Colour order systems

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INTRODUCTION

It is a monumental task to deal with the ten million or more colours that our eyes can distinguish and for most of us it is difficult to describe a colour, particularly with regard to its variation from other colours. Many people have therefore tried to solve the problem of colour description, including Nobel laureate W. Ostwald and the American artist A. H. Munsell, who studied the problem in great detail.

In the colorant production and application industries colours need to be communicated, compared, recorded and formulated on a regular basis. This necessitates systematic classification of colours, facilitating not only communication about colour over distance and time, but also the analysis and definition of the aesthetic relations among colours [1].

Objects can be classified in various ways in terms of colour, and a number of colour order systems have now been developed – originally on the basis of different visual attributes but more recently on the basis of instrumentally-assessed colour parameters. The Association Internationale de la Couleur (AIC) study group on colour order systems' computer-based annotated bibliography contains about 400 entries, out of which 115 references are to the Munsell system [2].

Recording colour

Colours can be recorded in various ways:

- *By preserving coloured physical samples.* Colour is a visual experience and the eye is the final arbiter for all colour decisions. Hence, physical samples such as coloured fabrics, yarns or fibre etc. are commonly used in the trade. The colour of physical samples does, however, change with time, especially if they are not protected from light, heat and moisture. The appearance of sets of coloured samples prepared many years ago may have changed greatly.
- *By recording in terms of common colour names.* Objects are frequently identified by commonly used colour names such as bottle-green, sea-green, china-blue etc., but such colour names are approximate, unreliable and largely subjective since their meaning tends to change with time, place, style, language, culture etc.
- *By instrumental colour measurement.* Colour measurement is the safest way to preserve the records of colours for future generation. Colorimeters and spectrophotometers are used to measure colour numerically, generally providing reflectance or absorbance data at various wavelengths throughout the visible range of light. The data are converted into various colour parameters by mathematical transformation. These instrumentally-measured parameters are not, however, equivalent to visually-assessed parameters.
- *By comparison with systematic collection of visual standards.* Dealing with physical samples for trade has various disadvantages, including slower communication between buyers and manufacturers, limited availability, soiling, fading and loss [3]. It is these problems that have led to the development of material-based colour order systems or colour-specifiers, which are further supported and sometimes modified with the instrumentally-measured data to assure accuracy and reproducibility. Faster global communication is possible since code names or identifiers can be used rather than exchanging physical samples.

COLOUR ORDER SYSTEMS: A DEFINITION

A colour order system is any systematic and rational method of arranging all possible colours or subsets by means of material samples selected so that they represent all object colours. Once the colours are arranged systematically they are named in some descriptive terms and/or numbered [3].

It is also desirable that the samples included in any colour order system are properly specified in terms of any standard colorimetric specification, the most common being the Commission Internationale de l'Eclairage (CIE) system. A few of the latest colour order systems, such as the RAL system, are based on instrumentally measured CIELAB values.

INSTRUMENTAL COLOUR SPECIFICATION

The CIE system defines colours as vectors in three dimensional space based on three primary colours. An object colour can be uniquely defined [4] by three numbers called tristimulus values (X, Y, Z). The disadvantage of the CIE tristimulus system is that it does not provide a visually uniform colour scale. Several mathematical transformations have been recommended to deal with this problem, the most successful being the CIELAB system recommended by the CIE in 1976. Non-linear transformation of CIE tristimulus values results in three attributes, L^*, a^* and b^*, representing lightness, redness–greenness and yellowness–blueness respectively.

VISUAL ATTRIBUTES OF COLOUR

Human eyes can distinguish only three dimensions of colour. Every colour sensation unites these three distinct qualities and one quality can be varied without disturbing the others.

The measures of the three attributes vary significantly from one system to another, but they are always related to the following visual and/or psycho-physical attributes defined by the CIE [5].

- *Lightness* – representing the fraction of incident light reflected by the sample.
- *Hue* – the similarity of a sample to one or a mixture of two of the perceived colours red, yellow, green and blue. Hue is the family name for a group of chromatic colours. Ostwald defined it as dominant wavelength [6], while psychologists stress that it should relate to a visual appraisal of colours. The Munsell colour order system divides hues into five principal hues on the basis of equal visual spacing.
- *Chromatic amount* – the degree by which a sample differs from achromatic colour of same lightness. The traditional term for chromatic dimension is saturation, but it has several attributes. Unless otherwise specified it denotes colourfulness (i.e. chromatic amount in proportion to brightness) [7] or chromaticness (which increases with luminance/illuminance).

