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PHILOSOPHY AND APPLICATIONS OF COLOR ORDER SYSTEMS

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Summary: The principles and use of perceptive color order systems both in general and of the opponent-hue type in particular - as a tool in education, visual science, environmental design, standardization and industry.

Keywords: philosophy, applications, natural, color, system

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PHILOSOPHY AND APPLICATIONS OF COLOR ORDER SYSTEMS

INTRODUCTION

> "For a systematic grouping of colors the only thing that matters is color itself. Neither the qualitative (frequency) nor quantitative (amplitude) physical properties of the radiation are relevant."

This is the famous Hering[1] principle for the classification of colors, given at the very beginning of his chapter on "The Natural Color System".

In a booklet called "A Color Notation", first published in 1905, Albert Munsell[2] starts by quoting a letter from the English author Stevenson, who is going to decorate a new home in Samoa and asks his friend in London to send him some wall-papers. And Stevenson describes the color he wants:

> ".... some patterns of unglossy - well, I'll be hanged if I can describe this red - it's not Turkish and it's not Roman and it is not Indian, but it seems to partake of the two last, and yet it can't be either of them because it ought to be able to go with vermilion. Ah, what a tangled web we weave - anyway, with what brains you have left choose me and send some - many - patterns of this exact shade."

Obviously Munsell was well aware that the choice of colors, and of colored materials, depends on the intended application. If, as in Stevenson's case, the application is the decorating of a home with a certain personal atmosphere in harmony with special geographical, climatological and cultural surroundings, those colors must be described just as they are intended to be seen, not by their physical stimuli. And the customer is little helped by the physical or chemical properties of the material. Obviously Mr Munsell's color order system had to be a perceptive one. How did he succeed?

A color order system may be

a system arranging color perceptions in some logical order

o r it may systematize the color stimuli producing the color perceptions

o r it may give the rules for mixing pigments, printing inks or other colorants used to make the material color samples (filters or surfaces of "colored" objects) transmit or emit radiation as color stimuli which in turn produce color perceptions in our sense of vision.

Whichever type of a color order system we want to make, we must start by setting up a basic theory, expressed in well defined concepts and variables, and a logic scheme for the work.

This is Not the point — a tangent on a tangent? The point is that — "None of the clearest and most forceful writers of English finds himself unable to describe the color he wants."

The answer is that we need a color notation "to convey one person's color conception to another."

This is the message of that quotation.

MATERIAL SYSTEMS

Material color order systems range

- from the first simple groupings of the artists pigments made by Lionardo da Vinci and the Swedish miniaturist Elias Brenner
- over the assortments of paints, lipsticks and nail varnishes in the drug store
- to sophisticated rules for describing the co-operation of pigments in a color print or of the fluorescent dots on a television screen.

They are mostly characterized by a short and direct link between the system and its application.

In technical and industrial applications of color, also in the graphic and photographic arts, the photographer, the printer or the television technician surely needs a system describing the combinations and interactions of the primaries in his particular technical process. Such systems are often well suited for educational and operational applications within that field of technology, but they do not describe the appearance of the color seen by a non-biased observer. The same applies to systematic arrays of pigments in the dyer's bath or on the painter's palette.

As their applications are different, the physical color systems are different, and their primaries are also different. Such systems - as indispensable as they may be to each group of users - are therefore not suited for general purpose.

There are also several systems where a systematic mixture of pigments or printing inks is presented as a color system (Hicketier[3], Villalobos[4], Kornerup[5] and Küppers[6]). Sometimes, as in the Maerz and Paul[7] "Dictionary of color", the arrays of halftone printed colors are combined with a list of color names. Otherwise, it is difficult to understand what kind of applications can be found, when a technical method for producing a consistent series of color samples is taken out of its technical context.

STIMULUS SYSTEMS

The CIE colorimetric system is the only color stimulus system of any importance to-day. It was originally conceived for the illumination engineer to specify a luminous radiation in terms of the expected color response. But it was soon applied also to the measurement of transmitting and reflecting samples of object colors.

The stimulus is compared with three arbitrarily (or at least not perceptually) chosen reference stimuli, defined by their frequencies and intensities. The procedure is worked out according to our best knowledge about how the human sense of vision evaluates the radiation psychophysiologically. But CIE values do not very well describe the appearance of colors and, as uni-dimensional variations in CIE space normally correspond to variations in several perceptual attributes, CIE is hardly suitable as a perceptive color order system.

