Experimental Determination of Laws of Color Harmony. Part 2: Harmony Content of Different Monochrome Color Pairs

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Abstract: In 1956, we came to the decision at the Budapest Technical University to start large scale experiments on color harmony. The experiments and the processing of the experimental results have been completed in 2006, after 50 years of research work. The focal point of the experiments published in the current article has been the practical experience that the span of intervals between saturations and brightnesses of the compositions influence the harmony content of the composition, namely they determine in what extent we perceive the color composition as a harmonic one. Within the framework of experiments compositions have been shown to the participants, first those consisting of color pairs featuring the same hues and saturations but different brightnesses then those consisting of the same hues and brightnesses but different saturations. The method of experiments consisted of comparisons in pairs. There were 780 compositions prepared for the tests. The number of elementary observations during the tests comprised 544 000. It has been established that the variation of harmony content as a function of brightness- and saturation-intervals could be described by a harmony function. It has been established that the variation of harmony content depending on brightness-intervals is not, but that of depending on saturation intervals is being influenced by the hues of colors of the color pair in the composition. It has been established that in case of compositions with the maximum harmony content the interval of brightnesses of the colors making the color pair in each case gives d30V (d9Y), the interval of saturations gives d30T or is near to it. Col Res Appl, 33, 262 – 270, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20416

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INTRODUCTION

Practical experience reveals that the span of intervals between saturations and brightnesses of the compositions influence the harmony content of the composition, namely they determine to what extent we perceive the color composition as a harmonious. In numerous cases, for example when a color pair with a properly chosen hue is being selected for the wall surface and sections of the façade, the differences in brightness and saturation of the members of the color pair will be primarily significant to endow a harmonic appearance to the façade.

The experiments described in this article have been focused to find correlation between the span of intervals of brightness and saturation of monochrome color pairs and the harmony content of the composition formed by the color pairs. Numerous researchers have been dealt with similar problems formerly; it is worth mentioning first of all the experiments conducted by Dimmick (1933), Katz (1935), Moon & Spencer (1944), Boring (1950), Granger (1955), Mori (1967), Ou-Luo (2004).[1–10] In contrast to these former experiments, saturation and brightness intervals have been defined in our experiments as the product of harmony thresholds and given integers—and not according to perception thresholds—that means they were defined not in the color space of Munsell color system,[11–15] but that of Coloroid color system.[16–20] The aim of the research gives the reasons: we are providing support to architects, artists and numerous other specialists working in daylight, not using eyes adapted to darkness. With an eye adapted to an average daylight, identical brightness intervals in the darker regions of Munsell color system are felt far smaller than those lying in the brighter regions. It is explained by the adaptivity of eye which is more orders of magnitude higher in the dark than in the bright surroundings. Our experiments are differentiated from former experiments by the fact that they cover not only some color ranges but try to cover the whole color space—within the limit of possibilities. As a consequence, it was necessary to conduct a very large number of elementary experiments. To characterize the line of experiments we have described only a couple of them. Our conclusions nevertheless are based on the whole pool of experiments conducted.

EXPERIMENTS

Within the framework of experiments compositions have been shown to the participants, first those consisting of color pairs featuring the same hues and saturations but different brightnesses, then those consisting of the same hues and brightnesses but different saturations. The method of experiments consisted of paired comparisons. Participants had to select the more harmoneous one of two compositions, until they have judged each possible composition pairs of the given phase of experiment.

The subjects of the experiments conducted between 1982 and 1987 were mostly 18 to 24-years-old students at the Faculty of Architecture of the Budapest Technical University. The experiments were taken in premises illuminated by light reflected from the Northern firmament, near to the window, where the level of illumination was about 1600–1800 lx. The composition pairs having individual dimensions of 50×50 cm^2 were positioned on a vertical surface. The environment of the tests has been a grey surface of $Y = 30$ light density factor. Illumination of the tests was at 45°, observation was made with 90° viewing angle from a distance of 150 cm. Before starting the experiments, the leader of the experiments showed the tests to the subjects of the experiment, and then explained their tasks in detail, according to which they had to select from the two compositions felt the most harmoneous one by their own judgment. Observers participated in the experiments in groups of 10 people. A part of the experiment have been repeated between 1999 and 2005 using the same compositions, but this time the observers were painter–artists. Each composition pair has been judged by 80–120 experimental persons. Within the framework of the series of experiments there were 780 compositions in 5440 pairs which meant 544 000 elementary observations.

