COLOUR DYNAMIC REQUIREMENTS AND THE COLOROID SYSTEM

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Introduction

For the architect designing coloured environment, colour may be both a technical and an artistic means. In the first case the possibility to define technical parameters assigned to different colours, in the latter case, to express the compositional relations between colours by numbers requires to identify each member of the group of colours by indices. Both requirements relate the problem of colour notation to that of colour systematization. The relation between the millions of distinct colours in the set and their indices cannot be an accidental one, but has to rely on colour systematization.

Many colour experts couple the concept of colour systematization almost entirely to colorimetry ([1] to [5]).

According to the well-known wording by G. WYSZECKI [6], colorimetry is a means for predicting if two visual stimuli of different spectral distribution will produce the same colour sensation under given conditions, by predicting the place of the two visual stimuli in a given colour space. If the colour-space co-ordinates of one stimulus equal those of the other one, a person with normal colour vision will feel the two colours to be equal.

This means is increasingly applied in modern industry, among others for numerically settling the difference between two colours. The endeavour to express the rate of change in colour perception by a proportional numerical change of colour indices has actually become the most important criterion of qualifying the colour systems.

For colour dynamics, the science of colour space design, to possess colour indices for numerically describing colour compositions has become a technical necessity by now, changing, however, the requirements for colour systems. This paper is going to deal with these new requirements as well as with the COLOROID colour system elaborated to meet them.

Research work in connection with the COLOROID colour system has been carried on since 1962 at the Technical University, Budapest. The work was started by creating different aesthetically uniform psycho-metric scales, that is, those felt to be uniformly varying when considered as a whole. "Considered as a whole" means that test subjects rated e.g. the brightness scale of about 20 to 100 members from white to black by viewing it at once, without concentrating on the relation between neighbouring colours in a section of the scale. The number of colours between each two colours of the scale was evenly increased up to a density where two adjacent colours could not be used anymore in a colour harmony design. The difference between these colours was named harmony interval. The number of harmony intervals between two neighbouring members of aesthetically uniform scales was found everywhere equal, contrary to the perceptionally even steps.

Scoring by over 70 thousand persons was used when creating the scale. Most of our results have been published successively [7—21]. During this work, our conception of the colour space of this colour dynamic system has been gradually modified. Thus, the set of our publications does not show the details but the different phases of development of the COLOROID. This is the first attempt to present in full the experiments made for creating the system, its interrelations and their application for colour composition.

1. The requirements of colour dynamics for colour systematization

The basic problem of colour systematization is rooted in the subjective colour perception, which is the result of highly compounded effects. It depends on the spectral energy distribution of the light source illuminating the coloured surface to be observed, on the luminance factor of the surface, on the geometry of observation and reflexion. Thus, in order to unambiguously express a colour perception, the *spectral energy distribution* of the light source, the *luminance factor* of the surface to be observed, and the *geometry* of observation and illumination have to be fixed.

Also the characteristics of the colour perception mechanism influence the colour sensation. Estimation of a colour is also affected by factors such as the *chromatic adaptation*, the *chromatic constancy*, the phenomenon of *colour contrast* and the *fatigue of the eyes*. Therefore, in defining a colour also its environment, the duration of observation, the state of the chromatic adaptation have to be fixed.

Besides, the colour sensation depends on the age, temperament, education, etc. of the viewer, therefore colour sensation grades can only be formed by statistically averaging the opinion of a great number of observers.

In the following we intend to enumerate the requirements of colour dynamics pointing beyond the general problems of colour systematization. Both the discussion and the conclusion will be facilitated by being definitely referred to the *Munsell* and the COLOROID colour systems.

1.1 Indices expressing the three characteristics of visual sensation: hue saturation and brightness

In different colour systems, ***colour indices*** are assigned to different numbers of colour samples. In the *Munsell* and COLOROID colour systems, similarly to other colour systems, these colour indices signify not only the place of the sample within the collection but also the relative values of the three characteristics of visual sensation: *hue, saturation* and *brightness.*

This is very important for colour dynamics. In everyday life we remember or describe a colour by these three qualities. Any difference or similarity in them induces us to speak of a colour different from or similar to another colour. Also aesthetical decisions, e.g. whether a colour composition is harmonious or disharmonious are made according to differences felt between colour characteristics.

1.2 Indices expressing the aesthetical continuity of the colour space

Colour sensations are not physical quantities to be characterized by physical units, but to be expressed by the change of the three colour sensation qualities in a given numerical range in both colour systems. Each colour sensation series consisting of colours evenly changing in relation to a certain quality is expressed by different colour index series in the two colour systems. Let us compare them.

The two colour sensation indices can only be compared by relating indices assigned to colour sensations produced by defined stimuli. Brightnesses and saturations in the two colour systems are related by:

$$V_c = 10\sqrt{1.2219V_m - 0.23111V_m^2 + 0.23951V_m^3 - 0.021009V_m^4 + 0.0008404V_m^5}$$

and

$$T = ab\sqrt[3]{C^2}$$

respectively, where V_c and V_m express COLOROID and *Munsell* brightnesses, T is saturation in the COLOROID system, C the *Munsell*-chroma; a and b in the second formula mean that the assignment of both COLOROID and *Munsell* indices to the saturation of a colour depends also on its brightness and hue.

The formulae show that to sensations elicited by identically changing stimuli, a set of indices changing according to a different law is assigned in each system. Thus, the two systems suggest different ways of measuring the colour sensation. Let us compare the two suggestions to see which one suits better the requirements of colour dynamics.

In the *Munsell* system a colour series evenly changing from the aspect of a certain parameter was developed with approximately equal, small colour differences between its members what means that between each index approximately the same number of shades can be distinguished. This characteristic of the *Munsell* system for describing colour differences has become increasingly important with the development of colour measurement.

It is undoubtedly important also for colour dynamics to fix how much the actual colour may be allowed to differ from the planned one. However, the particular colour dynamic problems arise beyond this field, referring to colour-compositional relationships to be fixed by colour indices.

The colours of our environment belong to various parts of the colour space. Therefore the planning of a coloured environment has to bring about harmony of hue, saturation and brightness between highly different colours. This is why far greater importance is due to the aesthetical evenness of the whole colour space than to the reliable equality of small colour differences. The endeavours of colour systematization resulting in the present form of the *Munsell* colour system produced psycho-physical scales fairly approximating the ability of the human eye to distinguish colours in various ranges but little suiting aesthetical applications.

In our experiments to be presented later, we found that in the *Munsell* system the brightness gradation of the colours was denser for dark colours than would be required by aesthetical evenness. In spite of the almost equal colour differences, the saturation steps were found to be aesthetically denser in dark areas of the colour solid than in bright ranges. Furthermore, the *Munsell* chroma steps were found in the highly saturated fields to be aesthetically far too scarce, whereas in the unsaturated fields far too dense.

To be concise, according to the second requirement of colour dynamics for colour systems, the index variation has to follow an aesthetically even variation of colours. This means that the requirements of colour dynamics are met by a colour space built on aesthetically equal colour differences, i.e. where large (rather than small) colour differences are equal. The colour space of COLOROID has been elaborated accordingly.

1.3 Visualizing the colour by indices

Two colours and their mixing rates are given, the colour resulting from their mixing has to be determined. In colour environment design this task is quite frequent, e.g. when a third, harmonious colour is looked for to match two given colours.

The indices in the *Munsell* system are of no help, they being in no direct relationship to the colour stimuli, physical quantities eliciting colour sensation.

The situation is quite different with the CIE XYZ system where for additive colour mixing the co-ordinates of the new colour can be determined. The tristimulus value Y changes linearly with the mixing rate of the tristimulus values Y of the colours to be mixed. On the other hand, the co-ordinates x and y shift towards the colour with the higher sum of tristimulus values. The point plotting the resulting colour is on the straight line between the two starting colour points. Its position on this line is in proportion of the two stimuli, if the sums of the tristimulus values of the colours are equal.

This is an exact determination of the co-ordinates of the mixed colour in the CIE system. But these co-ordinates still fail to indicate the saturation of our new colour. Its direct visualization is still a problem.

Coloured environment design will profit from the definition of colour-mixing by colour indices only if these suit numerical evaluation of the compositional e.g. harmonic relation between the new colour and the component colours. Another aim of colour indices is to simplify visualization of the theoretically mixed colour. The COLOROID colour indices can easily be converted to colour-mixing components for visualizing the colour.

1.4 Conversion of indices into the CIE XYZ system

The work of a colour designer is affected not only by exigencies but also by external features, such as the colours of building and decorating materials, often indicated only by their XYZ values by the manufacturer. The colour designer can make use of these data only if they can be converted into indices involved in his theoretical-practical composition. As his conceptions have often to be agreed with the choice of colours, a simple means of conversion is needed.

As the work of architects, interior designers and artists cannot be aided in the foreseeable future by large computers, they must rely for the conversion on small calculators, maybe on graphic construction.

These statements raise the fourth requirement of colour dynamics for colour systems: direct conversion of colour indices into CIE XYZ values and vice-versa, hence a mutually unambiguous relation between the two colour spaces of COLOROID and CIE XYZ is needed. COLOROID has been an attempt to fulfill this requirement.

2. Experiments for defining the COLOROID colour space

Colour points in a colour space representing colour perceptions form an aesthetically even relation only if the colour point indices suit to describe aesthetic relations of e.g. colour composition or colour harmony.