Dominant wavelength in the CIE chromaticity diagram - "hue angle" in some of its transformations - is often taken as a measure of the perceptive variable hue. Sometimes, there is a tolerable correlation, but often the perceptive hue shifts are far too great to be accepted by architects and designers, at least if they have become acquainted with the merits of a truly perceptive color order system. This is also true for the a*/b* axes of the CIELAB space, which do not really represent yellow, red, blue and green. Likewise. CIE purity is seldom informative as a visual attribute of color.

Often when CIE coordinates are used to describe perceptive relations (e.g. the appearance of signal lights), this is not because it is the most appropriate way to present results of visual experiments but a concession to the fact that CIE is the generally accepted way to handle data obtained in instrumental colorimetry. The important problem how to correlate the CIE values of a color sample with its changing appearance under changing illumination is still one of the hottest items in every CIE meeting. Differences in appearance are also regarded as insufficiently represented in spite of numerous attempts to transform XYZ values into some more uniform color space.

Those transformations, added to a series of 'standard" illuminants and a choice of two "standard" observers have caused considerable confusion, and so has the large variety of optical geometries in colorimeters and spectrophotometers. To put it roughly: one sometimes gets the impression that CIE recommendations instead of normalizing the technique of colorimetry, deliberately are made wide enough to accept any whims of color laboratories or instrument manufacturers. This has become a nuisance for colorimetrists who have lots of CIE specifications that are incomparable with each other, causing serious problems in all communication about color. The problem is also one for the application of color order systems. Let me give two examples:

Many textbooks on color give complete tables of CIE values for Munsell colors, but how can they be reproduced to-day? ~~If they~~ cannot~~, what is the use of the tables?~~

→ But they can – if instruments are kept in accurate calibration! – The Munsell 1943 tables are the std – not the papers, which merely represent the standard specification as close as possible.

We got a similar problem with the NCS, when our DMC25 collapsed and had to be replaced by a DMC26 giving significantly different results beyond the production tolerances of the NCS samples. The DMC25 values are those standardized, so all new measurements have to be recalculated until new standard tables can be issued.

Something wrong with standardizing and calibration of instruments. Measurements only represent std. conditions under which measurements are made.

The fact that almost any new colorimetric instrument measures differently is causing a growing disbelief in colorimetry as such and serious problems in many practical applications.

This is a very loose and inaccurate statement.

In spite of such shortcomings the CIE colorimetric systen has served for more than 50 years as a common language among colorimetrists and as a means of production control in numerous industrial applications.

!! A very biased view of colorimetry – and ~~[illegible]~~ basically inaccurate –

PERCEPTIVE SYSTEMS

With this I'm now turning to the perceptive color order systems, based on "color itself", not on frequencies and amplitudes of radiations, nor on physical or chemical materials generating or modulating radiation. Most perceptive systems are made to facilitate the choice of colors for design and art. The builder of the system is usually an ambitious man (unfortunately very few women as yet!) who sets out defining not only a set of perceptive variables and another set of harmony rules, but also the supposed relations between the perceived colors and their physical stimuli. Then starts the work to find color samples that may fit the pre-established rules.

This was the common procedure when the expectations in the natural sciences to solve all sorts of problems were very high, and when instrumental measurements were thought to be more true than subjective observations. Even artists like Albert Munsell relied on photometers and mechanical aids like Maxwell's discs in making his scales. Why did the artist not trust his visual sense?

At least two recent systems (the Uniform Color Scales and the NCS) were made by perceptive experiments. When these were finished the data were plotted and relevant psychophysical relations found. Hopefully this is also how future research will be done.

A fully perceptive color order system is capable of classifying each individual color and structuring the entire color space using the perceived attributes of color only, without reference to physical color samples or radiations.

--- OSA-UCS

With the Uniform Color Scales, the Optical Society of America aimed at a set of colors that were equidistant in as many directions of color space as possible. This cannot be done in traditional cylindrical coordinates. After extensive perceptive judgments on color differences, a rhombohedral lattice[8,9] with a lightness axis and two chromatic axes green/red and yellow/blue (but without qualitative requirements for the appearance of these hues, which would have been contradictory to the experiment) could be plotted in CIE and Munsell space.