Chroma resembles colourfulness at a given illuminance level, but the term can be confusing. Wright [8] has explained that in the US it is the attribute determining the degree of its difference from the achromatic colour most resembling it (i.e. equivalent to Munsell chroma or DIN saturation), while in the UK it is judged by the proportion of pure chromatic colours in the total sensation (i.e. similar to NCS chromaticness). These concepts will be discussed in more detail later.

Hunt has proposed three terms [5]:

- *Colourfulness,* i.e. total chromaticness
- *Saturation,* i.e. chromaticness in proportion to brightness
- *Perceived chroma,* i.e. colourfulness (of non-luminous related colours) in relation to average brightness of surroundings.

However, colourfulness depends on the level of illumination and is not usually considered for any colour order system.

Wright [9] has identified two sets of visual attributes. Group A attributes are lightness, hue and chroma, while group B attributes are whiteness, blackness and chromaticness. According to Wright, group B attributes are more useful because they are most easily understood and are more fundamental representations of colour appearance to an observer. However they are less studied in psychometric (equal perception) terms. The colours of outermost Munsell hue circles (group A) are close to full colours, which is a term for group B attributes.

THE MERITS AND DEMERITS OF COLOUR ORDER SYSTEMS

These have been reviewed in detail elsewhere [10].

Briefly, the advantages of material-based colour order systems are:

- The presence of physical samples enables the system to be understood easily: the eye is a better comparator than the memory [11].
- They are easy to use. In most cases, side-by-side comparisons are made under standard viewing conditions and, as such, no instrument is required.
- They are mostly calibrated in terms of tristimulus values, so they can be used for colour control work or colorant formulations by computer, even in the absence of samples.
- Visually uniform colour spaces can prove a useful way of organising the colours of a digitally controlled colour television monitor. Future uniform colour spaces will probably be defined with the aid of such monitors, which have higher flexibility and wider colour gamut than the complex pigment technology presently in use [12].

Some of their limitations are:

- A number of colour order systems are in use and they are not easily convertible.
- It is not possible to include all perceivable colours in any colour order system, so any system is a serious abridgement of the colour world. In other words, there are gaps between the available physical samples. Interpolation or extrapolation is, therefore, frequently necessary for colour specifications, the accuracy of which largely depends on the colour discrimination efficiency and experience of the observer.
- As any colour order system is composed of a limited number of physical samples, future inclusion of newer samples may be a problem. Although most of the systems have provision for addition of samples, it may occasionally be necessary to alter the spacing.
- It is difficult to compare samples with colour standards of different texture and material. However, to facilitate accurate assessments, some colour order systems have been prepared on multiple substrates.
- The visual spacing of the samples is valid only if standard illuminating and viewing conditions are maintained. The errors are not likely to be very high if typical indoor daylight is used, but viewing under artificial lights may result in serious errors.

- The assessment made by different observers may vary due to the phenomenon known as observer metamerism [13].
- As the systems use physical samples, there are chances of deterioration of the standards due to poor stability of the colorants on extensive use or long exposure to light. High chroma colours may require fluorescent dye or pigment, the use of which is restricted due to limited stability. Even if the manufacturer takes proper care to ensure good performance, after a certain interval of time the accuracy or genuineness of a sample may be questionable. The user may be completely unaware of such changes.
- As background may interfere with visual assessment due to simultaneous colour contrast, a specified background, such as white or neutral grey may be required for use during assessment.
- Most of the colour order systems cannot be used for self-luminous colours such as light sources unless ancillary apparatus is used.

With the aid of computers, colour no longer needs material representation. When generating colours rapidly on computer displays, chromatic characters of the hues and their arrangement or order are less important than the number of primaries used (RGB or RGBY) and the interval of colour generation. Some ideas and techniques for the (abstract) manipulation of colour in space are studied without relying on a preferred colour order [14].

Various aspects of computer-generated colour displays were discussed at the International Colour Association meeting, held in Toronto on 19–20 June 1986. These included calibration techniques for accurate colour reproduction. Monitors are reported to be normalised to a 9300 K white and 'noise' is reported to be greatest in the blue region.

COLOUR SPECIFIERS OR ATLASES

Colour-specifiers or atlases are a convenient two-dimensional form of colour order system, which can be produced in the form of books or charts [15].