It was attempted to fulfill these requirements with the COLOROID system. Colour-bearing surfaces of our environment contain simultaneously a great variety of colours with different hues, saturations and brightnesses. These colours are selected by the designer so as to be aesthetically related, thus pleasant to the eyes. The colours are easier to match if their aesthetic content varies in parallel to the indices, namely if the colours in a scale seen at once are of an aesthetically even gradation. The difference between the adjacent members of such a scale is that smallest interval by which a colour has to be altered to form a harmonious composition together with the original colour. This interval is not simply a multiple of the just noticeable colour difference but depends on the brightness and saturation as well.

The hue, saturation and brightness scales of COLOROID have been established experimentally.

The experiments were performed in a room, near to the window looking north. Illumination on the test samples was 1600 to 1800 lx.

Test subjects were male and female university students 19 to 23 years old. Some experiments were repeated with pupils of elementary schools and with adults.

Test samples 15 to 18 cm^2 in area lay on a horizontal surface and were lit by the light incident through the window at an angle of about 45°. Observation angle was 90°, observation distance 100 cm.

The surrounding of the test field was neutral gray, and no coloured light was reflected to the samples. Before tests, the subjects spent at least five minutes in the experimenting room to have their eyes adapted to the neutral environment. The time for choosing from among the colour samples and arranging them into harmonious scales was not confined.

2.1 Experiments for determining the relationship between hue and dominant wavelength

For a simple correlation with the CIE XYZ system, hues were identified by dominant wavelengths. Therefore the statement found in the literature and involved in establishing the *Munsell* system that the dominant wavelength changes with saturation and brightness has been checked in two test series.

In the first series the observers had to estimate the hue of samples representing *Munsell* hues of 2.5 G, 2.5 Y, 2.5 R, 2.5 P and 2.5 B. As no original *Munsell* samples were at our disposal, some 1000 samples were prepared for each of the five hues above, their tristimulus values measured, and carefully selected for the Munsell scales.

The samples corresponding to the hue of 2.5 G had the widest scatter of dominant wavelength (526 to 540 nm), therefore the problem is best illustrated by this experiment.

The observers were presented the appropriate *green* colour series consisting of 15 samples. The 7th sample of the series had *Munsell* co-ordinates 2.5 *G* 4/4, its dominant wavelength was 533 nm. Two neighbouring samples were of the same chroma and value, but their hue changed into *yellowish* and *bluish* to the right and to the left, resp. The hue difference between two adjacent samples corresponded to a dominant wavelength difference of 2 nm.

The 1250 test subjects, 20 to 22 years of age and of about equal sex distribution had to match 70 samples with a hue of 2.5 *G*, but with different chroma and brightness values one by one to the hue of one chip of the sample series. Results of dominant wavelength vs. *Munsell* value, and dominant wavelength vs. *Munsell* chroma are seen in Figs 1 and 2, resp. A single point averages 8 to 10 votes in the figures. The continuous lines are those corresponding to constant *Munsell* hue. The following conclusions were drawn from the experiments:

1. Not a single person gave answers in perfect agreement with the *Munsell* arrangement for all colours.

2. Only 5% of the observers answered correctly for more than 50% of the samples.

3. 75% of the observers ranged 80% of the samples in the wavelength band ΔH (see Figs 1 and 2) in an order exhibiting very low correlation between the *Munsell* sample order and the answers.

In the second experiment two compositions were shown the observers for choosing the more harmonious one, or for indicating if both compositions were found equally harmonious.

Both compositions consisted of 10 colours. One composition "A" consisted of *Munsell* hues 2.5 *G* 8/4, 8/2, 6/8, 6/6, 4/6, 4/4, 4/2, 2/2 with dominant wavelengths ranging from 526 to 540 nm.

The colours of composition "B" had only dominant wavelengths of about 533 nm. Brightnesses and chromas equalled those in composition "A", and so did the arrangements and frequencies of occurrence.

The same experiment was repeated with *Munsell* hues 2.5 *Y*, 2.5 *R*, 2.5 *G* and 2.5 *B*.

The results of these experiments can be summarized as follows:

1. 68% of the observers found no aesthetic difference between the two compositions.

2. 17% of the observers preferred composition "B", 15% composition "A"

These experiments permitted to conclude on the aesthetic irrelevance of reckoning with *Munsell*'s suggestion of the hue sensation to vary for the same dominant wavelength but varying saturation and brightness in establishing the hue scale. Laics were even found to have difficulties with establishing this change in dominant wavelength.

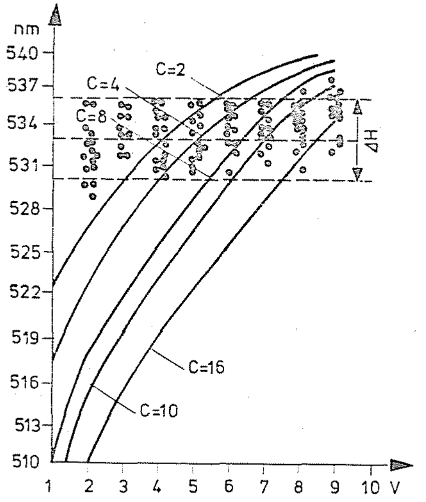

Fig. 1. Relationship between hue and dominant wavelength based on experiments on samples of *Munsell* hue 2.5 *G*, represented as dominant wavelength vs. *Munsell* value

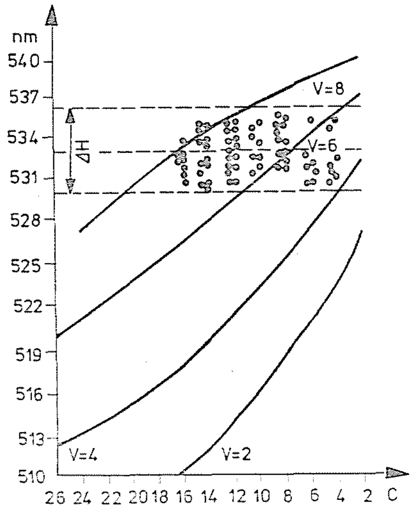

Fig. 2. Relationship between hue and dominant wavelength based on experiments on samples of *Munsell* hue 2.5 *G*, represented as dominant wavelength vs. *Munsell* chroma

2.2 Experiments on an aesthetically even hue scale

From our colour sample collection, 150 samples with *Munsell* chroma values of 6/12, but with varying hues have been selected.

The test subjects had to build up a colour circle with 50 samples chosen and arranged so as to show even steps in hue, if the entire colour circle was viewed simultaneously.

The hue differences between two adjacent samples of this circle were regarded as aesthetically equal hue intervals and denoted by ΔA. Test results were summarized by determining the number of hue intervals ΔA in every 10 nm dominant wavelength interval between 400 to 700 nm and (—490) to (—570) nm. The equation of the envelope curve would relate the dominant wavelength to the aesthetically even hue scale. After some trials, mathematical expression of the curve was found to be too complicated and unpractical. Therefore the relation between the COLOROID hue scale and the dominant wavelengths has been tabulated. Linear interpolation between the 48 points set out as basic colours was found to be adequate for all practical purposes (Fig. 3).

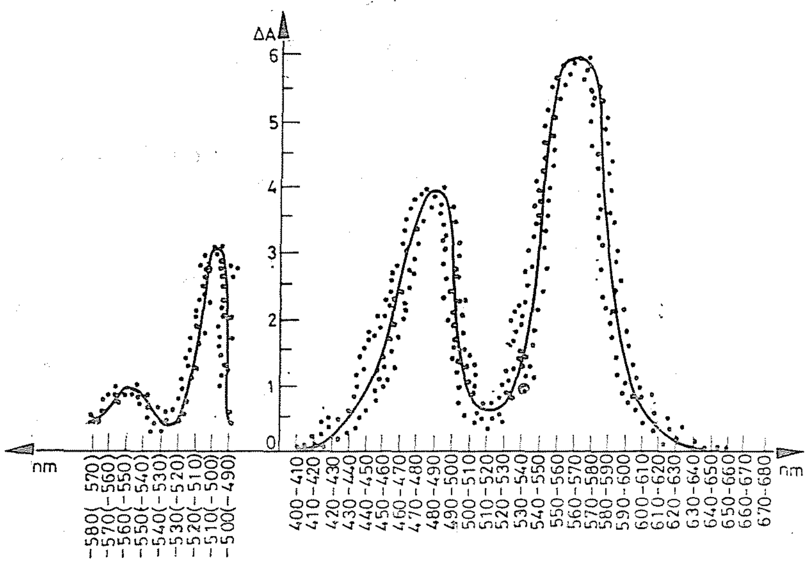

Fig. 3. Aesthetically even hue differences vs. dominant wavelength from experiment series on *Munsell* hue 2.5 *G* samples with $V/C = 6/12$ ratio

2.3 Experiments on the aesthetical evenness of the saturation scale

As a first step, experiments were carried out using *Munsell* colour samples. 6 to 10 further shades were painted between the following *Munsell* sample pairs:

For $H = 2.5Y$ and $V = 8$, between $C = 18, 16, 14, 12, 10, 8, 6, 4, 2$
for $H = 2.5Y$ and $V = 6$, between $C = 14, 12, 10, 8, 6, 4, 2$
for $H = 2.5B$ and $V = 8$, between $C = 12, 10, 8, 6, 4, 2$
for $H = 2.5B$ and $V = 6$, between $C = 16, 14, 12, 10, 8, 6, 4, 2$
for $H = 2.5G$ and $V = 8$, between $C = 22, 20, 18, 16, 14, 12, 10, 8, 6, 4, 2$
for $H = 2.5G$ and $V = 6$, between $C = 26, 24, 22, 20, 18, 16, 14, 12, 10, 8, 6, 4, 2$
for $H = 2.5R$ and $V = 8$, between $C = 10, 8, 6, 4, 2$
for $H = 2.5R$ and $V = 6$, between $C = 18, 16, 14, 12, 10, 8, 6, 4, 2$

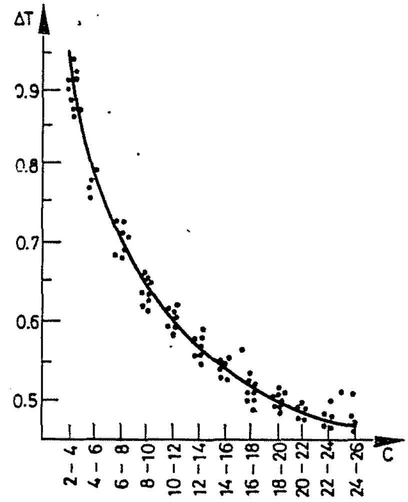

Fig. 4. Relationship between aesthetically even saturation differences ΔT vs. *Munsell* chroma C from *Munsell* sample experiment on the aesthetical evenness of the saturation scale

Thus 8 groups of 50 to 100 colour chips each were formed, with constant hue and value, but varying saturation (chroma) in each group. From each of these an arbitrary number of samples had to be selected, to build up scales of even saturation steps, when viewed simultaneously.

