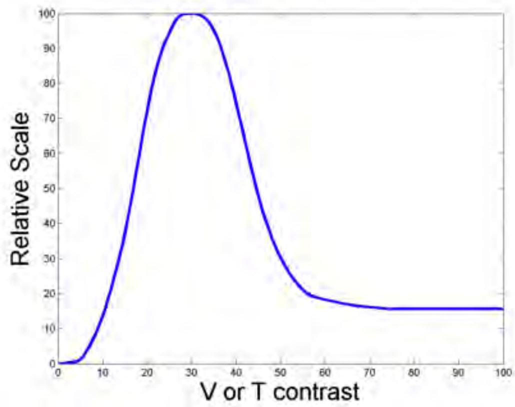

Figure 12: *The relative harmony value of the lightness contrast is not monotonously increasing. The same function is used for the saturation-contrast formula, but with a hue, and lightness dependent new variable*

and, after a normalization, relative frequencies and distributions, respectively.

One of the most important consequences of this experiment is, that the distributions of $luminance - contrast$ are hue independent and saturation independent from each other, in sense that these two latter attributes are arbitrary but constant in a sample-pair series. Therefore the relative harmony value as a function of the $luminance - contrast$ can be presented in a unique curve: see fig 12. Its maximum value 100 is at the luminance difference 30. The difference is zero under the unit, because it is not noticeable, and the function for large differences tends to the value 15,6. The relative lightness harmony is over 50, iff $17 \leq V \leq 45$. Even just this non evident result of the paper can be efficiently applied in the color planning.

3.2. Relative harmony value of saturation contrast

Experiments have been performed in 1983-84 by 1155 students with 187.000 elementary experiments. Other conditions have been the same as in section 3.1. In these experiments the distribution depends on the selected hue and luminance level. Interestingly, after a compression or stretching, the shapes of the distribution practically equal to one of the $luminance - contrast$ function. If the $luminance - contrast$ harmony function on fig 13 is notated with $V(x)$, $x \in [0, 100]$, than the appropriate function of saturation T can be expressed as

$$T(x) = V\left(\frac{30 \cdot x}{M(H,V)}\right) \qquad (1)$$

where M is the maximum locus of the curve stored in

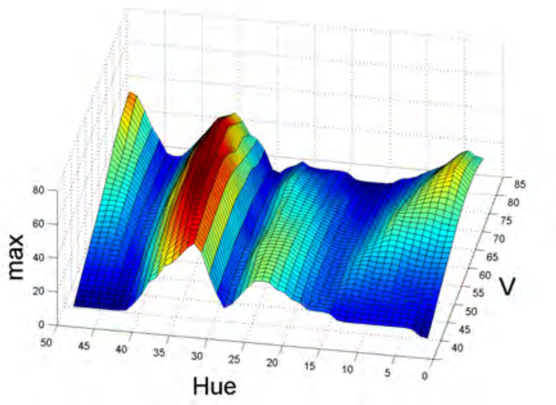

Figure 13: *Hue and lightness dependent surface of the function M(H,V), used in formula (1)*

a $2D$ table, according to fig 13. The Hue refers the limit-colors, using not the original Coloroid numbers A, which between the 7 color groups has jumps, but with a continuous numbering from 1 to 48. The other axis represents the luminance. The maximum locus M is between 10 and 60 of $saturation-difference$, if the luminance is between 40 and 80. Range of the saturation contrast x is clipped at given luminance by the gamut differently. The curve is not validated for values T less then $4-5$. This hue-dependent unsaturated range, the problems of nearly neutral colors, needs further investigation.

4. Color Plan Design

4.1. About the Color Plan Designer

The Coloroid system has been presented above with three different rules of color harmony, based on earlier experiments, which have been not processed up to now. The Coloroid research has generated many useful aesthetic rules. The Coloroid Color Plan Designer [Col04] has been developed by using some of these rules. This designer generates very simple and user-friendly harmonic color sets, and it can be applied in architecture, computer graphics, visualization, product design, web page planning, in the paint industry and other fields, where requirement of harmonic color sets occurs at all.