Although no specifier is expected to represent visually all the colours that can be detected by our eyes, they have many uses, for example:

- As a stand-alone design tool for colour ideas
- For quick communication of colour ideas over distance
- As a basis for specifying colours during colour formulations and colour ideas
- To support instrumental response or visual perception of instrumentally measured colours.

Selection of the substrate for a specifier is very important. Ideally a textile colourist needs a system that incorporates every fibre type and every dye range or class, but such a perfect specifier or collection is not commercially viable.

A specifier should also be highly stable and have good fastness properties. It should be simple and easy to understand. The samples should be reproducible and replacement pieces should be available. (Many earlier colour specifiers are no longer available.) Finally, a good colour order system will allow the user of the colour-specifier to locate the required shade areas with minimal delays.

TYPES OF COLOUR ORDER SYSTEM

Material-based colour order systems are of three types [3]:

- Colorant mixture systems
- Colour mixture systems
- Colour appearance systems.

COLORANT MIXTURE SYSTEMS

These systems display the range of colours that can be achieved with declared quantities of colorants. These are mostly prepared using pigments or printing inks. For textile applications, the final shade depends on a large number of factors, and a single atlas cannot represent quantities universally.

COLOUR MIXTURE SYSTEMS

These are coloured, physical standards arranged in a regular manner. The arrangements are mostly based on the performance of a tristimulus colorimeter or variations produced by the manipulation of a Maxwell disk. These include the following systems.

Colour Harmony Manual

The most important colour mixture system is the *Colour Harmony Manual* published by the Container Corporation of America in four editions between 1942 and 1972 [6,16]. It consisted of a set of 12 handbooks, each showing pairs of complementary hues. Each colour chip was specified on the Ostwald 24-step hue scale. Each hue-chart shows samples with varying black, white and full colour content represented by double-letter names such as 'na', 'ga', 'ca' etc. Although light colours and near-whites were not included in the manual, its first and fourth editions contained 680 and 949 chips respectively.

Uniquely, the chips were:

- Formed to include both matte and full gloss surfaces (one on each side)
- Removable from the slotted cards on which they are mounted
- Washable.

The publication of the manual was discontinued after 1972, mainly due to poor standard of reproduction [6]. In any case, the attributes of the system could not be readily translated into useful textile terms.

Dictionary of Colour

Maerz and Paul's *Dictionary of Colour* [17] shows a collection of over 7000 colours printed in the form of book.

Colour variations from copy to copy are reported – a result of printing inconsistencies. Near-blacks and light saturated colours are not included.

Colour atlases

Colour atlases have been developed by various dye manufacturers: the ICI colour atlas [18] is a collection of 1379 original colours and 27,580 variations (printed on paper), other such atlases include the Tootal Atlas (2200, fabric, 1970), the Hoechst Atlas, the Ciba–Geigy Colour Atlas (625, fabric, 1982) and the BASF Colorthek III (2580, fabric, 1970).

Pantone colour system

This system [19] is widely used in graphic art and also in textile industry mainly because of its low cost, although the colours are not equally spaced and the shades are prepared on paper using printing inks. The Pantone system is loosely based on a three-dimensional scale, using six-digit reference numbers, comprised of two-digit codes for colour strength, hue and tone (in that order). CIE specifications are not available.

Recently a textile version with 1001 reactive-dyed cotton samples has been introduced to the market.

COLOUR APPEARANCE SYSTEMS

Most of the earlier atlases tended to concentrate on including colours of long traditional usage, thereby emphasising tighter spacing of colours in some hue regions rather than uniform placement of the colour samples throughout the total space. Some areas of colour space are over-emphasised, while others are presented poorly or not at all.

The main emphasis of appearance-based systems is the visual uniform spacing. Six of the most popular systems are of this type. These are:

- Munsell system
- The Optical Society of America Uniform Colour Scales (OSA-UCS System)
- Natural Colour System (NCS)
- Ostwald system
- DIN colour system
- Coloroid system.

A few less well-known and/or newly developed colour order systems also exist. These include the Swiss Colour Atlas 2541, the Chevreul system, Colorcurve, the Eurocolour System, the Acoat System and the Pope Colour System [20]. Most of the above systems are defined by a set of 'aim-points' specified in the CIE system.

Munsell colour order system

This, the oldest and by far the most popular system [21], has been extensively studied [22]. The notation was first developed by Munsell in 1905 and the atlas released in 1915 and commercialised in 1929.