During the processing of answers given by the observers, the extent of color harmony content of each composition (which, at a concrete saturation of a concrete hue has meant the brightness difference, or, at a concrete brightness of a concrete hue has meant the saturation difference) has been expressed in percents, according to the following formula:

$$x_h = 100 n_h / m, \quad (1)$$

where x_h is the rate of preference of the composition in percents, n_h is the number of the votes given to the composition in question, m is the aggregate number of observers.[21–30]

Experiments Aimed at the Determination of Harmony Content of Brightness Intervals

The harmony content of different brightness intervals has been defined for 10 different hues, namely for yellows, oranges, reds, magentas, violets, two groups of blues, and three groups of greens. Within the Coloroid color system, colors characterized by identical wavelengths are located on identical axis sections, the so-called Coloroid color planes, and has the same hues. Successive declinations of color planes selected for the experiments were approximately the same. This method of selection was aimed at covering the whole color space. In Coloroid color system the notations of hues and characteristic wavelength of colors used in the experiments were as follows:

A10	λ547.836,	A16	λ580.949,	A25	λ593.981,
A35	λ-500.049,	A43	λ-539.174,		
A50	λ450.000,	A52	λ475.449,	A60	λ490.371,
A64	λ502.695,	A70	λ536.295		

Using colors of each of 10 Coloroid color planes containing colors of the same hue (at least 4, at most 6 colors with different saturations, depending on the hue) compositions have been constructed containing 2 colors each, so that within the limits of hues and saturations, the dV Coloroid brightness interval between these two colors amounted successively d5V, d10V, d15V, d20V, d25V, d30V, d35V, d40V, d4V5, d50V, d55V, d60V, d65V, d70V. The number of prepared and studied compositions were 385. From among these compositions 14 were selected for demonstration purposes in the article. From among the reds tending to magenta, 7 compositions compiled of colors marked as A35 Coloroid hue and T11.82 Coloroid saturations, where the brightness intervals between the colors are successively d10V, d20V, d30V, d40V, d50V, d60V, d70V, are shown in Fig. 1. Another seven compositions belonging to the blue domain, compiled of colors marked as A52 Coloroid hue and T11.76 Coloroid saturations where the brightness intervals between the colors are successively d10V, d20V, d30V, d40V, d50V, d60V, d70V are shown on Fig. 2. Figures are intended to represent the formal solutions of compositions and differences between visual appearances of different brightness intervals.

Coloroid coordinates and color components in CIE XYZ system of compositions appearing on Fig. 1 are shown on Table I, those of Fig. 2 on Table II. Colors

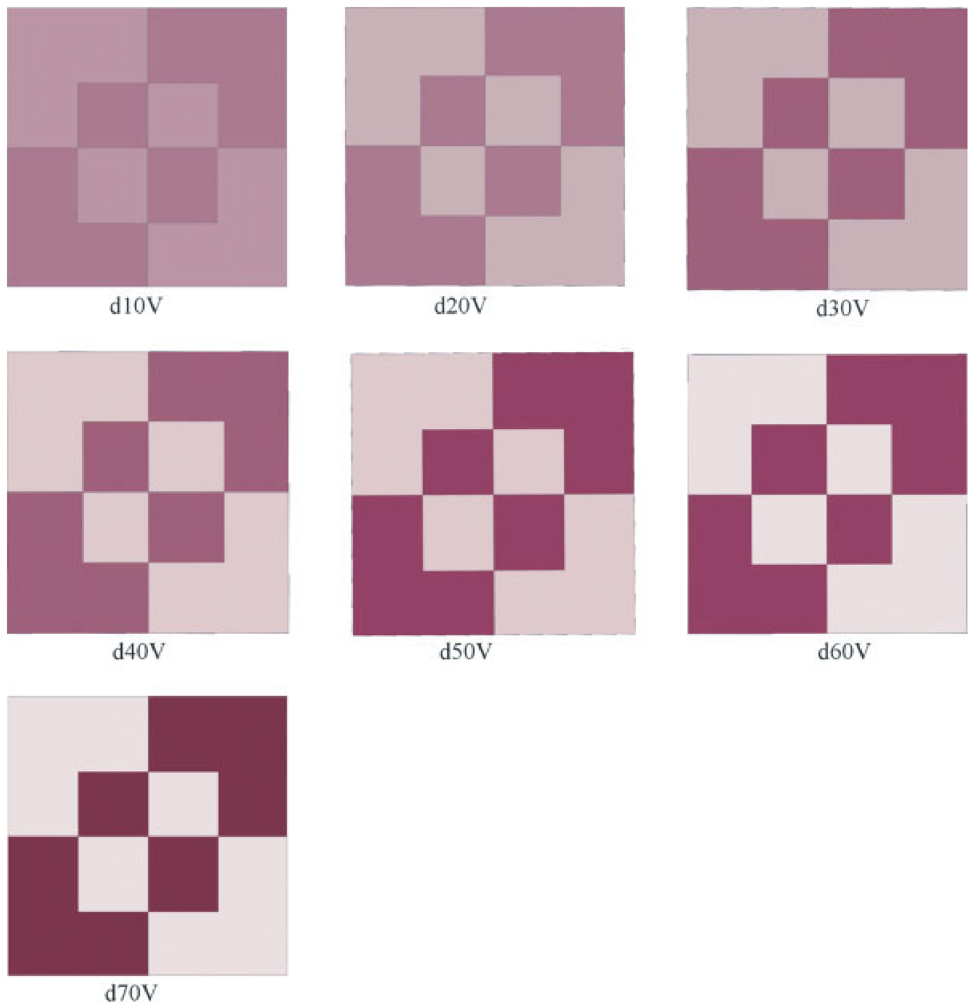

FIG. 1. Seven compositions compiled of colors marked as *A35* Coloroid hue and *T11.82* Coloroid saturations where the brightness intervals between the colors are successively d10V, d20V, d30V, d40V, d50V, d60V, d70V.