The aesthetically equal saturation difference found between the adjacent samples was denoted by ΔT. The number of steps ΔT found between each two *Munsell* chroma steps was noted by every observer. The evaluation of the experiments (see Fig. 4) resulted in the following equation:

$$\sqrt{(\Sigma \Delta T)^3} = \mathrm{C}\,(a\,b)\,.$$

After the *Munsell* chroma scale turned out to be aesthetically uneven, a new experiment was launched: New groups of colour chips were produced as additive mixtures of chromatic samples of saturated *blue*, *green*, saturated warm *yellow*, saturated *red* with dominant wavelengths of 484, 520, 579 and 610 nm, resp., and achromatic *white* and *black* surfaces. The samples were attached to *Maxwell* discs to exhibit various percentages of one chromatic and two achromatic surfaces. The perceived colour apparent on the rotating disc was reproduced by tempera paints. Several thousand samples were prepared and those with tristimulus values $Y = 60$ and $Y = 30$ selected.

The sample groups equal in hue and brightness but varying in saturation were presented to test subjects asked to select ten chips each and to order them into saturation scales seeming to vary uniformly if viewed simultaneously. It was found that in most cases the amount of colour needed for one saturation step to reach the next one was constant as an average (Fig. 5):

$$p_{i+1} - p_i = p\,.$$

Therefore the COLOROID saturation concept was formulated as follows: *Colours are regarded as equally saturated if they can be produced by additively mixing the same percentage of saturated colour of the same dominant wavelength with white and black.*

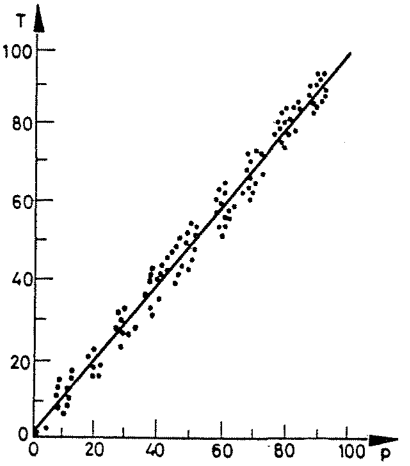

Fig. 5. Relationship between the COLOROID saturation scale aesthetically felt even and the COLOROID hue, from experiments on the aesthetical evenness of the saturation scale, made on COLOROID samples with equal hue differences

2.4 Experiments on the aesthetic evenness of the brightness scale

Groups of colour chips for brightness scale experiments were generated in the following way: Additive colour mixes were prepared from a saturated colour, white and black at two saturation levels and different brightnesses by using *Maxwell* discs and were reproduced again by tempera painting.

The following saturated colours were used:

red	$x = 0.5675$,	$y = 0.3221$,	$Y = 20.32$
yellow	$x = 0.4627$,	$y = 0.4685$,	$Y = 66.32$
green	$x = 0.2649$,	$y = 0.4622$,	$Y = 32.21$
blue	$x = 0.1768$,	$y = 0.2465$,	$Y = 17.81$.

The saturated colours were used in the experiments in two proportions: they covered either 15% or 50% of the *Maxwell* disc, resulting in 8 groups of about 250 colours each of equal hue and saturation, but different brightness. Tristimulus values were measured and Y values recorded.

The 2800 observers, half men, half women, had to choose 20 samples from each group and to order them for decreasing brightness so that the scale should seem evenly darkening if viewed at once.

The brightness difference between two adjacent samples of a brightness scale was called *aesthetic brightness interval* and denoted by ΔV. The experiments were evaluated by counting the steps ΔV in each interval of 5 Y in the entire range from $Y = 5$ to $Y = 80$. Fig. 6 shows the results described by the equation:

$$\left(\frac{\Sigma \Delta V}{10}\right)^2 = Y.$$

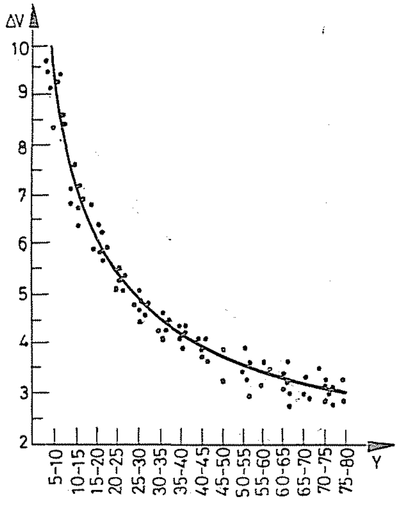

Fig. 6. Relationship between an aesthetically even brightness scale and the CIE Y value from experiments on colour samples of various CIE Y values

Thus, an aesthetically even brightness scale is described better by a square root formula than by a cubic root one, inducing us to adapt the former for COLOROID.

The *Munsell* gray scale of 20 elements has been compared with a 20-element brightness scale built on the principle of the square root formula. The observers found the square root scale aesthetically more even than the *Munsell* one.

All the colour samples were measured three times by means of the MOMCOLOR tristimulus instrument of the *Department of Drawing and Composition,* and the results were averaged. From time to time control measurement were performed on other instruments.

3. The COLOROID

The COLOROID system is built on, and mutually convertible with. the CIE XYZ system. The COLOROID indices have been directly deduced from the CIE tristimulus values, but so as to define perceptual COLOROID characteristics; the COLOROID saturation, COLOROID brightness and COLOROID hue concepts in good agreement with our colour perceptions. Colours have been arranged in COLOROID to raise the feeling of aesthetic evenness in the average man.

These statements mean that the empirical psychometric scales representing aesthetically uniform colour space needed to be adapted to CIE to cope with practical requirements. Hence, COLOROID is no ideal synthesis between aesthetically perfectly even perception and CIE but a relation at the level of practical colour dynamics.

The strive of COLOROID colour space to aesthetic evenness does not rely on the *Helmholtz* idea of "visually homogeneous colour space", so that his known tests for determining the line elements have not been involved in its development. Therefore the colour dynamically adequate COLOROID colour space is essentially different from transformations by CIE, UCS and, recently, by CIELAB and CIELUV, coping with colorimetry requirements, and also from the rhombohedral lattice system developed by OSA.

Because of the direct dependence on the CIE XYZ system, also COLOROID involves additive colour mixing. Colours are considered to be mixes of the saturated basic colour, white and black, and the co-ordinates of the point representing the colour in the COLOROID system can be calculated from these components and their proportions.

COLOROID is essentially different from the OSTWALD system describing colours by hue, white and black contents, in that its colour components determine perceptual features.

3.1 Description of the COLOROID system

COLOROID accommodates the three-dimensional set of colour perceptions — as do most colour perception systems — in a cylindrical co-ordinate system: *hue* varies along the *surface, saturation* along the *radius* and *brightness* along the *axis* of the *cylinder*. Thus, achromatic colours from absolute black to absolute white are located along this axis. Planes perpendicular to this axis contain colours of equal brightness. Further away from the axis, saturation increases. Colours of equal saturation are located on a cylindrical surface each. Colours of equal hue are found on half-planes containing the axis. The about elliptical outline of a skew section of the cylinder is the locus of the spectrum colours and the purples (limit colours). To 48 such limit colours, felt to be aesthetically even spaced, integer numbers were assigned as indices, these have been settled as COLOROID basic colours.

Every limit colour is connected to the absolute white and the absolute black by a boundary line, in the plane defined by the achromatic axis and the limit colour. Surfaces accommodating all the boundary lines form the COLOROID colour space (Fig. 7), a confined space that contains all perceptible colours arranged according to the COLOROID perception system.

The achromatic axis of the COLOROID colour space has been divided into 100 equal parts, and so are the cylinder radii from the achromatic axis to the cylindrical surface of the colours. Divisions represent aesthetically equal steps of saturation.