Prior to 1943, the Munsell system was defined by the physical samples comprising the 1929 Munsell Book of Colour colour chips and thus the basic specification of the Munsell system was the spectral reflectance function of each colour chip. The spacing of the chips was intensively studied by the colorimetry committee of the Optical Society of America and in 1943 the CIE tristimulus values of ideally spaced chips were published as the Munsell Renotation system [23]. There are thus many important physical and psycho-physical differences between the earlier and later versions of the system [24].

The Munsell system is based on steps of equal visual perception. It describes all perceivable colours in terms of three coordinates – Munsell hue (*H*), Munsell value (*V*) and Munsell chroma (*C*). Munsell hue is on an interval scale [25] (i.e. equal numerical interval indicates equal perceived difference of attribute), whereas Munsell value and Munsell chroma are ratio scales (i.e. an interval scale having natural origin).

The Munsell colour space is shown in Figure 1 [26]. Hues are represented along the circumference of a circle. The circle is divided into the five principal hues, red (R), yellow (Y), green (G), blue (B) and purple (P). These are further subdivided into five intermediate hues – YR, GY, BG, PB and RP. Each of these portions is again subdivided into 10 divisions to give a total of 100 hues. Hue can also be expressed in continuous scale numbered from 1 to 100.

Munsell value can be represented vertically along the axis of the circle and is divided into 10 equal steps. Chroma is represented by the distance from the centre (chroma = 0) to a maximum of 17. The complete Munsell specification of a sample is expressed as H V/C (e.g. 5R 4/ 8). The Munsell system has problems evaluating near-neutral samples, and hence the Nearly Neutral Collection was developed and has been marketed since 1990. Unfortunately it is difficult to combine the two atlases during evaluation.

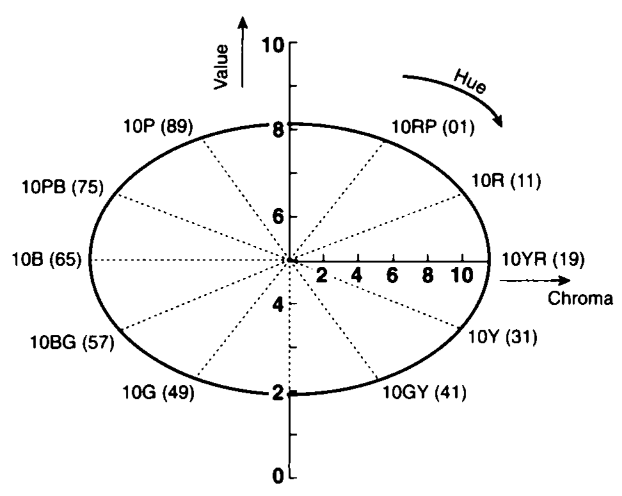

Figure 1 Munsell colour order system. Hues are represented along the circumference of a circle divided into the five principal hues [red (R), yellow (Y), green (G), blue (B) and purple (P)] and subdivided into five intermediate hues (YR, GY, BG, PB and RP). The 10 portions are then subdivided into 10 divisions to give a total of 100 hues. The figures in parentheses reflect hue expressed on a continuous scale between 1 and 100. Munsell value, represented vertically along the axis of the circle, is divided into 10 equal steps. Chroma is represented by the distance from the centre to a maximum of 17

The chips in the Munsell Book of Colour are spaced on the order of 20 just-perceptible differences apart. The equality of visual spacing is such that one value step (on a scale of 10 between white and black) is equal to two steps in chroma and 0.3 major hue steps (3 steps on a 100-step hue scale) at chroma 5 [27].

The colour sensations as well as visual spacing of the Munsell samples vary when the source of illumination is changed [28,29]. The Munsell colour system is, therefore, meaningful only as a colour sensation system to be viewed under specific illumination. The relations between Munsell and CIE variables are very complex. In a CIE chromaticity diagram, lines of constant Munsell hue are curved and location changes with change of Munsell value.

The Munsell value scale (V) is related to the CIE luminance factor (Y) by the following complex, fifth-degree polynomial equation (Judd's polynomial) [30]:

$$Y = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5, \tag{1}$$

based on the use of magnesium oxide, assigned a value of absolute reflectance of 1.026 for 45/0° illumination and viewing.

Ladd and Pinney [31] proposed the following simpler equation:

$$V = 2.468Y^{1/3} - 1.636 \tag{2}$$

No simple relation has been reported so far for Munsell hue or chroma. The NBS computer program [32] requires the use of look-up tables followed by interpolation. A simple and faster program has been recently proposed by Simon and Frost [33]. Artificial intelligence computer programmes such as artificial neural networks (systems that imitate some functions of the human brain) have been utilised to convert Munsell coordinates into CIE coordinates [34].