listed in the tables have been compiled into composition with the following pairs:

d10V = Color 04 and Color 05,
d20V = Color 05 and Color 03,
d30V = Color 03 and Color 06,
d40V = Color 06 and Color 02,
d50V = Color 02 and Color 07,
d60V = Color 07 and Color 01,
d70V = Color 01 and Color 08.

The processing of experimental results treated the answers of men and women separately. In the former experiments there were male and female participants approximately in the same number. Fifteen years later in the experiments repeated with artist painters men were in majority. The standard deviation of answers both of men and of women did not exceed 4%. It has been a surprise for us that experimental participants have judged the harmony content of hue pairs with different brightness variances in a similar way, in all saturation domains of all 10 hue domains. As a function of hue and saturation the standard deviation of answers was varying only between 2 and 4%. As a conclusion of all aforementioned it became possible to describe the harmony content of brightness intervals between colors of studied saturation of studied hues with one curve (Fig. 3). This figure illustrates the harmony content of brightness intervals of colors of any saturation of any hue.

The line of experiments has revealed another important result, the experimental participants—regardless of whether they were male or female, and regardless of whether they were relatively in experienced architectural students or practical artistic painters with a lot of experience with colors, have judged as most harmoneous the hue pair with d30V brightness interval in all saturation domains of all 10 hue domains. Brightness interval d30V in Coloroid system corresponds d9Y in CIE XYZ system.

Experiments Aimed at the Determination of Harmony Content of Saturation Intervals

Preceding the large-scale experiments there have been trial experiments conducted with 12 participants to determine whether the harmony content of saturation intervals

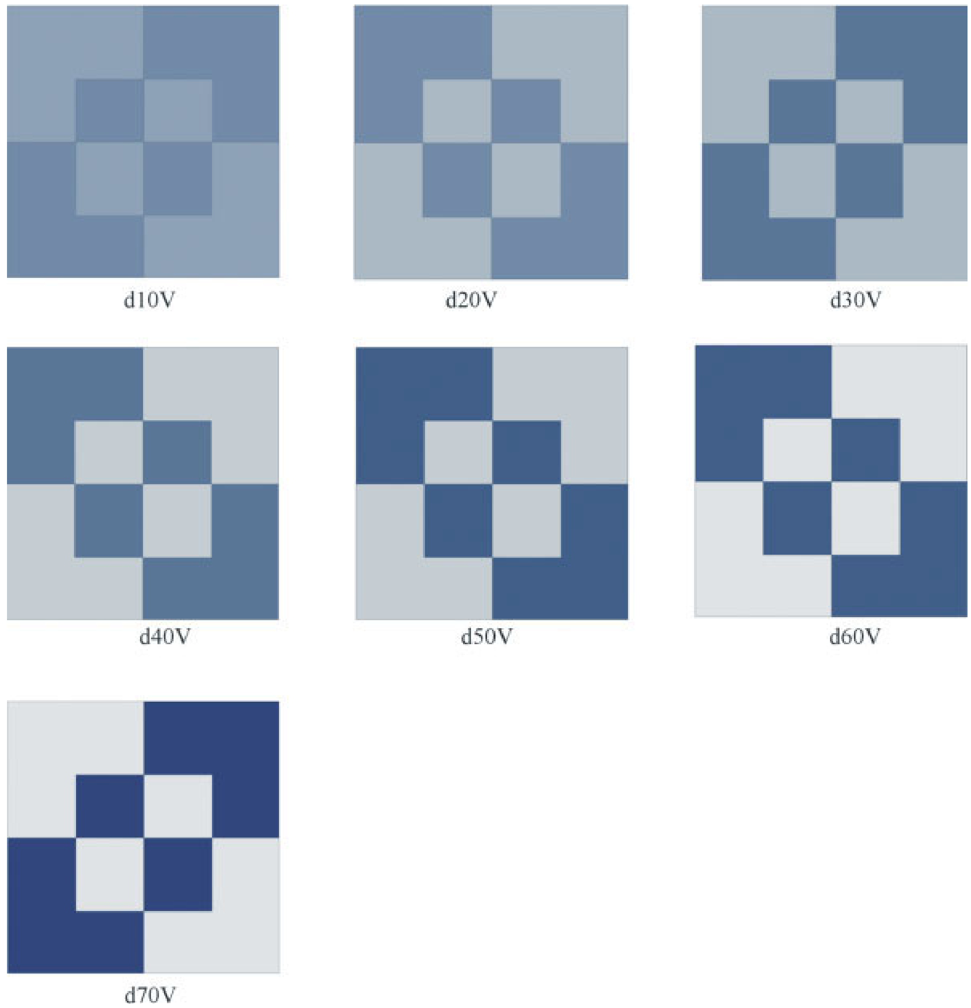

FIG. 2. Seven compositions compiled of colors marked as *A52* Coloroid hue and *T11.76* Coloroid saturations where the brightness intervals between the colors are successively d10V, d20V, d30V, d40V, d50V, d60V, d70V.