Position of Yellow was adopted — all other samples fell where they may — to accord with the principle of equal color spacing between nearest neighbors.

The experimental data give valuable information on human color vision, in spite of the rather low correlation[10] between observed data and those predicted from the equations, indicating that a color difference may not be one-dimensional but has to be analyzed in terms of its perceptual components.

The set of OSA-UCS color samples illustrates many interesting relations in perceptive color space, but their notations give a poor idea of color appearance.

--- Ostwald

Wilhelm Ostwald[11] probably wanted to make a perceptive system but made the mistake - like so many others - to believe that mixtures of color stimuli in simple numerical relations means a perceptively good color order and that equispaced sets of colors in a geometrical model will make harmonious combinations of colors.

Ostwald wanted to anchor his hue-circle in Hering's Urgelb (elementary yellow), which he assumed to be an optimal color stimulus. The opposite primaries on the hue-circle were to be colorimetrically complementary. But his conditions were inconsistent and the system impossible to realize. Add to this a grey scale spaced photometrically according to the Weber-Fechner law with black at infinity, and it is quite clear that such a system will be very difficult to apply.

--- DIN

The DIN system[12] and its sisters in France and Hungary represent efforts to derive perceptual attributes of color (hue, saturation, darkness or lightness) for simple relations in CIE space, but this is inconsistent with strictly perceptive attributes. The concept of "darkness" (Dunkelstufe), conceptually similar to Ostwald and NCS "blackness" is scaled as a mathematical function of the luminance factor of the optimal color stimulus with the same chromaticity. The deviations from true perceptive concepts may be unimportant in certain applications e.g. for specifying tolerance limits along semi-perceptual variables, but they are disastrous in other connections.

Dorothy —

--- Munsell

Munsell set out to describe colors in terms of three visual qualities, each of which "may be varied without disturbing the other".

The first quality is the HUE, where a strict visual equality is required within each hue. As Munsell did not recognize any other natural reference points than white and black, he had to invent his hue scale. Five color samples of different hues but equal photometric luminance factor, were mounted in equal proportions on a spinning disk, and the choice of colors was adjusted until they blended to a neutral grey. One of the colours was arbitrarily chosen to be a green acting as a balance point dividing the hue scale in warm (yellow, red) and cold (blue, purple) colours.

The second Munsell quality is VALUE distinguishing "a light color from a dark one" in ten steps from black to white, chosen with a photometer using a square root function of luminance factor. The photometric function was later altered to a fifth degree polynomial. This choice of a photometric quantity to represent a perceptive entity may be questioned, especially since perceptive lightness was reported to correlate badly with photometric luminance factor. But as shown later the NCS here may give Munsell a perhaps unexpected support.

The third Munsell quality is CHROMA distinguishing "strong colors from weak ones" giving the degree of departure from the corresponding neutral (i e of the same Value) on the gray scale. Albert Munsell postulated that Chroma /5 should be as distant from mid-grey as this is from white and black and assumed that the product value x chroma further multiplied by the area of that color should give its balancing "weight" compared to another color in the scene. For the Munsell chroma scale there is no principal limit, it is theoretically always possible to accomodate colors of higher chroma produced by new pigments.

Albert Munsell based his system on perceptive principles with perceptive applications in mind. But he didn't know of perceptive scaling so he used the methods his physicist friends told him. Nor was he aware of any natural anchors in color space. Therefore - as in most other systems - a color's notation must be determined by visual comparison with color samples of known coordinates.

But the Munsell system for a long time was closest to a perceptive color order system. If Munsell during his travelling in Europe had met Hering's ideas directly and not only through Ostwald, would he then have found those natural anchors for his hue scale that he now had to replace by rather arbitrary assumptions?

--- NCS

"There are six elementary colors, each of which shows no resemblance to any of the others."

"All perceived colors can be described by their resemblance to the elementary colors only."

Those are the dogma to which any believer in the Natural Color System must swear. Its name was given by Hering 110 years ago. But he had a forerunner in Sigfrid Aron Forsius[13], a Swedish clergyman, astrologer and professor of science, who already in

1611 wrote a treatise "On the Sight" where he sketched a color space (Fig.1) very similar to the Natural Color System.