Earlier textile colourists used paper-based specifiers which were not entirely satisfactory. The Munsell atlas is usually available on painted paper in glossy (1488-chip) and matte (1277-chip) forms. Additionally the original Munsell Book of Colour had a poor collection of high chroma samples.

SCOTDIC

SCOTDIC [35] is a textile colour order system created by the fusion of two quite different systems – Standard Colour of Textiles, Japan and the Dictionnaire Internationale de la Couleur, France. It has incorporated many bright colours and the number of constant hue pages has been increased to 54. The system has three versions – glossy (2450 colours on polyester crepe fabric), matte (2020 colours on cotton poplin fabric) and yarn (890 colours on wool yarns). Colours are specified by six-digit codes, two each for hue, value and chroma successively.

The SCOTDIC system consists of a hue circle and constant hue pages (as in the Munsell system). The chips in a row have equal Munsell values, whereas the chips in a column have equal Munsell chroma values.

With the help of a suitable programme 6000 SCOTDIC colours can be generated on the monitor of a computer and printed with an inkjet printer [36].

OSA-UCS system

Like the Munsell system, the guiding principle in this case is the best possible uniform visual spacing of colours [37]. However this system is not based on the separate scaling of three attributes. Instead, samples are arranged in a regular rhombohedral lattice [22] so that the distances between a sample and each of its 12 nearest neighbours corresponds to equal perceived colour difference at any point in the lattice.

The position of a sample in the lattice is defined by its position along three orthogonal axes, similar to opponent colour scales and named lightness (L), yellowness/blueness (j) and greenness/redness (g). The basic geometry used to describe the rhombohedral lattice is cuboctohedron formed by removing eight corners of a cube. Figure 2 shows this shape, along with the locations of the L, j and g axes, the centre and 12 neighbouring lattices.

CIE tristimulus values can be converted into L, j and g coordinates by a series of mathematical equations [37,38]. Hue and chromatic amount has no meaning in the OSA system, although the American Society for Testing and Materials subcommittee E12.07 has recently proposed the concept of OSA hue and OSA chroma where

$$\text{OSA hue} = \arctan(g/j) \tag{3a}$$

and

$$\text{OSA chroma} = (j^2 + g^2)^{1/2} \tag{3b}$$

NCS

The origins of this Swedish colour order system [39] go back to the six primary colours suggested by Leonardo da Vinci [40] and opponent colour scale proposed by Hering [41]. Here the colours are scaled according to their degree of resemblance to the six elementary colours white, black, yellow, red, blue and green (see Figure 3).

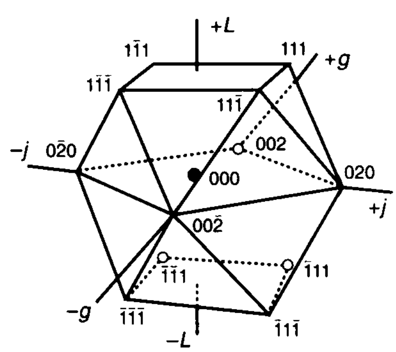

Figure 2 Cuboctohedron of OSA-UCS colour order system. The position of a sample in the lattice is defined by its position along orthogonal axes of lightness (L), yellowness/blueness (j) and greenness/redness (g)

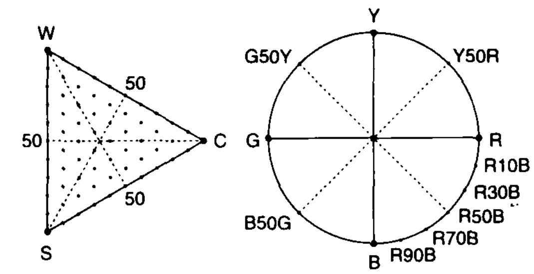

Figure 3 NCS constant hue triangle and hue circle. Colours are scaled according to their degree of resemblance to the six elementary colours white, black, yellow, red, blue and green. Hue is resemblance to the nearest chromatic elementary colour (e.g. Y30R indicates 30% resemblance to red and 70% to yellow), chromaticness is the resemblance to the colour of the same hue of maximum possible chromatic content and blackness or whiteness is the resemblance of the colour to the perfect black or white. The sum of these must be 100%.