are influenced by hues, or, similar to the judgment of brightness intervals, they prove to be indifferent. We have observed that hue has a core role in judging saturation intervals, therefore their harmony content has been studied during the large-scale experiments for 24 hues defined by color planes of Coloroid color system featuring approximately similar successive inclinations expressed in degrees. From among the hues studied there were four hues belonging to the yellow color region, three hues to orange region, three hues to red region, three hues to purple-violet region, three hues to blues and seven hues to green region. Notation in Coloroid color system and characteristic wavelength of hues participating in the experiments (In Coloroid color system all colors with the same hue shows the same characteristic wavelengths):

A10	λ547.836,	A12	λ574.384,	A14	λ577.699,
A16	λ580.949,	A21	λ584.453	A23	λ588.519,
A25	λ593.981,	A30	λ602.717,	A32	λ625.000,
A34	λ-496.554	A40	λ-504.836,	A42	λ-524.590,
A44	λ-549.456,	A46	λ-563.846	A51	λ468.715
A53	λ479.294,	A55	λ484.292,	A60	λ490.371,
A62	λ495.280,	A64	λ502.695	A66	λ520.396,
A71	λ548.149,	A73	λ560.739,	A75	λ566.783

TABLE I. Coloroid coordinates and CIE XYZ color components of colors in compositions of Fig. 1.

	X	*Y*	*Z*	*A*	*T*	*V*
Color 01	84.66	83.93	92.70	35.00	11.82	91.61
Color 02	68.20	66.61	73.83	35.00	11.82	81.61
Color 03	53.64	51.28	57.15	35.00	11.82	71.61
Color 04	40.97	37.96	42.64	35.00	11.82	61.61
Color 05	30.21	26.64	30.32	35.00	11.82	51.61
Color 06	21.35	17.32	20.17	35.00	11.82	41.61
Color 07	14.39	9.99	12.19	35.00	11.82	31.61
Color 08	9.33	4.67	6.40	35.00	11.82	21.61

TABLE II. Coloroid coodinates and CIE XYZ color components of colors in compositions of Fig. 2.

	X	*Y*	*Z*	*A*	*T*	*V*
Color 01	79.55	83.34	101.27	52.00	11.76	91.29
Color 02	63.14	66.08	82.48	52.00	11.76	81.29
Color 03	48.64	50.82	65.87	52.00	11.76	71.29
Color 04	36.04	37.57	51.43	52.00	11.76	61.29
Color 05	25.34	26.31	39.17	52.00	11.76	51.29
Color 06	16.54	17.05	29.09	52.00	11.76	41.29
Color 07	9.64	9.79	21.19	52.00	11.76	31.29
Color 08	4.64	4.53	15.46	52.00	11.76	21.29