By observing the phenomenon of color, Hering found six elementary colors in terms of which any other color can be described. Two of the elementary colors are achromatic (white W and black S) and the other four chromatic (yellow Y, red R, blue B and green G). For each elementary color there is an elementary attribute (whiteness w, blackness s, yellowness y, redness r, blueness b, grenness g) giving the degree of resemblance of a given color to the elementary color on a 0...100 scale.

As the pairs yellow/blue and green/red mutually exclude each other in a color perception - there is no color that resembles both yellow and blue at the same time, and no one resembling red and green - it is natural (but not absolutely necessary) to place them in opposite positions on the hue-circle. Hence this type of color order system is called an opponent-hue system.

The hue of an arbitrary color is defined by the ratio of its resemblances to the two nearest chromatic elementary colors. Hue is therefore a complex attribute of color, made up of two elementary attributes (except if the hue happens to be one of a chromatic elementary color).

Black and white form a third opposite pair of colors, different in character from the pairs of opponent hues in that all greys show both blackness and whiteness simultaneously.

If hue is the ratio between the two chromatic attributes of a color, then chromaticness is the sum of the same attributes. Here also, when we see two or more colors together we may combine these attributes to judge differences in chromaticness. Used together with the complex attribute of hue, chromaticness is the degree of resemblance to the maximal (full) color of the same hue.

When Tryggve Johansson[14] introduced Hering's ideas in Sweden around 1930 he scaled the variables by successive bipartition and replaced blackness by a lightness variable of the same type as Munsell Value, supplemented by clearness (reminding of DIN Dunkelstufe). The system became very popular and Johansson devoted most of his spare time to instruct teachers, architects, textile and handicraft designers and others who liked the possibilities to communicate by descriptive color notations. He disliked Sven Hesselgren's[15] idea of making a color atlas, as the notations for the samples in the atlas could be valid for one illuminant only. One might thus forget the universality of a natural color system.

Johansson[16] also strongly objected against harmony theories based on geometrical configurations. "There are not beautiful or ugly colors." Instead he made a theory for describing the characters of "scale intervals" between colors depending upon their positions on the hue circle:

Identity	I :	no separating elementary hue
Indifference	L :	one "
Polarity	P :	two " hues

Similarly he analyzed intervals between colors of constant hue.

This type of analysis has successfully been applied also to the new NCS.

It is often said against opponent-hue systems that the hue-circle is not equi-spaced. However, even if the red-blue quadrant contains more distinguishable hue steps than the green-yellow, they cannot form any more fundamentally different color combinations. The general character of a color combination changes dramatically when one of its components is changed across an elementary hue. Besides, what is "equi-spaced" when different color systems claimed to be so show very differently spaced hue-circles[17]?

As the elementary colors are virtual colors, which we are always carrying with us as mental ideas in our mind. It is therefore possible to recreate the NCS even in a hypothetical situation when not only all color samples but also all other documentation should get lost (if a human being should survive such a global catastrophe!). There is no other color order system with that capacity.

When a revision of the Hesselgren atlas began in 1964, Anders Hård[18] soon discovered that the observers were able to give NCS notations to an arbitrary color sample viewed against a neutral surround without any physical references present in the field of view. This was in contrast to all previous scaling of color atlases, when one- or twodimensional sets of color samples were presented to an observer, who had to judge color steps and color differences under inducing and adapting interactions between two or more colors.

The choice of parameters was strongly influenced by the experiences from earlier applications. Clearness was found more relevant than lightness and also easier to judge. But its complement the elementary attribute blackness was still better understood by the observers, gave more consistent results and was more useful in practical applications. It was therefore taken as a part of the NCS notation.

Within experimental errors, colors with equal hue and equal CIE luminance factor were found to fall on straight lines, and such lines for different luminance factors to converge way outside the color triangle in a position varying from hue to hue. Each color triangle in the NCS atlas contains a set of nomographic scales from which luminance factors may be read.

Due to the limitations in real pigments, the maximal colors are impossible to produce as a surface color. With good care we can get quite close to white and black, but even the "clearest" shade of any chromatic color sample shows some blackness, and even the strongest shade that can be produced shows traces of both whiteness and blackness. (Please note that we are now talking about color appearance, not about pigments.)