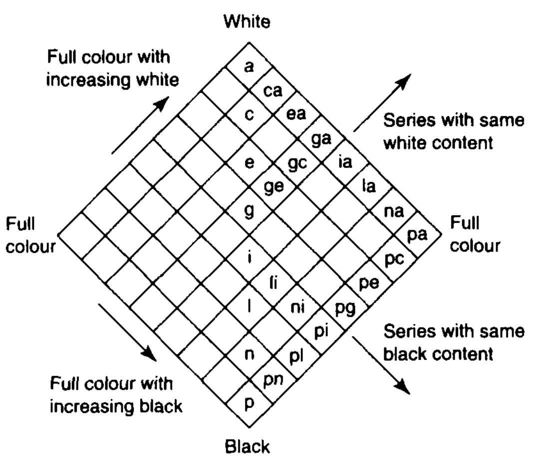

Figure 4 A constant hue page of the Ostwald system. All colours are defined as a mixture of full colour, white and black

NCS hue is defined as the degree of resemblance of the test colour to the nearest chromatic elementary colour. Y30R indicates 30% resemblance to red and 70% to yellow. *NCS chromaticness* is the resemblance of the test colour to the colour of the same hue having maximum possible chromatic content. *NCS blackness* or *whiteness* is the resemblance of the colour to the perfect black or white. The sum of the chromaticness, blackness and whiteness is 100%. The NCS system is presented in diagrammatic form as equilateral triangles, but the maximum purity colours are not shown at the points of triangles. In over half the hues, the full colour is sampled by 2 or 3 colours in a vertical row inside the triangle.

No simple correlate of CIE lightness or Munsell value is proposed in this system, as NCS blackness is claimed to be more readily perceived. The colours of different hues, but having equal NCS blackness and chromaticness are described by the colour designers as having a certain equivalence, called equality of nuance or weight.

The spacing of NCS and aim-points in the CIELAB system have been studied [42], but no accurate analytical relations could be derived. Some non-uniformities were observed in chromaticness and hue spacing, while analysing the NCS system with a non-linear colour-appearance model probably resulted in inaccuracy in the assessing and scaling method. Based on this analysis, a method for conversion into CIE tristimulus value has been suggested [43].

Ostwald system

The German chemist Ostwald devised this colour order system in 1915–16 [44,45]. Although the various physical models are no longer available, the system is favoured by artists and designers because of the similarity between its construction and an artist's method of preparation of colour mix.

Figure 4 shows a constant-hue page of the Ostwald system. Ostwald defined all colours as mixture of full colour, white and black. The runs of colour are straight, symmetrically arranged and the end-point colours easily recognisable. An Ostwald solid, constructed of equilateral triangles, is much simpler in structure than the Munsell solid.

DIN system

The DIN system [46] was developed by Richter. The work started in 1938 and the first edition (1960–62) contained 600 samples; a glossy edition with 1000 samples were released in 1978–83. A number of compromises were made to keep a simple relation between DIN and CIE coordinates. The equality of visual spacing is maintained locally and not globally in all three dimensions.

The system defines three scales:

1. *Darkness degree*, designated D, is the relative lightness scale with respect to optimal colour of the same chromaticity. This is calculated as follows:

$$D = 10 - 6.1723 \log[(40.7\, Y/Y_0) + 1] \qquad (4)$$

   where Y_0 is the maximum possible luminous reflectance of a surface colour defined by MacAdam [47].
2. *DIN hue*, designated T, utilises 24 equally-spaced hues of the Ostwald hue circle with some simplification as a result of defining lines of constant hue as straight lines in the chromaticity diagram.
3. *Saturation degree*, designated S, is the chromatic amount measured by the distance from an achromatic sample of the same luminance factor.

The DIN colour solid is shown in Figure 5 [10]. Methods for conversion of CIE and DIN coordinates have been discussed [48]. The RAL atlas (BS:5252) is a successor to the German DIN atlas, based on CIELAB colour space.