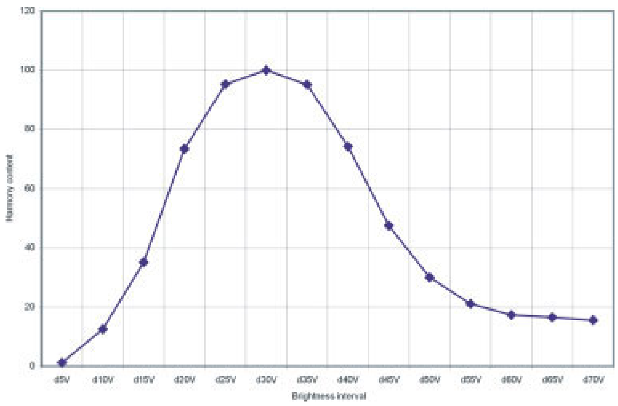

FIG. 3. Harmony content of brightness intervals between colors of any saturation of any hue are illustrated by th curve of this figure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Using colors of each Coloroid color plane containing colors of the same hue (at least 4, at most 12 colors with different brightnesses, depending on the hue) compositions have been constructed containing 2 colors each, so that within the limits of hues and brightnesses, the dT Coloroid saturation interval between these two colors amounted successively d5T, d10T, d15T, d20T, d25T, d30T, d35T, d40T, d45T, d50T, d55T, d60T, d65T, d70T. The number of constructed compositions has been 395. From among these compositions there are 13 ones selected for demonstration in the article. From among the warm yellows there are five compositions shown in Fig. 4, made of colors featuring Coloroid hue A12 and Coloroid brightness V80.97 where the saturation intervals between colors are successively d10T, d20T, d30T, d40T, d50T. From among colors of the orange region there are four compositions shown in Fig. 5 made of colors featuring A16 Coloroid hue and V71.29 brightness where the saturation intervals between colors are successively d10T, d20T, d30T, d40T. From among colors of the blue region there are six compositions shown in Fig. 6 made of colors featuring A55 Coloroid hue and V71.29 brightness where the saturation intervals between colors are successively d10T, d20T, d30T, d40T , d50T, d60T. These figures are intended to demonstrate formal solutions of compositions and the differences between visual appearance of different saturation intervals.

Coloroid coordinates and CIE XYZ color components of compositions shown in Fig. 4 are contained by Table III, those of Fig. 5 are contained by Table IV and those of Fig. 6 by Table V. Colors listed in Tables III and IV are paired into compositions of Figs. 4 and 5 as follows:

d10T = Color 03 and Color, 04,
d20T = Color 04 and Color 02,
d30T = Color 02 and Color 05,
d40T = Color 05 and Color 01,
d50T = Color 01 and Color 06.

Colors listed in Table V are paired into compositions of Fig. 6 as follows:

d10T = Color 04 and Color 05,
d20T = Color 05 and Color 03,
d30T = Color 03 and Color 06,
d40T = Color 06 and Color 02,
d50T = Color 02 and Color 07,
d60T = Color 07 and Color 01

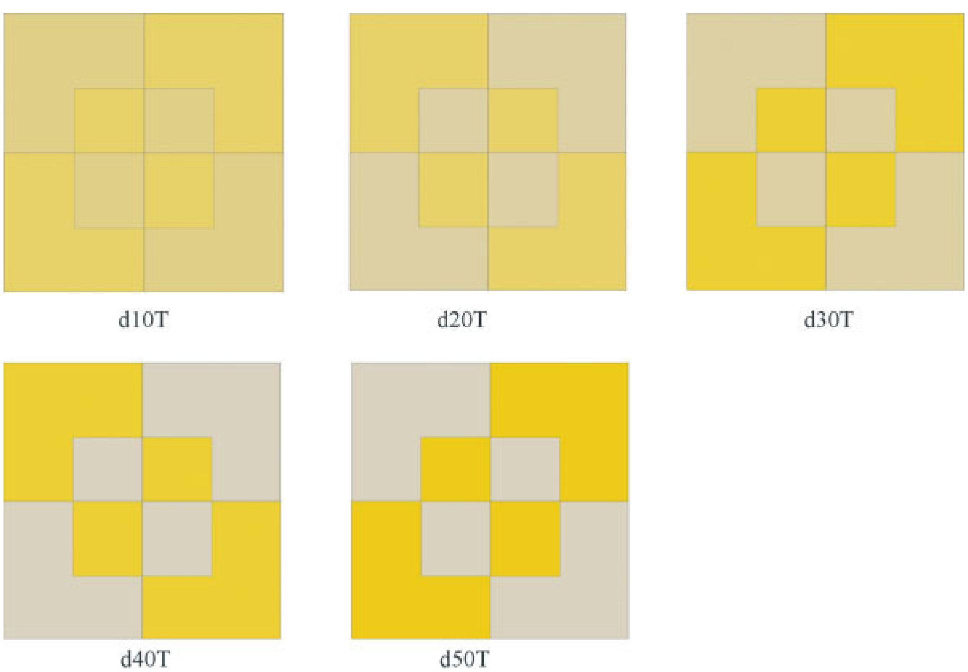

FIG. 4. Five compositions compiled of colors with 80.97 Coloroid brightness of A12 Coloroid hue, where the saturation intervals between colors are successively d10T, d20T, d30T, d40T, d50T.