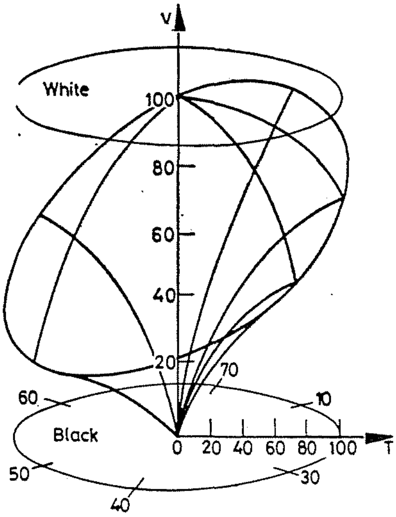

Fig. 7. COLOROID colour space is a subspace containing all visible colours arranged according to the COLOROID perceptual system

The COLOROID colour space contains the COLOROID colour solid, locus of the surface colours (see Fig. 8). The most saturated colours of the COLOROID colour solid form a noncircular cylindrical surface.

Relation between the COLOROID and CIE *XYZ* systems can be visualized by drawing the COLOROID achromatic axis so as to coincide in an (x, y) diagram with the co-ordinates of CIE illuminant *C*. Half planes edging at the

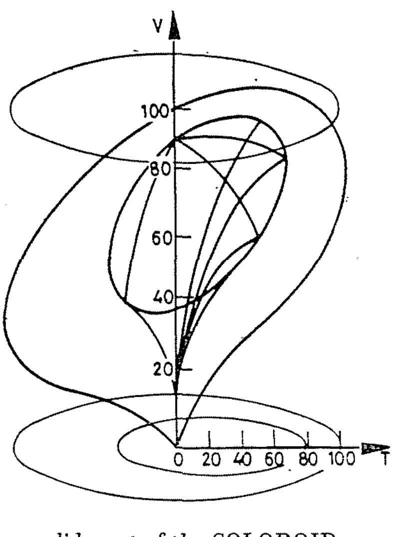

Fig. 8. The COLOROID colour solid, part of the COLOROID space containing surface colours

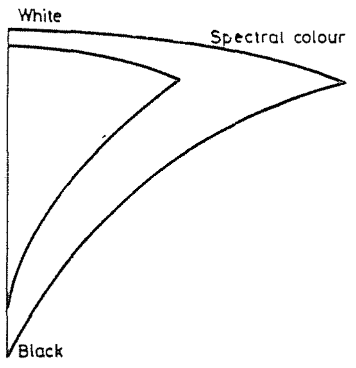

Fig. 9. COLOROID colour plane outlined by the achromatic axis and the boundary curves of the COLOROID colour space. Boundary curves of surface colours, cut out of the COLOROID colours solid, are similar to, and located inside, the former

achromatic axis contain colours with equal COLOROID hue and constant CIE dominant or complementary wavelength.

The sections of the COLOROID colour space cut out by the half-planes are the COLOROID hue planes, confined by the achromatic axis and two limit curves. The COLOROID hue and the dominant wavelength of each colour in a COLOROID hue plane are identical.

Curves of intersection between the COLOROID colour solid and the half-plane boundary curves of the surface colours are similar to, and lay inside, the boundary curves (Fig. 9).

Points of any COLOROID section along lines parallel to the achromatic axis represent colours of equal COLOROID saturation, and perpendicular to them, of equal COLOROID brightness (Fig. 10).

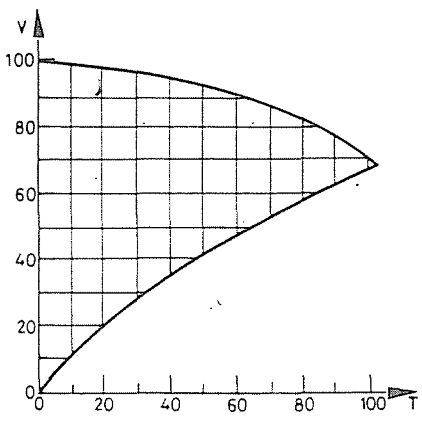

Fig. 10. Colours along straight lines parallel to the achromatic axis are of identical COLOROID saturation. Colours along straight lines perpendicular to them are of identical COLOROID brightness

While the configuration of a COLOROID space section depends only on the brightness of the spectrum colour or purple on its tip, that of a COLOROID solid section depends both on the COLOROID brightness and saturation of the most saturated surface colour in the plane (Fig. 11).

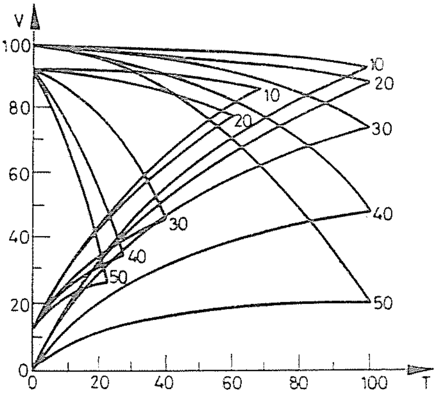

Fig. 11. Various sections of the COLOROID colour space and colour solid

3.2 Definitions in COLOROID

In COLOROID, every colour is regarded as an additive mixture of the specific limit colour, absolute white and absolute black. In the mixture the percentage of the limit colour is denoted by p, that of absolute white by w and of absolute black by s; these are the tristimulus values in the COLOROID system.

Tristimulus values of a colour always add up to unity:

$$p + w + s = 1. \tag{1}$$

Accordingly, the XYZ tristimulus values of a COLOROID colour point can be written as sum of the tristimulus values of the limit colour, the absolute white and the absolute black. Thus:

$$X = pX_\lambda + wX_w + sX_s \tag{2}$$

$$Y = pY_\lambda + wY_w + sY_s \tag{3}$$

$$Z = pZ_\lambda + wZ_w + sZ_s \tag{4}$$

where X, Y, Z are the CIE tristimulus values of the given colour, X_λ, Y_λ, Z_λ those of the limit colour, X_w, Y_w, Z_w and X_s, Y_s, Z_s those of absolute white and absolute black, resp.

Denoting one per cent of the sum of the tristimulus values for a colour point by ε, the hundredth part of the sum of Eqs (2), (3) and (4) can be written as:

$$\varepsilon = p\varepsilon_\lambda + w\varepsilon_w + s\varepsilon_s \tag{5}$$

a convenient form of expressing the COLOROID colour points as sum of the COLOROID tristimulus values: *hue content, whiteness content* and *blackness content*. In addition to representing COLOROID colour points as additive mixtures of the limit colour, absolute white and absolute black, they can also be described as additive mixtures of a colour of equal hue, but higher saturation, and two achromatic colours, one brighter, the other darker than the actual colour, if their CIE tristimulus values are known. Thus:

$$p_t + w_t + s_t = 1 \tag{6}$$

hence, in conformity with the COLOROID principle:

$$X = p_t X_{t\lambda} + w_t X_{tw} + s_t X_{ts} \tag{7}$$

$$Y = p_t Y_{t\lambda} + w_t Y_{tw} + s_t Y_{ts} \tag{8}$$

$$Z = p_t Z_{t\lambda} + w_t Z_{tw} + s_t Z_{ts} \tag{9}$$

and thus

$$\varepsilon = p_t \varepsilon_{t\lambda} + w_t \varepsilon_{tw} + s_t \varepsilon_{ts}. \tag{10}$$

The limit colours, the absolute white and the absolute black have been defined by their CIE tristimulus values.

COLOROID *limit colours* are the spectrum colours ranging from 450 nm to 625 nm in the (x, y) diagram, as well as colours along the straight line connecting them (Fig. 12). By definition these equal the CIE spectral tristimulus functions, provided $\bar{y}(555) = 100$ has been chosen, involving $\bar{y}(\lambda) = V(\lambda)$ (visibility curve). Thereby the brightness of the limit colours had been defined. Y values of the COLOROID limit colours range from 0 to 100 and equal hundred times the spectral tristimulus function $\bar{y}(\lambda)$.

The spectral tristimulus functions of the COLOROID limit colours $(\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda)$ and their sums

$$\varepsilon_\lambda = \bar{x}_\lambda + \bar{y}_\lambda + \bar{z}_\lambda = \frac{X_\lambda + Y_\lambda + Z_\lambda}{100} \tag{11}$$

have been tabulated with 1 nm steps, based on Tables 3.3 in [6]. In the range of purple colours the sums of CIE tristimulus functions of the COLOROID limit colours have been determined by additively mixing blue of $\lambda = 450$ nm and red of $\lambda = 625$ nm. The limit points were at the intersection of the line

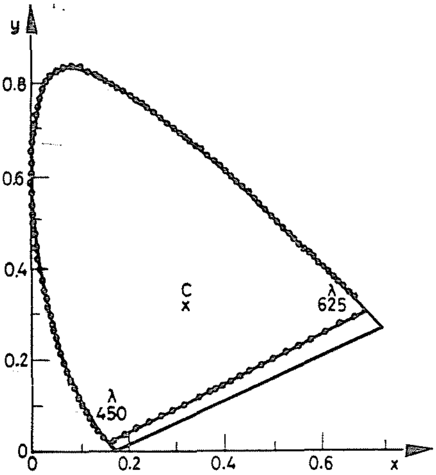

Fig. 12. Limit colours of COLOROID plotted in the CIE (xy) diagram

connecting wavelengths of 450 and 625 nm and the lines incident to the CIE chromaticity point C at different slopes $\operatorname{tg} \varphi$. The intersections were determined mathematically, using the equations of the lines.

Since the COLOROID saturation of a colour also depends on the sum of the tristimulus values of the involved limit colour, the too low CIE tristimulus values on the purple line induced us to assume the COLOROID limit colours inside, rather than along, the CIE purple line. Otherwise, mixtures with colours at or near the CIE purple line would be rather unsaturated, even short of medium saturation.