Swiss Colour Atlas 2541

The Swiss Colour Atlas 2541 was developed by Müller [49], the number 2541 representing the total number of

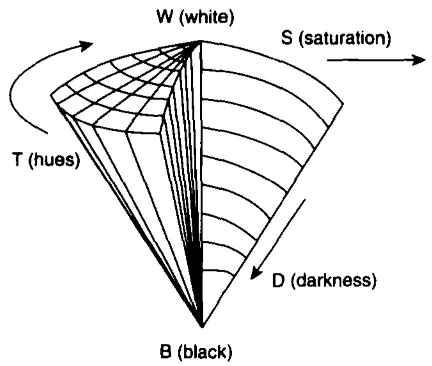

Figure 5 DIN colour solid with *T*, *S* and *D* attributes

coloured samples. The system is similar to the Ostwald system, but regular triangular arrays are based on equal visual spacing, rather than on colour mixing. However, the number of constant hue planes (60) is greater than in Ostwald's original system or the Colour Harmony Manual (24) [16].

Coloroid system

The Coloroid colour system [50,51] is of Hungarian origin. It was designed by Nemcsics and co-workers particularly for use by architects. The system aims to space colours evenly in terms of their aesthetic effects rather than colour differences, as in the Munsell system, or perceptual content, as in the NCS system. The equality of spacing is considered to produce evenness of appearance in all scales of colours in the system.

The system represents colours by three numbers – hue (A), saturation (T) and lightness (V). There are 48 basic *hues* which have constant dominant or complementary dominant wavelength and are numbered between 10 and 76 (with some missing numbers). Intermediate hues are represented by decimal fractions. The extreme reds and violets, beyond dominant wavelengths 625 and 450 nm respectively, are omitted from the system. Both the *saturation* and the *lightness* are represented on a scale of 1–100. Saturation is defined as the percent spectral colour (or the nonspectral purple) required in an additive mixture with perfect black and perfect white to match the colour.

A linear relation exists between excitation purity and Coloroid saturation. The relation between CIE Y and Coloroid lightness is the same as that reported by Hunter [52]:

$$V = 10\,Y^{1/2} \tag{5}$$

Chevreul colour order system

This is an old, but less well-known colour order system [53] based on a 3-dimensional colour space in the form of a hemisphere, the base of which is formed from 12 pure colour chromatic circles.

Colorcurve

This, the newest colour order system [54], is based on additive mixing of tristimulus values in the CIE 1964 space and displayed on grids of constant lightness with neutral grey at centre and four major axes Y, R, B and G at right angles like a^*–b^* grids. The atlas contains 1231 coloured samples.

Practical Colour Coordinate System

The Chroma Cosmos 5000 atlas [55], which is based on this Japanese colour order system, was published in 1978. Billmeyer and Loppnow [56] reported that the chips are denoted by Munsell notations, but the accuracy of many chips is as high as three CIELAB colour difference units. The atlas consists of 23 planes of constant chroma, on which value is plotted against hue.

Eurocolour system

This system exhibits planes of constant CIELAB hue angle on which CIELAB chroma is variable. An atlas has been published by Schwabenmuster in Germany [57].

Acoat system

This system consists of a cylindrical space with hue and lightness coordinates and the third coordinate, chromatic content – but does not distinguish saturation or chromaticness [58]. An atlas based on the system has been published by Sikkens in the Netherlands.

COMPARISON OF COLOUR ORDER SYSTEMS

The most common concept across all colour order systems is the representation of human visual perception of colours.

Smith and co-workers [59] have compared different colour scales, taking the OSA-UCS as benchmark and mapping OSA-UCS atlas samples onto other colour spaces to check the perceptual spacing of the respective colour atlases. They observed that the NCS system is the most radically different in hue spacing from the OSA-UCS system. OSA chroma, Munsell chroma and NCS chromaticness have similar but non-identical axes, while OSA chroma, DIN saturation and Coloroid saturation are distinctly different from each other. The NCS, DIN and Coloroid achromatic scales are distinctly different from the OSA-UCS lightness scale, and the Munsell and OSA-UCS spaces are closer.

Judd and Nickerson [60] derived idealised relations between the NCS and Munsell systems. Billmeyer and Bencuya [61] found a simple relation between NCS hue, NCS chromaticness and NCS blackness against Munsell hue, Munsell chroma and Munsell value respectively. However no analytical relation could be written, possibly due to incompatibility of their respective aim-points. It is claimed that a colour notation conversion programme for conversion between the Munsell, OSA-UCS, NCS, DIN, Coloroid and CIE systems has been developed [62].

Smith and Billmeyer [63] compared the attributes of different colour order systems and their findings can be summarised as follows.

Representation of hue

The OSA-UCS and Colorcurve systems use a grid arrangement that has only four constant hue planes. Most of the other colour order systems represent constant hue along radial lines. All but the NCS colour order system have colours spaced at visually equal steps around achromatic axis.