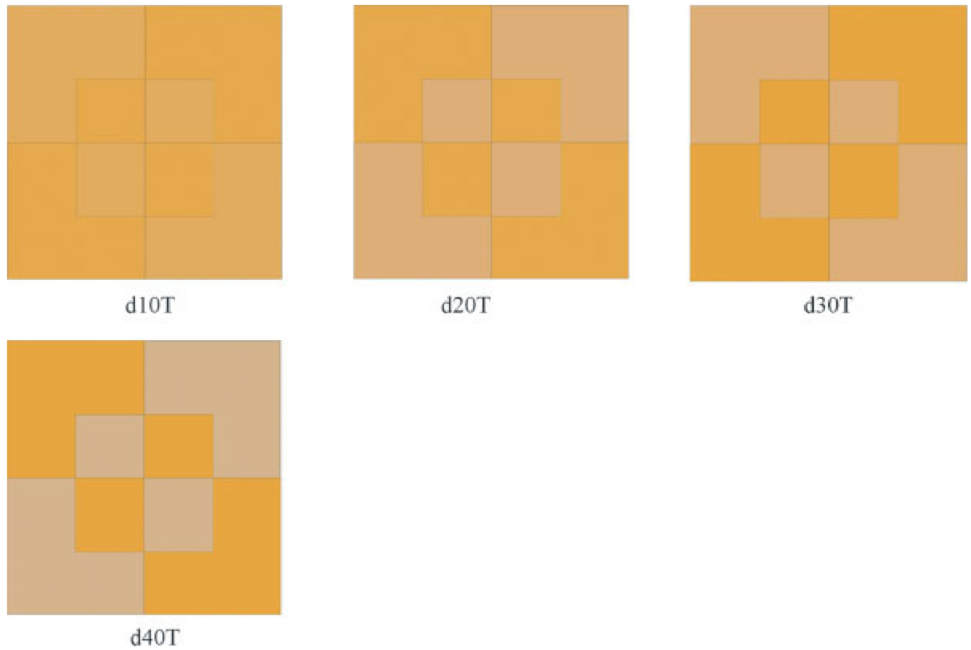

FIG. 5. Four compositions compiled of colors with 71.29 Coloroid brightness of A16 Coloroid hue, where the saturation intervals between the colors are successively d10T, d20T, d30T, d40T.

The processing of experimental results treated answers of men and women separately, as in case of brightness intervals. In the experiments started in 1988 there were approximately the same number of male and female participants. In the experiments started in 2001 with artist painters men were in majority. The standard deviation of answers both of men and of women and in relation between men and women did not exceed 5%.

After the processing phase it has been established that the harmony content of different saturation intervals are significantly influenced by the hue and brightness of color pairs. It has been established also that in addition to differences there are also significant similarities in the judgment of harmony content of saturation intervals of color pairs of different hues and brightnesses. From saturation interval d5T on, parallel to increasing the intervals, harmony content will rise, at the beginning only slowly, then more rapidly to a maximum value between d20T and d35T, then decreasing again, approximately at saturation interval d60T it becomes steady. This tendency is shown in Fig. 7 demonstrating the harmony content of different saturation intervals of a color pair with Coloroid hue A55 (λ484.292) and Coloroid brightness of V71.29.

It has been established that maximum of harmony content appears in color pairs where the colors are of the same brightness, have hues A21 (λ584.453), A35 (λ-500.049), A44 (λ-549.456), A51.5 (λ472.126), A64

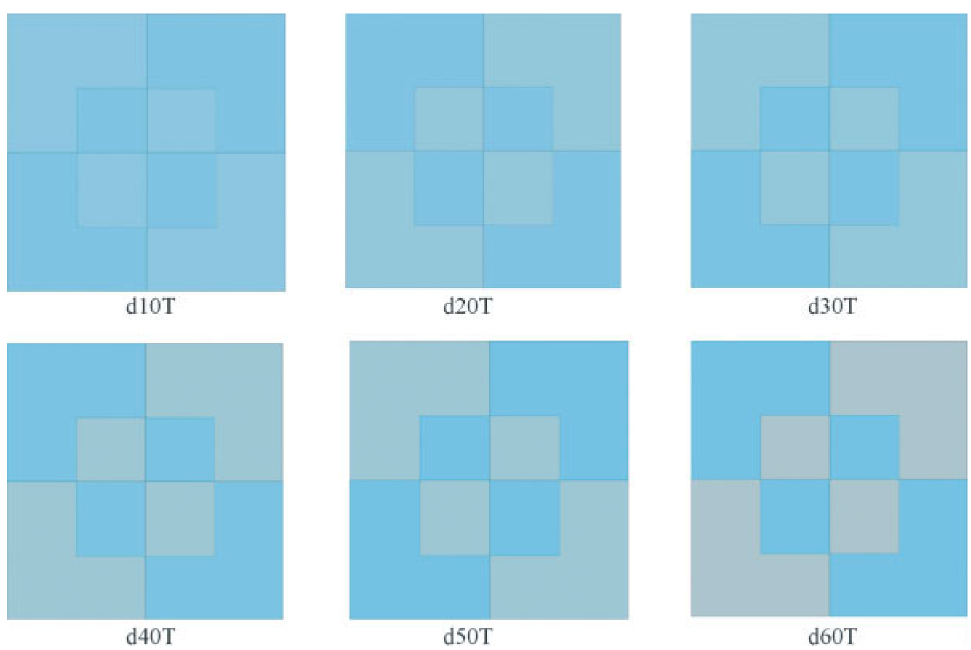

FIG. 6. Six compositions compiled of colors with 71.29 Coloroid brightness *of* A55 Coloroid hue, where the saturation intervals between the colors are successively d10T, d20T, d30T, d40T, d50T, d60T.

TABLE III. Coloroid coodinates and CIE XYZ color components of colors in compositions of Fig. 4.