In a recent study by Hård and Sivik[19] it is shown that if the concept of Minimally Distinct Border - as introduced by Boynton and Kaiser - is used as an operational definition of equality of lightness, then perceived lightness and luminance factor (equal to Munsell Value!) coincide remarkably well.

Dorothy

COMPARING MUNSELL AND NCS

While Munsell ~~took~~ the ~~traditional~~ perceptive attributes hue, value (for lightness), and chroma (for what in American English is called saturation) for ~~granted~~, Hering looked ~~deeper~~ in the phenomenon of color and ~~discovered the~~ six ~~elementary~~ colors ~~and the corresponding primary attributes~~.

A ~~logical but somewhat astonishing consequence~~ of the Hering postulate and the NCS dogma is that neither hue nor chromaticness are primary variables of color but combinations of two elementary attributes. We can easily observe those two chromatic attributes in the appearance of each color. When the ratio between them varies we perceive this as a variation in the combined attribute of hue, when their sum changes it is perceived as a change in chromaticness.

HV/C are "attributes" of color not color primaries (of which there can be many sets)! e.g. psychological primaries, physical ", colorant ", etc.

~~Even if~~ color space ~~still~~ ~~is~~ three-dimensional, ~~we now see that there are~~ more than three different variables. We have already discussed six ~~elementary attributes~~ ~~and two complex ones~~. NCS chromaticness is often taken as corresponding to Munsell chroma, and Judd and Nickerson have shown ~~the correlation~~ on a preliminary set of NCS data. However, chroma is the degree of difference from ~~the~~ neutral, while chromaticness is the degree of resemblance to the full color. In NCS saturation is defined as the ratio of ~~the elementary attributes of~~ whiteness and chromaticness. ~~This is also in accordance with the CIE vocabulary~~.

Paper should be referenced.

NCS APPLICATIONS

The Natural Color System was approved as Swedish Standard[20] in 1973, and was immediately used in Sweden, Norway and Denmark, even if it was not published until 1979. The atlas was not necessary but it strongly facilitated the applications of the system. There are four standard documents: the NCS System, the NCS Atlas and two tables of nominal CIE values for the system and measured values for the atlas. With this month the NCS is also Norwegian Standard, and Danish standardization is probably very close.

NCS notations are now successively introduced in other Swedish standards. The "colours for coding purposes" (Swedish Standard SS 03 14 11) were carefully chosen to be easy to recognize also under adverse illuminations. The same standard was adopted in Norway even before NCS itself. There are also standards for the colors of paper and print, for quality coding in the steel industry etc. International standards are published in Sweden with the nearest NCS samples, which is cheaper than a rather poor three-color printing. With an ISO standard for safety colors we are having problems, as we find the internationally adopted ISO colors very bad for the purpose.

The Natural Color System is now recommended for use in all Swedish schools. In many big Swedish companies it is the system for communication about colour. CIE is only used for instrumental production control against standards specified by their NCS notations. One multinational company producing household appliances for the world market claims to have improved their result by

CIE is necessary for color mixture problems – for TV, e.g.

several million crowns yearly by using the NCS for color specification.

In a letter from the Department of Justice the colors of the Swedish flag are prescribed as 4055-R95B and 0580-Y10R.

Company trade marks are NCS notated to secure the image of the company in letter heads, on advertising signs, delivery cabs etc. Producer of metal sheets for facades, of carpets, of wall-papers and paint[21] give NCS notations for the benefit of architects and other prescribers of colour schemes.

Thanks to the correspondence between notation and appearance the NCS is extremely easy to learn, to use and to explain to both technical and non-technical people. "It's easier for me to memorize an NCS notation than my own telephone number" said one designer to me a few weeks ago. A simple diagram (Fig. 2) composed of the color circle and the color triangle, further facilitates the communication about color. It is also extensively used in reporting results of psychological research on color.

(true even for Munsell notation!)

Another reason for the popularity of the NCS is the rich supply of additional material[22] tailored to every-day work: loose samples in sizes from 37x52 mm (A9) to 420x594 mm (A2), tear-off booklets and spread-out fans of the smaller sized samples etc. In sale's value this material exceeds the atlas by almost a factor of ten.

In the major cities in Sweden there are to-day paint stores, one-re the shopkeeper feeds your NCS prescription into a desk computer that calculates the recipe for the correct mixture. Some of you present here had the opportunity to see such a system in function at the Forsius symposium last year.