The light of CIE illuminant C reflected from a surface of a perfect diffuse reflector is regarded as *absolute white*. Its luminance factor $Y = 100$ is in accordance with the Y values of the COLOROID limit colours. One hundredth of the sum of the tristimulus values of absolute white referred to CIE standard illuminant C is

$$\varepsilon_w = \frac{X_w + Y_w + Z_w}{100} = 3.162955 \tag{12}$$

and

$$Y_w = 100\,. \tag{13}$$

The *absolute black* can be visualized by illuminating a perfectly absorbing cavity with $\varrho = 0$ by CIE standard illuminant C. The ε_s value is thus

$$\varepsilon_s = \frac{X_s + Y_s + Z_s}{100} = 0 \tag{14}$$

and

$$Y_s = 0. \tag{15}$$

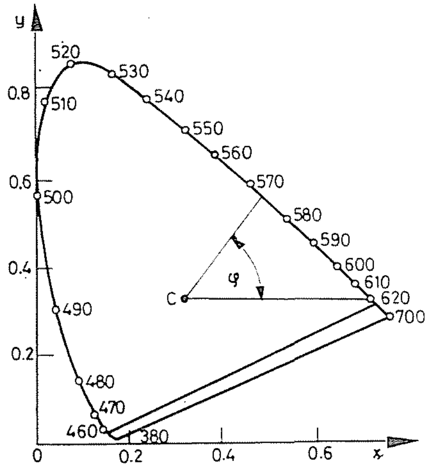

Fig. 13. Colours of identical COLOROID hue are along half lines starting from the colour point of CIE standard illuminant *C* in the (xy) diagram

Thus, the absolute COLOROID black is at the intersection of the COLOROID neutral axis by the plane $Y = 0$ of CIE 1931, hence, in case of a radial distribution *C*, its co-ordinates are:

$$x_s = x_0 = 0.31006 \qquad y_s = y_0 = 0.31616.$$

The position of a colour point in the COLOROID colour space is given by its COLOROID co-ordinates, denoted by the symbols:

A = COLOROID hue

T = COLOROID saturation

V = COLOROID brightness.

Colours are of equal COLOROID hue if they can be reproduced by additively mixing a COLOROID limit colour, absolute white and absolute black. The COLOROID hue depends on the hue of the limit colour defined by its dominant wavelength. Colours with equal COLOROID hue are on a half-line joining in the (x, y) diagram the chromaticity locus of CIE standard illuminant *C* with the chromaticity point of the given limit colour (Fig. 13). The hue can also be given as the direction tangent to this line. Be φ the angle between this line and the horizontal, then the slope of the line is $m = \operatorname{tg} \varphi$, thus:

$$A = A_\lambda; \qquad A = f(\varphi); \qquad A = f(\operatorname{tg} \varphi). \tag{16}$$

The COLOROID system involves 48 basic hues in correspondence with the 48 basic colours, with integer numbers as indices. These correspond to the wavelengths and direction tangents in Table 1, indicating also the tristimulus values, chromaticity co-ordinates and ε_λ values of the COLOROID basic colours.

Hues lying between the basic ones are denoted by fractions where the integer part of the hue index denotes the nearest lower basic hue and the fraction part entering in the hue $A = A_i + \vartheta$ results by additively mixing ϑ times the limit hue A_{i+1} with $(1 - \vartheta)$ times the limit hue A_i. Identical COLOROID saturation is attributed to colours resulting from equal percentages of a limit colour with any percentage of absolute white and absolute black, numerically expressed as product of the saturation of the limit colour by the percentage:

$$T = pT_\lambda. \tag{17}$$

By definition, the COLOROID saturation of the limit colour is 100, those of absolute white and absolute black are zero, thus:

$$T_\lambda = 100; \quad T_w = 0; \quad T_s = 0. \tag{18}$$

COLOROID saturation of a colour can also be expressed by the saturation of a more saturated surface colour of equal hue:

$$T = p_t T_{t\lambda}. \tag{19}$$

COLOROID brightnesses are equal for numerically equal tristimulus values Y, converted to COLOROID brightness:

$$V = 10\sqrt{Y}, \tag{20}$$

square root of 100 times the CIE tristimulus value Y.

The COLOROID brightness of absolute white is 100, that of absolute black is zero, i.e.:

$$V_w = 100; \quad V_s = 0. \tag{21}$$

The COLOROID brightness of a colour is ten times the square root of percentage sums of tristimulus values Y of its limit colour, of absolute white and absolute black. Written in terms of Eqs (3), (13) and (15):

$$V = 10\sqrt{pY_\lambda + 100w} \tag{22}$$

or, using tristimulus values Y of a surface colour of the same COLOROID hue but higher COLOROID saturation, of a real white and a real black:

$$V = 10\sqrt{p_t Y_{t\lambda} + w_t Y_{tw} + s_t Y_{ts}}. \tag{23}$$

3.3 COLOROID colour codes

Three numbers are used to identify a colour in the COLOROID system. First of these refers to the COLOROID hue A, the second to the COLOROID saturation T and the third to the COLOROID brightness V, always in this sequence.

The colour of COLOROID hue 13, COLOROID saturation 22 and COLOROID brightness 56 is thus coded as 13—22—56, and another colour coded

12—22—56 is more green;
14—22—56 is more orange;
13—21—56 is less saturated;
13—23—56 is more saturated;
13—22—55 is darker;
13—22—57 is brighter.

3.4 Conversion between COLOROID codes and CIE tristimulus values

CIE and COLOROID systems are in an unambiguous relationship so that COLOROID codes of the colour space and CIE co-ordinates are easy to convert into each other in either direction.

Conversion from CIE XYZ system to COLOROID starts from given x, y, Y to calculate the A, T, V values.

The COLOROID hue is read off the table of limit colours with $\Delta\lambda = 1$ nm steps applying Eq. (16):

$$\operatorname{tg}\varphi = \frac{y - y_0}{x - x_0}.$$

If necessary, linear interpolation may be used.

The COLOROID saturation is calculated from the following equations by using Eqs (2) and (3), taking also Eq. (14) into consideration. Eqs (24) resulted from the well-known formula of the XYZ system and the definition of ε in section 3.2:

$$X_\lambda = \frac{x_\lambda \varepsilon_\lambda}{100}; \qquad X_w = \frac{x_0 \varepsilon_w}{100};$$
$$Y_\lambda = \frac{y_\lambda \varepsilon_\lambda}{100}; \qquad Y_w = \frac{y_0 \varepsilon_w}{100}; \tag{24}$$

After substitutions:

$$X = \frac{px_\lambda \varepsilon_\lambda + wx_0 \varepsilon_w}{100}; \qquad Y = \frac{py_\lambda \varepsilon_\lambda + wy_0 \varepsilon_w}{100}. \tag{25}$$

Again substituting (24), (25) and (5) into the standard formulae of the XYZ system involving ε:

$$x = 100 \frac{X}{\varepsilon} \quad \text{and} \quad y = 100 \frac{Y}{\varepsilon}$$

expresses CIE chromaticity co-ordinates in terms of COLOROID colour components:

$$x = \frac{px_\lambda \varepsilon_\lambda + wx_0 \varepsilon_w}{p\varepsilon_\lambda + w\varepsilon_w} \quad \text{and} \quad y = \frac{py_\lambda \varepsilon_\lambda + w}{p\varepsilon_\lambda + w\varepsilon_w}. \tag{26}$$

Expressing w from Eq. (3) in respect of (13) and (15):

$$w = \frac{Y - pY_\lambda}{100} \tag{27}$$

which substituted into Eq. (26), expressing p, yields:

$$p = \frac{Y(x_0 \varepsilon_w - x\varepsilon_w)}{100(x\varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda(x_0 \varepsilon_w - x\varepsilon_w)} \tag{28}$$

and

$$p = \frac{Y(1 - y\varepsilon_w)}{100(y\varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda(1 - y\varepsilon_w)}. \tag{29}$$

Substituting (29) into (17) and taking (18) into consideration yields the COLOROID saturation:

$$T = 100 \frac{Y(x_0 \varepsilon_w - x\varepsilon_w)}{100(x\varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda(x_0 \varepsilon_w - x\varepsilon_w)} \tag{30}$$

or

$$T = 100 \frac{Y(1 - y\varepsilon_w)}{100(y\varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda(1 - y\varepsilon_w)}. \tag{31}$$

The values of $x_\lambda, y_\lambda, Y_\lambda$ and ε_λ are found in the COLOROID tables for limit colours with $\Delta\lambda = 1$ nm steps, namely: $x_\lambda = f(\text{tg}\ \varphi)$; $y_\lambda = f(\text{tg}\ \varphi)$; $Y_\lambda = f(\text{tg}\ \varphi)$; $\varepsilon_\lambda = f(\text{tg}\ \varphi)$.

The COLOROID *brightness* is calculated using Eq. (20).

Conversion from the COLOROID system into the CIE XYZ system is shown on the example of calculating x, y, Y from given A, T, V values.