	X	Y	Z	A	T	V
Color 01	61.82	65.56	59.76	12.00	11.61	80.97
Color 02	61.40	65.56	49.76	12.00	21.61	80.97
Color 03	60.98	65.56	39.76	12.00	31.61	80.97
Color 04	60.56	65.56	29.76	12.00	41.61	80.97
Color 05	60.15	65.56	19.75	12.00	51.61	80.97
Color 06	59.73	65.56	9.75	12.00	61.61	80.97

(λ502.695), A74 (λ564.183), respectively, and the members have between each other d30T saturation intervals. (These intervals may be expressed even in the CIE XYZ system using Coloroid-CIE transformation equations.)

It has been established that to reach the maximum harmony content there is a need for a saturation interval having a value more than d30T in case of yellow-greens, yellows, magentas and blues and less, than d30T in case of oranges, reds, violets, and greens. These two latter findings are shown in Fig. 8, where the points of the curves for monochrome color pairs of different hues are located at saturation intervals resulting the maximum of harmony experiences.

It has been established that harmony content of different saturation intervals depends not only on their hues but also on their brightnesses. It has been also established that color pairs featuring d30T saturation intervals are felt to be the most harmonic ones if they have V60 (Y36) brightness in case of greens, yellows, oranges, and reds.

It has been also established that color pairs featuring d30T saturation intervals are felt to be the most harmoneous ones if they have V50 (Y25) brightness in case of magentas and violets. It has been also established that at any brightness values of color pairs having hues A35 (λ-500.049) and A63 (λ498.450), respectively, the most harmony content is being felt at saturation interval d30T.

Color pairs of greens, yellows, oranges, and reds being brighter, than V60 need bigger saturation interval than d30T to reach the maximum harmony content, those pairs being darker than V60 need smaller saturation interval than d30T for the same.

Color pairs of magentas, violets, and blues being brighter than V50 need smaller saturation interval to reach the maximum harmony content, those pairs being darker, than V50 need bigger saturation interval for the same. These last six establishments are demonstrated in Fig. 9 where the points for monochrome color pairs of some

TABLE IV. Coloroid coodinates and CIE XYZ color components of colors in ompositions of Fig. 5.

	X	Y	Z	A	T	V
Color 01	50.49	50.82	37.00	16.00	19.61	71.29
Color 02	51.38	50.82	29.51	16.00	27.61	71.29
Color 03	52.27	50.82	22.03	16.00	35.61	71.29
Color 04	53.16	50.82	14.55	16.00	43.61	71.29
Color 05	54.05	50.82	7.07	16.00	51.61	71.29

TABLE V. Coloroid coodinates and CIE XYZ color components of colors in compositions of Fig. 6.

	X	Y	Z	A	T	V
Color 01	47.17	50.82	60.90	55.00	12.04	71.29
Color 02	45.92	50.82	67.06	55.00	25.38	71.29
Color 03	44.67	50.82	73.22	55.00	38.71	71.29
Color 04	43.42	50.82	79.38	55.00	52.04	71.29
Color 05	42.16	50.82	85.54	55.00	65.38	71.29
Color 06	40.91	50.82	91.70	55.00	78.71	71.29
Color 07	39.66	50.82	97.86	55.00	92.04	71.29

deliberately chosen hues are located at saturation intervals of different brightnesses resulting the maximum of harmony experiences.

CONCLUSIONS

The system of our experiments tried to establish the harmony content of brightness and saturation intervals of monochrome color pairs—beyond of former experiments—for nearly all surface colors of the color space.

The differences of brightness and saturation intervals being studied with our experiments—beyond of former experiments—using scales of the Coloroid color system built on harmony thresholds, in relation to a daylight adapted eye, proved to be uniform.

Our line of experiments reflect the opinion of a population being more orders of magnitude larger than that of former experiments.

The results of our experiments featuring less than 5% standard deviation—beyond of former experiments-represent two experimental periods with 15 year between them.

During the experiments-in consonance with a part of former experiments it has been established that the harmony content of compositions constructed of monochrome pairs depends on brightness and saturation intervals between the colors of a pair.

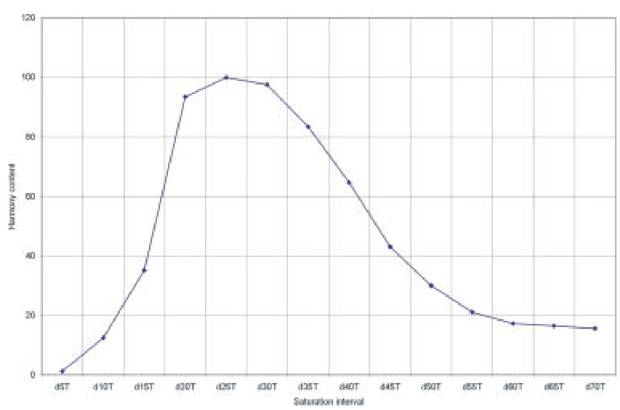

FIG. 7. Harmony content of color pairs of A55 Coloroid hue and V71.29 Coloroid brightness with different saturation intervals. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