The NCS is based on four elementary colours located 90° apart on opponent axes as in the CIELAB colour scale. In the Munsell system the hues are arranged so that equal small hue differences occupy equal angles around the entire hue circle and, hence, the unique hues are located at irregular angular spacings: red to yellow, 67°; yellow to green, 75°; green to blue, 90°; and blue to red, 128°. This difference in hue spacing is because the NCS system is based on colour-appearance magnitude, while the Munsell system is based on colour-appearance differences.

Representation of chroma/saturation

The notations of chromatic amount are of three types: chroma, saturation and a combination of whiteness, blackness and chroma. Munsell chroma is independent of Munsell value. The saturations of the DIN and Coloroid systems are radically different despite the fact that both take into account the effect of lightness. In a perceptual uniform colour space, colours of equal Munsell chroma lie on the surface of a cylinder, whereas colours of equal DIN saturation lie on the surface of a cone [64]. In the NCS and Swiss Colour Atlas systems, the concept of chroma is tightly bound between two achromatic scales – the sum of the chroma, blackness and whiteness values is always constant.

Smith and Billmeyer [63] summarised that the three approaches to chromatic scales are not comparable. The NCS and Swiss Colour Atlas chromas are closer to Munsell and OSA-UCS chroma than the DIN and Coloroid saturations.

Judd and Nickerson [65] attempted to derive chroma–chromaticness conversions and postulated the following simple proportionality between NCS chromaticness, c, and Munsell chroma (C):

$$c \sim 5 \times C \tag{6}$$

Billmeyer and Bencuya [61] found a good approximation in:

$$C = Ac + B \tag{7}$$

where A and B vary with hue.

Representation of achromaticity

There are two approaches to achromatic notation:

- The lightness axis in the Munsell, OSA-UCS, Colorcurve and Coloroid and DIN systems (where the opposite notation is darkness)
- The blackness–whiteness–chroma combined relationship of the NCS and Swiss Colour Atlas.

These two approaches produce substantial underlying scaling differences.

Billmeyer and Bencuya [61] suggested the following relation for achromatic colours between Munsell value, V, and NCS blackness, S.

$$V = 10.03 - 0.1248S + 1.209 \times 10^{-3}S^2 - 8.793 \times 10^{-6}S^3 \tag{8}$$

The relationship for chromatic colours is considerably more complicated.

ACCURACY OF COLOUR ORDER SYSTEMS

The accuracies of the NCS, DIN and OSA-UCS systems have been studied [66] and the accuracies of the DIN and OSA-UCS systems found to be similar. Initially it was reported that these systems are on an average 3.5 times more accurate than NCS colour atlas samples. However this was later corrected [67] to say that the errors of NCS atlas samples were, on an average, approximately one CIELAB colour difference unit: the error for the DIN and OSA-UCS systems varies between 0.11 to 6.48 CIELAB unit, whereas that of NCS system varies between 0.04 to 16.21 CIELAB unit. The major source of inaccuracy in the NCS is samples located on the edge of the colour solid. The samples of NCS blackness = 0 or NCS whiteness = 0 are highly inaccurate [68].

The uncertainties during visual interpolation have been shown by Döring to be independent of colorimetric precision of the colour samples in the atlas [69]. This study also showed that the mean colour differences (ΔE_{ab}^*) between colour notation by colour measurement and by visual interpolation were 2 ± 2.7 and 4 ± 3.9 respectively for the DIN and NCS systems, reducing to 1.2 ± 2.8 and 1.7 ± 2.6 for low to medium chroma samples.

CONCLUSIONS

Different colour order systems are based on different principles and are not compatible. Each system serves some specific field or purpose. At present several nations have adopted a specific colour order system as a national standard. These include DIN in Germany, NCS in Sweden and other Scandinavian countries and the Munsell system in many countries, including Japan and Italy. As yet there is no internationally accepted colour order system to facilitate rapid quick global communication – although Tonnquist [70] has suggested that the Munsell and NCS colour order systems could mutually benefit from each other.

A perfect model for colour perception can be created only in non-Euclidean space, and no colour space has achieved such perfection. As it would be impossible to collect samples of all possible colours, interpolation or extrapolation will always be necessary. Since this can result in controversy between observers, equal visual spacing is absolutely essential. This spacing is also dependent on illumination, so conditions of illumination must be specified.

While the concept of a colour atlas is not new, more and more advanced specifiers continue to appear on the market as a result of new ideas and new product development.

* * *

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