Expressing x and y from Eqs (30) and (31):

$$x = \frac{100\, Y \varepsilon_w x_0 + 100\, T \varepsilon_\lambda x_\lambda - T Y_\lambda \varepsilon_w x_0}{100\, T \varepsilon_\lambda - T Y_\lambda \varepsilon_w + 100\, Y \varepsilon_w}$$

and

$$y = \frac{100\, Y}{100\, T \varepsilon_\lambda + 100\, T \varepsilon_w Y_\lambda + 100\, \varepsilon_w Y}\,.$$

Expressing Y from Eq. (20), and knowing that $Y_\lambda = 100\, \bar{y}_\lambda$, these values are substituted into the former equations to yield:

$$x = \frac{\varepsilon_w x_0 (V^2 - 100\, T \bar{y}_\lambda) + 100\, T \varepsilon_\lambda x_\lambda}{\varepsilon_w (V^2 - 100\, T \bar{y}_\lambda) + 100\, T \varepsilon_\lambda} \tag{32}$$

$$y = \frac{V^2}{\varepsilon_w (V^2 + 100\, T \bar{y}_\lambda) + 100\, T \varepsilon_\lambda}\,. \tag{33}$$

$\bar{x}_\lambda$, $\bar{x}_\lambda$ and ε_λ are again read off the $\Delta\lambda = 1$ nm tables of the COLOROID limit colours, namely $\bar{x}_\lambda = f(A)$; $\bar{y}_\lambda = f(A)$; and $\varepsilon_\lambda = f(A)$, hence

$$Y = \left(\frac{V}{10}\right)^2\,. \tag{34}$$

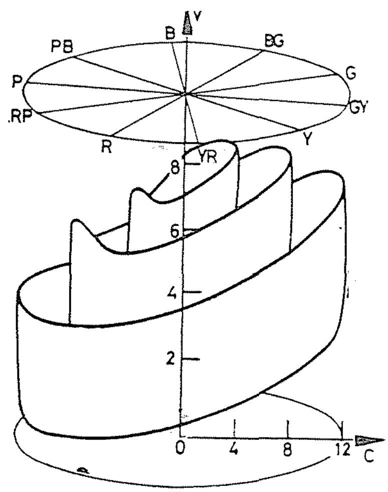

Fig. 14. Cylindrical surfaces containing colours of *Munsell* chroma 4, 8, 12 in the *Munsell* colour solid

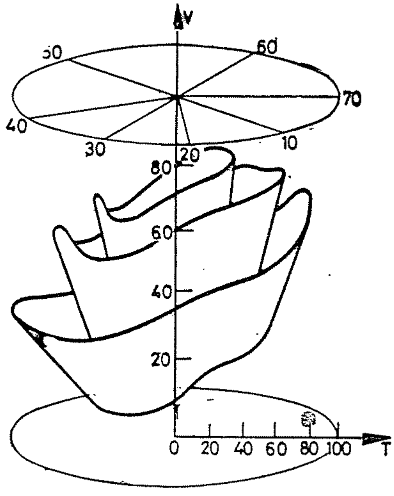

Fig. 15. Conic surfaces containing colours of *Munsell* chroma 4, 8, 12 in the COLOROID solid

3.5 Comparison of COLOROID with other colour systems

COLOROID co-ordinates of every sample of the *Munsell* colour collection — practically considered as reference in determining perceptually even colour differences and widely used, have been calculated and tabulated. Figs 14, 15, 16 and 17 truly reflect the saturation differences between the two systems.

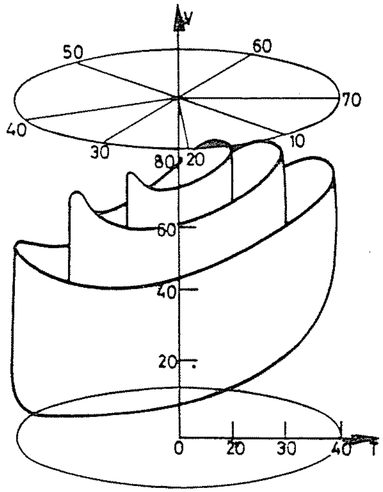

Fig. 16. Cylindrical surfaces containing colours of COLOROID saturation $T = 20, 30, 40$ in the COLOROID colour solid

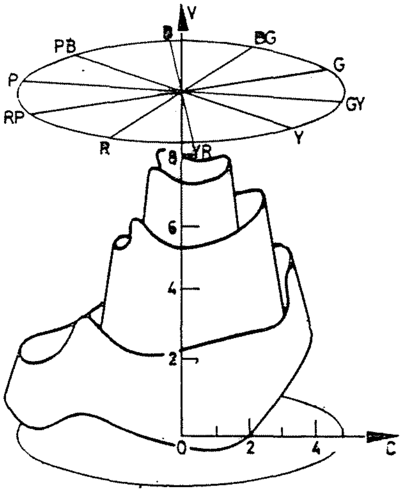

Fig. 17. Conic surfaces containing colours of COLOROID saturation $T = 20, 30, 40$ in the *Munsell* colour solid

Also COLOROID co-ordinates of the samples of the DIN colour collection have been tabulated.

The Tables showing the 3072 perceptually equidistant COLOROID colour points expressed in the CIE 1931 XYZ system, the CIELUV and CIELAB systems are rather instructive. Figs 18, 19, 20, 21 drawn from these Tables truly reflect the differences between these colour spaces.

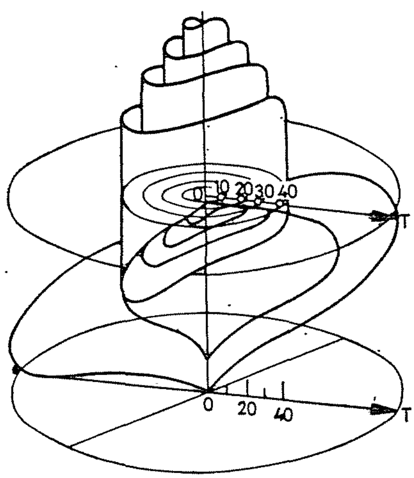

Fig. 18. Cylindrical surfaces containing colours of COLOROID saturation $T = 10, 20, 30, 40$ in the COLOROID colour space

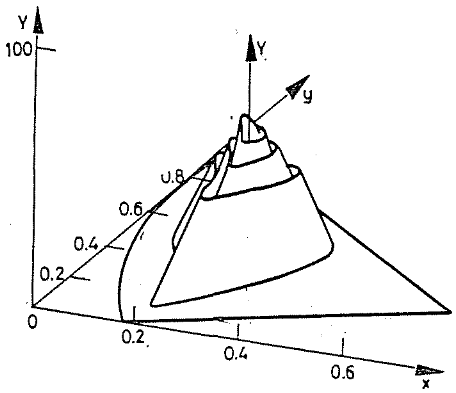

Fig. 19. Conic surfaces containing colours of COLOROID saturation $T = 20, 30, 40$ in the CIE 1931 colour space

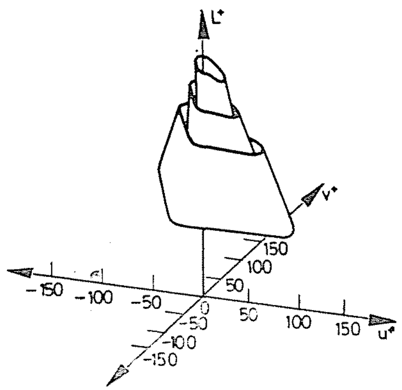

Fig. 20. Conic surfaces containing colours of COLOROID saturation $T = 20, 30, 40$ in the CIELUV colour space

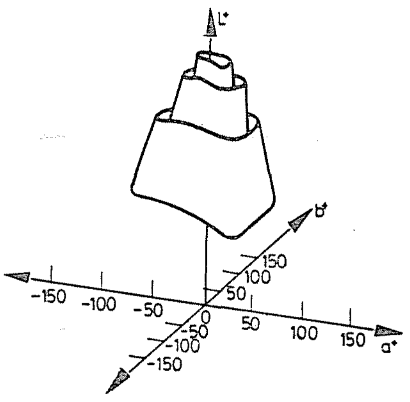

Fig. 21. Conic surfaces containing colours of COLOROID saturation $T = 20, 30, 40$ in the CIELAB colour space

Fig. 22 is a comparison between gray scales of the *Munsell* system, the *Color Harmony Manual,* the DIN system and the COLOROID.

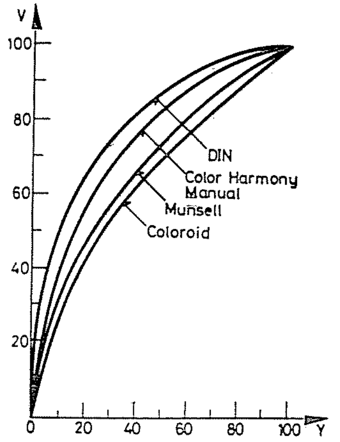

Fig. 22. Comparison of gray scales according to DIN (*Richter* 1953), *Color Harmony Manual (Foss* 1944), *Munsell (Newhall* 1943, *Ladd* and *Pinney* 1955) and COLOROID *(Nemcsics, Béres* 1974)

4. The architectural use of the COLOROID codes

The COLOROID codes may have manifold uses in architectural design and construction.

These codes unambiguously identify the colours, permit them to be visualized and estimated in their setting. The code system points to the compositional relations between colours, of great architectural importance, it suits to describe and even visualize them.

4.1 Colour trueness evaluation

The even changes in COLOROID codes correspond to even changes in the colours they represent. Therefore COLOROID codes suit evaluation of the trueness of the colour. Its adoption both by designers and by manufacturers of building materials and paints would simplify to state adherence to the design and the degree and direction of deviations.

Recently the system has been introduced both in design and in construction. At a difference from other industries, in the building industry colour deviations were found to be inadequately described by one colour difference value. Maximum difference in the hue must not exceed one COLOROID hue unit, saturation and brightness differences 5 COLOROID saturation or 5 COLOROID brightness units [22, 23, 32, 34, 36].

4.2 *Reference data in colour design*

Experiments on the man to colour relation are very important for the colour design.