The Designer supports monochromatic, dichromatic and trichromatic harmonies, based on 1, 2 and 3 basic hues, respectively. A wide observation set has proven (see e.g. [Nem80]) that linearly or logarithmically uniform series, replaced on a hue page, have the highest harmony value. Accordingly to this rule, the software firstly lets the user select the number of hues, and afterward permitted hue combinations will be presented in according to the loci of the highest values of the Just Harmonic Saturation curve (fig 10). The

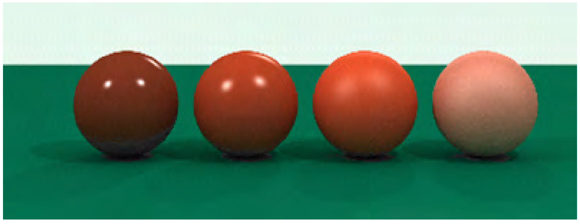

Figure 14: *A dichromatic scene, where colors of diffuse parts build a harmonic set. It was used in a BRDF study*

Figure 15: *A dichromatic BRDF study, containing 3 diffuse colors of the other BRDF study*

trichromatic selection is based on 3 dichromatic hue-pairs and on some additional observation. After the hue selection, the same regular grid will appear with 1, 2 or 3 layers, with selectable lattice constant and free rotation angle. Finally, uniform series can be selected on these common grids of hue-layers.

All of these series, also used multiple grid points on the hue-layers results in harmonic color sets. We can create quite interesting effects by using some additional receipt, offered in the Help, formulating practical and short rules instead of complicated formulas, based on the experiences of the Coloroid author.

The software takes the level of ambient light into consideration, using a color appearance model, which is currently $CIECAM97$, but it will be changed to $CIECAM02$ soon. Coordinates of colors, selected interactively by mouse or by defining coordinates, will be transformed in several color system, like $CIE\ XYZ$, xyz, Lab, Luv, $Hunter\ Lab$, $display\ RGB$ with the corrected γ values, and $linear\ rgb$ in $[0,1]$ assuming the $sRGB$ primaries, and also all of Coloroid related data, like A, T, V, φ, additive components of s, w and p, and all of the hue-angles and A hue coordinates of hues with highest harmony. A message appears, if the color is invalid, not displayable or if it can not be realized by realistic first and second derivatives, as a spectral reflectance curve of a solid color.

4.2. Examples, Applications

We demonstrate some images, created by using the software and also some manually painted examples, made at TU Budapest, based on Coloroid harmony rules. Fig 1 (a) shows a dichromatic composition. In order to show the total harmony appearance of a color set, the software generates either randomly ordered color patches or a caleidoscope. The given example contains two hues with 130° difference, the grid size is 20 and the grid is rotated with 120° (CCW), see Fig 1 (b).

Let us see some computer graphics applications. A BRDF study in [NNSK99] has applied a dichromatic color set with 130° (fig 14, fig 15). A kitchen has been generated by a similar color world, using a little additional third hue, namely a lilac color [MSN03]. The color set contains only 6 elements. It can be illustrated like a bitmap (fig 18) using *sRGB* values. The colors of the set are listed in Table 1 by their $CIE\ XYZ$, Coloroid ATV, and linear r, g, b triplets with *sRGB* primaries.

	X	Y	Z	A	T	V	r	g	b
C0	85.8	88.1	89.8	23.0	7.4	93.9	0.98	0.86	0.82
C1	48.3	40.4	7.0	22.0	42.5	63.6	0.91	0.29	0.02
C2	65.5	62.0	47.3	23.0	24.0	78.7	0.94	0.55	0.41
C3	13.5	17.0	16.1	65.4	5.3	41.3	0.10	0.20	0.14
C4	49.0	54.6	56.8	65.4	5.6	73.9	0.47	0.57	0.52
C5	18.8	16.8	20.8	41.0	7.0	41.0	0.25	0.14	0.20

Table 1: *Trichromatic color set*

Two manually painted dichromatic façades (fig 19 and fig 20) are created at TU Budapest in 80's in frame of color dynamics curses.