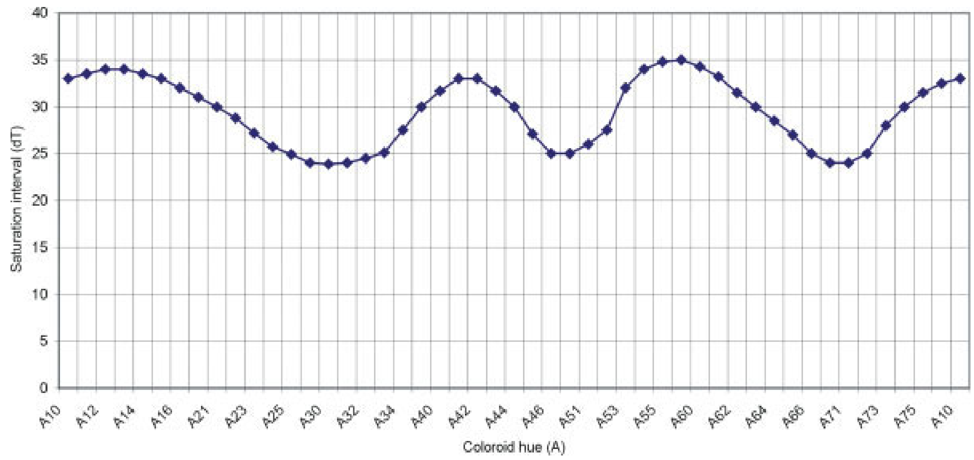

FIG. 8. Saturation differences resulting in maximum harmony experience for monochrome color pairs of different hues. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Beyond of former results it has been established that the variation of harmony content depending on brightness and saturation intervals may be described on an exact way.

Contrary to some former conclusions it has been established that variation of harmony content depending on brightness intervals is not being influenced by hue and saturation of color pairs constituting the composition.

It has been established-beyond former conclusions—that those compositions have the highest harmony content, where the brightness interval between colors of a pair with identical hue and saturation, expressed in Coloroid system gives d30V, in CIE XYZ system d9Y.

It has been established that—in consonance with a part of former conclusions—that the variation in harmony content depending on saturation intervals will be influenced also by the hue and saturation of colors of the color pair comprising the composition.

It has been established, beyond former conclusions that maximum of harmony content appears in color pairs where the colors are of the same brightness, have Coloroid hues A21, A35, A44, A51.5, A64, A74, respectively, and the members have between each other d30T saturation intervals. (These intervals may be expressed even in the CIE XYZ system using Coloroid-CIE transformation equations.)

It has been established, in addition to the former conclusions that to reach the maximum harmony content there is a need for an exactly describable Coloroid saturation interval having a value more than d30T in case of yellow-greens, yellows, magentas and blues and less, than d30T in case of oranges, reds, violets, and greens.

Also, it has been established, that color pairs featuring d30T saturation intervals are felt to be the most harmonic ones if they have V60 (Y36) brightness in case of greens, yellows, oranges, and reds.

We found that color pairs featuring d30T saturation intervals are felt to be the most harmoneous ones if they have V50 (Y25) brightness in case of magentas and violets, and that at any brightness values of color pairs having Coloroid hues A35 and A63, respectively, the most harmony content is being felt at saturation interval d30T.

In addition, color pairs of greens, yellows, oranges, and reds being brighter, than V60 need bigger saturation interval than d30T to reach the maximum harmony content, those pairs being darker than V60 need smaller saturation interval than d30T for the same.

Finally, it has been established, that color pairs of magentas, violets, and blues being brighter than V50 need smaller saturation interval to reach the maximum harmony content, those pairs being darker, than V50 need bigger saturation interval for the same.

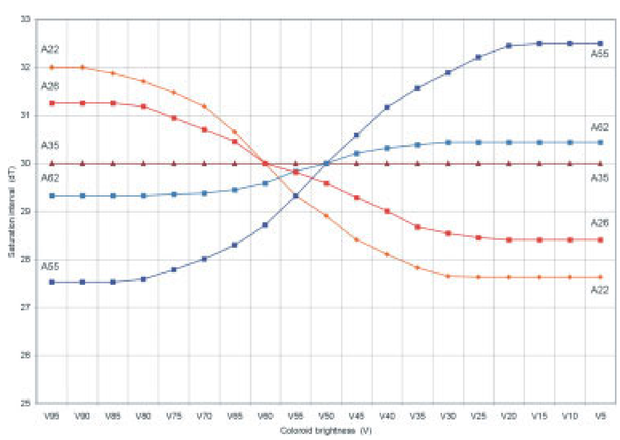

FIG. 9. Saturation differences resulting in maximum harmony experience in case of monochrome color pairs with different brightnesses. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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