Colour-dynamical experiments on the *man to colour relation* have been carried out at the Technical University, Budapest since the early sixties. Investigations concerning *colour preferences* of different age groups, associations, colour effects on *space and mass perception, physiological effects*, etc. have been related to COLOROID codes. Generalizing our results has led to develop a COLOROID *colour-dynamical design aid*, involving a system of colour harmony relations based on COLOROID codes [24 to 31].

4.3 *Visualization of the proposed colour*

An important feature of COLOROID is the possibility to convert its codes into colour-mixing components permitting the designer to reproduce any surface colour on a Maxwell disc using a disc of the desired hue or two chromatic sample discs deviating by less than $\varphi = 30°$ on either side from the colour-space location of the hue of the colour to be reproduced, a white and a black disc [33, 35]. The rotating disc has to be covered by $p_t\%$ of the chromatic, by $s_t\%$ of the black sample. Mixing percentages are from Eq. (19):

$$p_t = \frac{T}{T_{tp}}; \tag{35}$$

from Eq. (23):

$$w_t = \frac{p_t(Y_{ts} - Y_{tp}) + \left(\frac{V}{10}\right)^2 - Y_{ts}}{Y_{tw} - Y_{ts}} \tag{36}$$

and from Eq. (6):

$$s_t = 1 - (p_t + w_t). \tag{37}$$

4.4 *Formulation of colour composition relations*

Designers are often facing the problem to design a colour composition taking the colour features of a given building or cladding material into consideration. In the following, some examples will be presented on how to determine the colours fitting the features.

First example: Given are the colours of two coating materials. Both colours are of the same hue but of greatly different saturation and brightness. These features are to be involved to produce an interior with colours of the same hue with the specific monochromatic atmosphere.

Be the two colours coded as:

$$F_a(A, T_a, V_a); \; F_b(A, T_b, V_b).$$

The designer plans to use other n colours in the same space. These n surface colours should be of the same hue as the two pre-existing ones but of saturations and brightnesses intermediary between both so as to produce a harmonic scale.

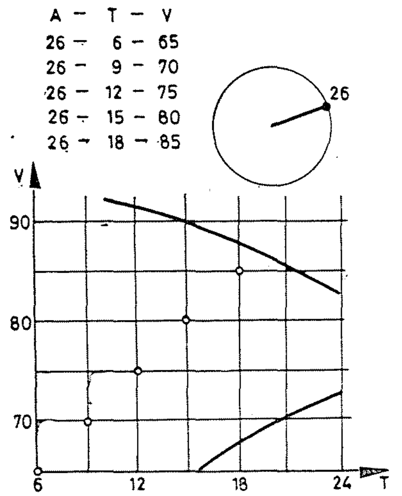

Fig. 23. Colours forming a harmonic series in the $A = 26$ COLOROID hue plane

From our great many experiments it can be concluded that in general, colours along a straight line in the COLOROID hue plane are felt as harmonic (Fig. 23). Saturation and brightness differences between the $n + 2$ members of this colour scale for $T_b > T_a$ and $V_b > V_a$ are:

$$q_T = \frac{T_b - T_a}{n}; \qquad q_V = \frac{V_b - V_a}{n},$$

to be coded as:

$$\begin{array}{ll} F_a & (A, T_a, V_a) \\ F_{a+1} & (A, T_a + q_T, V_a + q_V) \\ F_{a+2} & (A, T_a + 2q_T, V_a + 2q_V) \\ \ldots & \ldots \\ F_{a+n} & (A, T_a + nq_T, V_a + nq_V) \\ F_b & (A, T_b, V_b). \end{array}$$

To reproduce the colours in the scale, a colour of the same hue but of higher saturation, with CIE XYZ or COLOROID codes, a white and a black surface are needed. Be the codes of the chromatic surface:

$$p_t(x_{tp}, y_{tp}, Y_{tp}) \text{ or } (A_{tp}, T_{tp}, V_{tp}),$$

of the white surface:

$$W_t(Y_{tw}) \text{ or } (V_{tw}),$$

and of the black surface:

$$S_t(Y_{ts}) \text{ or } (V_{ts}).$$

The colour components of point F_{a+n} will be determined as follows. The proportion of the chromatic surface on the *Maxwell* disc is, according to Eq. (35):

$$p_t = \frac{T_a + nq_T}{T_{tp}};$$

the proportion of the white surface is given by Eq. (36):

$$w_t = \frac{p_t(Y_{ts} - Y_{tp}) + \left(\frac{V_a + nq_v}{10}\right)^2 - Y_{ts}}{Y_{tw} - Y_{ts}}$$

and of the black one by Eq. (37):

$$s_t = 1 - (p_t + w_t).$$

Second example: There are given two colours with complementary hues and a third colour of intermediary saturation and brightness, and either of the same hue as one of the two former or an achromatic colour is sought for.

First, the COLOROID co-ordinates of point Q on the line connecting the complementary colour points P and R have to be determined.

Hence $P(A_p, T_p, V_p)$
and $R(A_R, T_R, V_R)$ are given;
$Q(A_Q, T_Q, V_Q)$ is sought for.

Let us take an amount β from colour P and an amount $(1 - \beta)$ from colour R assuming $0 \leq \beta \leq 1$. The COLOROID co-ordinates of the mixed colour Q are

$$T_Q = \beta T_p - (1 - \beta)\, T_R,$$

$$V_Q = 10 \sqrt{\beta \left(\frac{V_P}{10}\right)^2 + (1 - \beta) \left(\frac{V_R}{10}\right)^2}.$$

For $T_Q > 0$; $A_Q = A_p$,
for $T_Q < 0$; $A_Q = A_R$,
for $T_Q = 0$, the colour is an achromatic one.

From these data the COLOROID components of colour Q can be computed using Eqs (35), (36) and (37), and the colour Q can be reproduced on the *Maxwell* disc. Diametral scales produced by mixing complementary colours are seen in Fig. 24 in COLOROID sections. COLOROID co-ordinates of the scale members can be approximated by graphical means as well. The heavy continuous line in the horizontal section represents the saturation of the most saturated pigment colours.

Third example: Two separate colours are given, differing by hue, by saturation and by brightness. The designer fancies to insert further colours intermediary between the former for all three colour parameters so as to produce a harmonic series. In the following, a single colour in this imaginary scale between the two pre-existing ones will be determined.

First, the COLOROID co-ordinates of the new colour have to be determined. Given are the COLOROID co-ordinates of colours V_1 and F_2:

$$F_1(A_1, T_1, V_1) \text{ where } A_1 = f(\varphi_1)$$

$$\text{and } F_2(A_2, T_2, V_2) \text{ where } A_2 = f(\varphi_2).$$

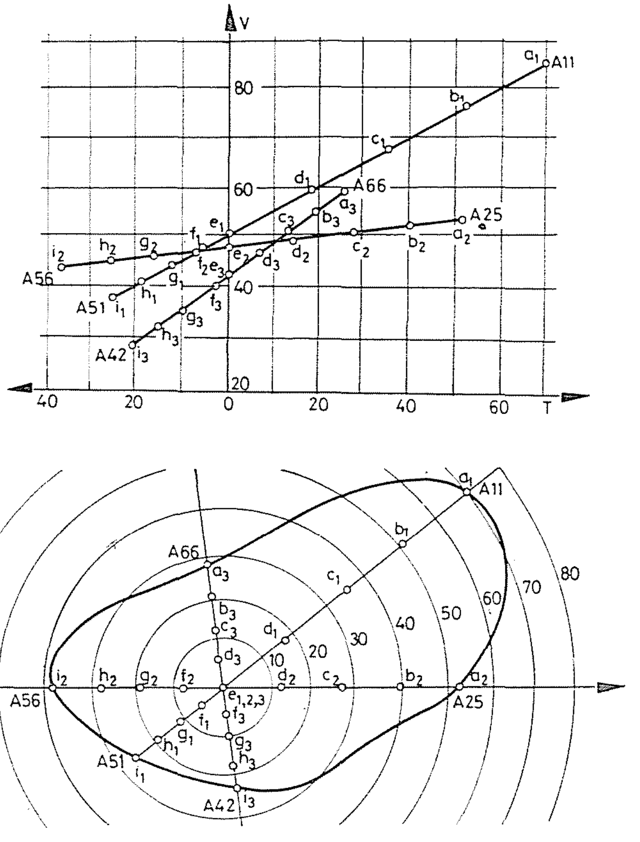

Fig. 24. Diametral scales produced by mixing complementary colours. The heavy continuous line shows the COLOROID saturation values of the most saturated pigment colours

COLOROID co-ordinates

$$F(A, T, V) \text{ where } A = f(\varphi)$$

of colour F are wanted.

An amount β of colour F_1 and an amount $1 - \beta$ of colour F_2 are mixed to get colour F, assuming $0 \leq \beta \leq 1$.