We introduced the just harmonic curve and surface for 2 hues, but we show trichromatic examples too. Fig 21 shows a simple artistic arrangement, practical colorization of a segmented image, which occurs often in different contexts in imaging. The appropriate colors in the Coloroid system are demonstrated in fig 22. In this case it is necessary but not sufficient, that the dichromatic rules are fulfilled for all of the 3 possible hue-pairs. The exact trichromatic rules are not derived in this paper. A further trichromatic example from the Coloroid project at TU Budapest is shown in fig 23. Finally we demonstrate a polychromatic example, which colors are under the $Just\ Harmonic\ Saturation$ Curve, and fulfill also other rules, which are not detailed here. This picture was painted by Antal Nemcsics in 2003; its title is "Nestor".

5. Results and further investigations

We have presented new rules of color harmony, derived from the original data base of Coloroid experiments supplemented with additional new measurements. Firstly, we studied an evergreen problem of color dynamics: which hues can build a harmonic pair. We have concluded that any two hues can be harmonic, but only with given appropriate saturations. One

Figure 16: *Mostly dichromatic interior in daylight using the color set of Table 1*

Figure 17: *Mostly dichromatic interior lit by a small area lightsource, using the color set of Table 1*

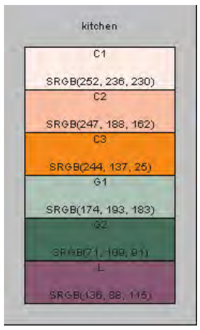

Figure 18: *The 6 colors of the kitchen scene, according to Table 1, generated by the Color Plan Designer software. It computes this image for other graphics softwares using option 'Export as bitmap', giving also the color coordinates in sRGB system*

Figure 19: *Manually painted plan of a dichromatic façade from a Coloroid curse in the 80's*

Figure 20: *Another dichromatic façade plan*

Figure 21: *A trichromatic color study*

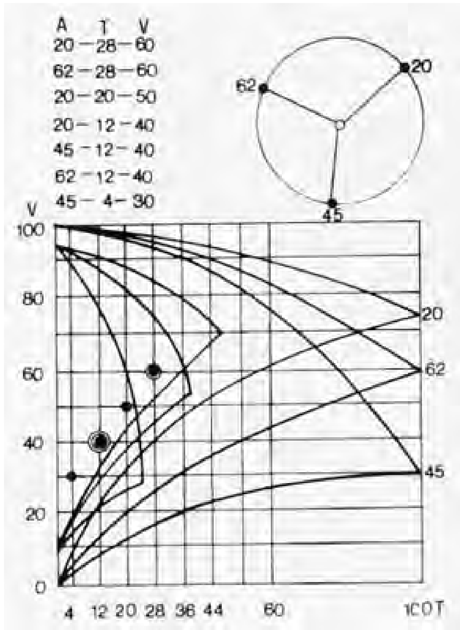

Figure 22: *The colors of the Figure 21 in three hue planes of the Coloroid system with the ATV coordinates*

Figure 23: *A trichromatic interior. The hues are selected with the* Coloroid Color Wheel

Figure 24: *Antal Nemcsics: Nestor, 2003. A polychromatic artwork. All of the occurring color-pairs are under the just harmonic saturation curve of Figure 10*

result of particular importance is the border-surface of harmonic and disharmonic hue-dependent saturation fields; see section 2, fig 10. Another important result is given in fig 12, describing the relative harmony value of lightness contrast, which is, not evidently, hue and saturation independent.

The last presented new result is about the relative harmony value of saturation-contrasts. Here we have found a two-step approach. For a color pair with the same hue and lightness values, the relative harmony value has practically the same curve as used for the lightness-contrast. But, in a second step, we had to stretch it at most 2-times or compress it at most 3-times, depending on hue-lightness values, presented by fig 13.

Finally, we have presented the *Color Plan Designer* software and shown examples in computer graphics, architecture and art.

This paper is just one report of a running color harmony research. We would like to describe the unified quantitative dichromatic harmony formula for arbitrary two colors, in the future. Furthermore, the appropriate polychromatic harmony rules based on dichromatic results are under investigation.

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