The NCS is used for systematic coloring not only of individual buildings but also of whole residential areas. In a renewal project of eight high-rise buildings situated on a hill the houses were due to be very dominant. Something had to be done. Could it be done with color? Two architects made a coordinated color scheme for the whole area with light blue colors, blending with the sky and shining in low afternoon sunlight. To break the monotony, each house was assigned its own hue within the blue part of the hue circle. For the individual plates a certain tolerance had to be allowed, also to facilitate future replacement, and each house was given its limits for hue, chromaticness and blackness. In the same way colors for the brown basement walls were specified, all in NCS coordinates. Some tiles also were artistically decorated and the facades are now signed as pieces of art.

Another example - believe it or not -: Mrs Grete Smedal of Bergen has used the NCS to make a color scheme for a coal mining village on Svalbard in the Arctic Sea, a scene of black and white that certainly needs some chromatic colors!

It has of course to be admitted that the NCS is not the only possible color order system for all applications mentioned here. But also in cases where any complete, good quality system would do users give preference to the NCS because of its simplicity in design and notation.

In other applications a truly perceptive color order system has quite unique capacities, especially for those who have learned the not too difficult art to judge an NCS notation directly from visual inspection. Experiments[23] have shown that such judgements can be made by a group of twenty observers with a confidence interval of 05 NCS units on a 95% level. This contradicts the often heard statement that a color order system has to be manifested by a color atlas. The atlas is even confused with the system. NCS is the proof that a strictly perceptive color order system is capable of giving an unambigous description of any color without reference to physical color samples.

In studies on color rendering and color adaptation, NCS therefore enables[24] the description of how a perceived color changes with changing illumination of the scene and changing adaptation of the eye. It is also possible to use visual inspection and NCS notations to study induction effects in architectural environment etc. Many more applications of this sort are surely to be found.

Ewald Hering founded his Natural Color System on a physiological theory of catabolism and metabolism, two opponent modes of reaction in the retina. Hurvich and Jameson have shown that the current description in most textbooks as a photosensitive decomposition or reconstitution of the "Sehsubstanz" depending on wavelength, is an erroneous interpretation of Hering's ideas. Even if they are now partly obsolete, they were not so impossible as his contemporaries thought, and Hering's postulate of opposite modes of response in the neural tissue was very much in advance of his time. Now, modern vision research has provided strong evidence for the existence of a signal processing in the retina and brain in accordance with the principle of opponent hues. Prof. Gunnar Svaetichin[25], speaking before the Swedish Colour Group shortly before his untimely death in 1982, acknowledged the importance of the Natural Color System for his research work.

THE FUTURE

The history of color science tells us of some remarkable controversies between different ideas and hypotheses: Goethe vs Newton, Hering vs Helmholtz.... Although Ewald Hering conceived the NCS some 30 years before Albert Munsell published "A Color Notation", the last mentioned controversy delayed the breakthrough of Hering's ideas on a larger scale by almost a hundred years. To-day we have, at the side of the Munsell system with its long and well established tradition, the NCS based on more consequently perceptual definitions applied to modern psychometric methods of scaling and supported by the remarkable physiological findings of Svaetichin et al.

Neither the Munsell System nor the NCS as we know them to-day will be the last word said on color order systems. Both of them were developed on perceptive principles and with perceptive applications in mind. Both of them have proved to be extremely useful for people working with color. Both of them still have their shortcomings. Both of them are still restricted to non-luminous objects, while the luminous colors are becoming more and more important. At the Forsius symposium 1983 it was claimed that equality in blackness and equality in lightness give color combinations of fundamentally different character, and that therefore both types of atlas sampling were needed.

Both Munsell and NCS are surely capable of further developments, where both may profit from each other. Are those developments going to be just another struggle between two systems, or a common search for new knowledge in color science?

This was what Judd and I thought before the Swedish charts were finally published. But they went ahead without paying attention to our work —

If (the NCS) could have adjusted its white + black points — and a few other points — we could have ended up with 2 systems that could be very directly — and simply — interrelated — each system representing a different way of mapping the same color space — the OSA-UCS, a 3rd way of mapping that same space!

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Note to the editor:

Please check the American edition of No 5. F.Birren says it has 1266 colors, but my Danish book has 1410 color patches.