The needed equations are deduced by changing first from the COLOROID polar co-ordinate system to the Cartesian co-ordinate system (Fig. 25). Parameters of colours F_1 and F_2 will be u_1, v_1, n_1 and u_2, v_2, n_2, resp. As all the T values are contained in the plane u, v in conformity with Fig. 25:

$$u = \beta\, T_1 \cos\varphi_1 + (1 - \beta)\, T_2 \cos\varphi_2$$

$$v = \beta\, T_1 \sin\varphi_1 + (1 - \beta)\, T_2 \sin\varphi_2.$$

Returning to polar co-ordinates, it is written:

$$T = \sqrt{u^2 + v^2} \quad \text{and} \quad \operatorname{tg}\varphi = \frac{v}{u}.$$

Table I

The 48 basic colours and basic hues of COLOROID expressed in CIE units

Basic hues					Basic colours					
A	λ	φ	tg φ	ctg φ	$\bar{x}_\lambda$	$\bar{y}_\lambda$	$\bar{z}_\lambda$	x_λ	y_λ	s_λ
10	+570.83	59.0		+0.600 9	0.775 745	0.946 572	0.002 032	0.449 87	0.548 95	1.724 349
11	572.64	55.3		0.692 4	0.805 130	0.933 804	0.001 910	0.462 48	0.536 41	1.740 845
12	574.38	51.7		0.789 8	0.832 782	0.920 395	0.001 808	0.474 51	0.524 44	1.754 986
13	576.06	48.2	1.118 0	0.894 1	0.858 841	0.906 482	0.001 764	0.486 01	0.512 98	1.767 088
14	577.50	44.8	0.933 0	1.007 0	0.880 488	0.893 741	0.001 724	0.495 78	0.503 25	1.775 953
15	579.31	41.5	0.884 7		0.906 652	0.876 749	0.001 672	0.507 90	0.490 52	1.785 074
16	580.95	38.2	0.786 9		0.929 124	0.860 368	0.001 612	0.518 74	0.430 35	1.791 104
20	582.65	34.9	0.697 6		0.950 909	0.842 391	0.001 531	0.529 80	0.469 34	1.794 831
21	584.46	31.5	0.612 8		0.972 454	0.824 779	0.001 431	0.541 37	0.457 83	1.798 665
22	586.43	28.0	0.531 7		0.993 753	0.799 758	0.001 308	0.553 67	0.445 59	1.794 822
23	588.59	24.4	0.453 6		1.014 350	0.774 090	0.001 170	0.566 80	0.432 53	1.789 610
24	591.06	20.6	0.375 9		1.034 402	0.774 014	0.001 067	0.581 28	0.418 11	1.779 484
25	594.00	16.6	0.297 4		1.052 466	0.707 496	0.001 021	0.597 66	0.401 76	1.760 984
26	597.74	12.3	0.218 0		1.062 544	0.660 001	0.000 898	0.616 53	0.383 00	1.723 444
30	602.72	7.7	0.135 2		1.056 125	0.596 070	0.000 696	0.638 96	0.360 61	1.652 892
31	610.14	2.8	0.048 9		1.001 027	0.501 245	0.000 335	0.666 19	0.333 58	1.502 608
32	625.00	−2.5	−0.043 5		0.751 400	0.321 000	0.000 100	0.700 61	0.299 30	1.072 500
33	−492.79	−8.4	−0.147 7		0.726 603	0.304 093	0.105 941	0.639 25	0.267 53	1.136 638
34	−495.28	−19.8	−0.360 0		0.689 620	0.278 886	0.263 780	0.539 62	0.226 31	1.232 286
35	−498.45	−31.6	−0.615 2		0.659 523	0.258 373	0.392 224	0.503 40	0.197 21	1.310 122
40	−502.69	43.2	−0.939 1		0.633 815	0.240 851	0.501 944	0.460 41	0.174 95	1.376 610
41	−509.12	54.6		−0.710 7	0.609 810	0.224 490	0.604 392	0.423 86	0.156 03	1.438 692
42	−520.40	65.8		−0.449 4	0.585 492	0.207 915	0.708 175	0.389 91	0.138 46	1.501 583

43	−536.31	76.8		−0.234 5	0.558 865	0.189 767	0.821 815	0.355 86	0.120 83	1.570 447
44	−548.11	86.8		−0.055 9	0.529 811	0.169 965	0.945 807	0.321 95	0.103 28	1.645 584
45	−555.96	95.8		+0.101 6	0.496 364	0.147 168	1.088 551	0.286 57	0.084 96	1.732 085
46	−564.18	−108.4		+0.332 7	0.425 346	0.098 764	1.391 643	0.222 02	0.051 55	1.915 754
50	+450.00	−117.2		0.514 1	0.336 200	0.038 000	1.772 110	0.156 64	0.017 71	2.146 310
51	468.71	−124.7		0.692 4	0.210 174	0.086 198	1.353 567	0.127 36	0.052 27	1.649 940
52	475.44	−131.8		0.894 1	0.137 734	0.114 770	1.020 911	0.108 13	0.090 20	1.273 415
53	479.00	−138.5	+0.884 7		0.101 787	0.135 067	0.843 955	0.094 14	0.125 06	1.080 809
54	482.04	−145.1	0.697 6		0.079 004	0.150 709	0.727 863	0.082 49	0.157 41	0.957 577
55	484.29	−152.0	0.531 7		0.062 658	0.164 626	0.641 692	0.072 06	0.189 58	0.868 977
56	487.31	−163.4	0.298 1		0.044 691	0.185 949	0.541 091	0.057 87	0.241 09	0.771 732
60	490.40	−177.2	0.048 9		0.030 372	0.211 659	0.455 077	0.043 53	0.303 78	0.697 110
61	492.72	171.6	−0.147 7		0.021 655	0.234 022	0.400 126	0.032 91	0.356 96	0.655 804
62	495.28	125.4	−0.360 0		0.013 989	0.261 843	0.348 126	0.022 40	0.419 71	0.623 969
63	498.45	148.4	−0.615 2		0.007 215	0.301 137	0.287 685	0.011 96	0.499 54	0.596 037
64	502.69	136.8	−0.939 1	−1.065	0.002 586	0.366 425	0.238 402	0.004 25	0.603 21	0.607 414
65	509.12	125.4	−1.407 0	−0.710 7	0.007 260	0.485 346	0.167 317	0.010 99	0.735 42	0.659 924
66	520.40	114.2		−0.449 4	0.066 010	0.717 274	0.076 233	0.080 50	0.833 91	0.859 523
70	536.31	103.2		−0.234 5	0.242 272	0.926 325	0.027 086	0.202 59	0.774 74	1.195 684
71	548.11	93.2		−0.055 9	0.406 663	0.990 587	0.010 284	0.288 07	0.704 60	1.410 097
72	555.96	84.2		0.101 6	0.527 646	0.999 862	0.005 321	0.344 22	0.652 30	1.532 830
73	560.74	77.3		0.225 4	0.606 873	0.993 224	0.003 695	1.378 38	0.619 30	1.603 793
74	564.18	71.6		0.332 7	0.664 599	0.981 981	0.002 868	0.402 90	0.595 33	1.649 449
75	566.78	66.9		0.426 5	0.708 358	0.970 252	0.002 470	0.421 41	0.577 16	1.681 081
76	568.92	62.8		0.514 0	0.744 182	0.958 592	0.002 205	0.436 47	0.562 22	1.704 981

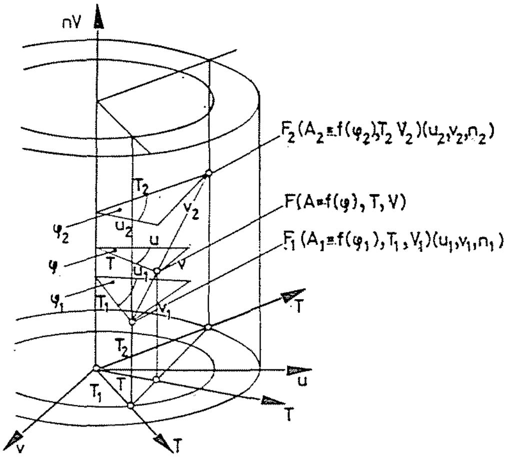

Fig. 25. COLOROID co-ordinates of a colour F produced by additively mixing two colours (F_1, F_2) in the COLOROID colour space

To determine the code of hue A, first the φ value is determined:

$$\varphi = \text{arc tg}\, \frac{\beta T_1 \sin \varphi_1 + (1 + \beta) T_2 \sin \varphi_2}{\beta T_1 \cos \varphi_1 + (1 - \beta) T_2 \cos \varphi_2}\,.$$

The A value for this φ is taken from Table 1, by linear interpolation.

The saturation T of the colour F is determined along similar lines:

$$T = \sqrt{[\beta T_1 \cos \varphi_1 + (1 - \beta) T_2 \cos \varphi_2]^2 + [\beta T_1 \sin \varphi_1 + (1 - \beta) T_2 \sin \varphi_2]^2}\,.$$

The COLOROID brightness V of colour F is given by

$$V = 10 \sqrt{\beta \left(\frac{V_1}{10}\right)^2 + (1 - \beta) \left(\frac{V_2}{10}\right)^2}\,.$$

Percentages p_t, w_t and s_t, determined as before, are set on the *Maxwell* disc that will be rotated to reproduce the colour.

Summary

Colour is both a technical and an artistic tool for designers of coloured environment. Unambiguous distinction by codes is required in the first case to assign technical parameters to colours and in the second case, to express numerically colour composition relations.

By now, to describe colour compositions by colour codes became imperative for colour dynamics, raising requirements for colour systems different from those of colorimetry.

Two decades of work were spent on the development of the COLOROID colour system at the Technical University, Budapest, taking the colour-dynamic requirements into account. Experiments on the aesthetically even COLOROID colour space are described in detail, the concepts defined, its relations to the CIE XYZ system established, and the architectural use of COLOROID codes outlined.

Development of the COLOROID colour system aimed at providing a means for architects, colour designers and artists to express colour composition relations, being in direct relation with the CIE *XYZ* system. Thereby new fields of activity are opened the COLOROID system. Those areas of science and technology, where aesthetical aspects of colour are important but up to now only the CIE *XYZ* system was used, might gain by the introduction of the COLOROID system.

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