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Chromatic adaptation and colour constancy

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Abstract: With change of illumination the sensitivity of our eyes also changes due to chromatic adaptation, in a way such that the colour of the object remains approximately constant. Various chromatic adaptation models formulated by Hunt, Nayatani and CIE (CIECAM97s and CIECAM02) are discussed in detail. Different light sources can result in different colours of the same object surface. Fortunately, human beings have colour constancy: they perceive the same object colour despite large changes in illumination. A number of colour constancy indices, dependent and independent of chromatic adaptation, are discussed.

Key words: colour appearance, chromatic adaptation transforms (CAT), corresponding colours, viewing conditions, CIECAM02, colour constancy, colour inconstancy index.

6.1 Introduction

Colorimetry is the science of quantitative measurement of colour. Hunt (1977) identified three phases of development of colorimetry – colour matching, colour difference evaluation and, lastly, prediction of colour appearance. In the first two cases, a pair of specimens (or stimuli) are compared for relative difference in colour while being viewed under the same specified conditions, or instrumentally in terms of any colour difference formulae such as the CIELAB, CMC (l:c) or BFD (l:c) colour difference formulae. Such measures are relative and cannot be used for evaluation of real or absolute colour appearance under a defined viewing condition. Various colorimetric attributes can be derived from the reflectance spectra, but those are valid for the specific illuminant. Therefore, the appearance attributes of an object under two illuminants cannot be compared directly. For prediction of colour appearance under one illuminant to that under a second illuminant, mathematical transformations are necessary, based on suitable mathematical models. The measurement of colour appearance involves a large number of factors, interrelated in very complicated ways (Roy Choudhury, 1995).

While the CIE system of colorimetry has proved to be extremely useful, it also has its limitations. The inherent limitation of the tristimulus system is that it is based on colour matching. The tristimulus system can accurately predict colour matches for an average observer, but it incorporates none of the information necessary for specifying colour appearance of those matching stimuli. This domain is covered by colour appearance models. The types of scale may be nominal, ordinal, interval and ratio (Chapter 1, Section 1.6). Tristimulus values may be considered as a nominal (or at the best ordinal) scale of colour. They can be used to determine whether two stimuli match or not. The specification of colour difference requires interval scales. The description of colour appearance requires interval scales for hue, and ratio scales for brightness, lightness, colourfulness and chroma. In conjunction with tristimulus values, additional information is necessary to derive these sophisticated scales of colour appearance (Fairchild, 2006).

Two stimuli with identical CIE XYZ tristimulus will match in colour for an average observer subject to certain constraints. These factors include the retinal locus of stimulation, the angular subtense, and the luminance level. In addition, the two stimuli must be viewed with identical surrounds, backgrounds, size, shape, surface characteristics and geometry of viewing. If any of the constraints is violated, the stimuli will no longer match in colour. For such applications, tristimulus colorimetry needs to be enhanced to include the influences of these variables. Such enhancements are colour appearance models. Various colour appearance phenomena break the simple tristimulus system, and some of the relationships between changes in viewing conditions and changes in appearance are:

- Bezold-Brücke Hue Shift
- Abney Effect
- Helmholtz-Kohlrausch Effect
- Hunt Effect
- Simultaneous Contrast
- Crispening
- Helson-Judd Effect
- Stevens Effect
- Bartleson-Breneman Equations
- Chromatic Adaptation
- Colour Constancy
- Memory Colour
- Object Recognition.

Most of the phenomena are discussed in Volume 1 of this book in Chapter 5.

6.2 Adaptation

The word *adaptation* is used to describe a process of favourable or useful adjustment by an organism to environmental conditions. In physiology, such processes are called *homeostatic* or *compensatory processes*. This implies constancy for the particular sensation under varying conditions. Adaptation applies to all domains of perception. Adaptation mechanisms can act over extremely short durations (of the order of milliseconds) or very long durations, such as weeks, months or years. Adaptation makes the observer less sensitive to a stimulus when the physical intensity of stimulus is greater. In the domain of vision, three types of adaptation are important – light, dark and chromatic.

6.2.1 Light adaptation

Visual sensitivity decreases with increase in the overall level of illumination. Millions of stars can be seen on a clear night, but we are unable to perceive them in daytime. This is because in daytime the overall luminance level is several orders of magnitude higher than at night.

6.2.2 Dark adaptation

Dark adaptation is similar to light adaptation, but it refers to changes in the opposite direction. Dark adaptation is the increase in visual sensitivity experienced upon decreases in luminance level.

Dark adaptation takes place much more slowly than light adaptation. On entering a dark theatre after having been outdoors in bright sunlight, after a short period objects in the room begin to become visible. After several minutes, objects will become quite visible, and there is little difficulty identifying other people, finding better seats, etc. This is because the mechanism of dark adaptation gradually increases the overall sensitivity of the visual system. Light and dark adaptation in the visual system are analogous to automatic exposure controls in cameras.

6.2.3 Chromatic adaptation

This is far more important and must be included in all colour appearance models. When the illuminant under which the objects are seen is changed, it is well-known that the colour appearance of various objects changes in varying degrees. The change of colour is, however, not solely based on difference in spectral energy distribution of the two illuminants. The sensitivity of our eyes also changes such that the colour of the object remains approximately

constant. This unique property of our eyes is called chromatic adaptation. Chromatic adaptation can be defined as follows:
'The change in the eye's sensitivity to compensate for changes in the spectral quality of a light source.'

In everyday life, chromatic adaptation occurs constantly in more or less complicated ways, though we hardly realize its occurrence. In the absence of chromatic adaptation, objects' appearance would change continuously as the light sources surrounding us, and their illuminance, change with time and bodily movements. When the eye is exposed for a long time to a scene illuminated by an incandescent light, the average colour entering the eye is roughly equivalent to that of the light source itself. Since such light is weakest at the blue end of the spectrum and strongest at the red end, the eye tends to become most sensitive to blue and least to red. All stimuli are seen in this condition as long as the illumination is unchanged. As the eye sensitivity distribution is opposite to the energy distribution of the source, a non-selective surface, illuminated by such red-rich light source, tends to appear white, i.e. final output to the brain is same as that in daylight. Furthermore, all normal colours will tend towards their appearance as in daylight because the deficiency of the light source is compensated by readjustment of the sensitivities of the cones. The colour of the objects tends to remain constant in spite of the change of the spectral energy distribution of the light source. This makes the colour as a property of the objects, which otherwise would have been variable if the receptor sensitivities were fixed (Evans, 1948).

A piece of paper is seen as white, whether it is being read in outdoor daylight or in an office under incandescent lamp or fluorescent lamp, each of which has different spectral energy distributions. However, when we move from daylight to indoor incandescent light, initially the white material may look distinctly yellow; but within a short time the sensitivities are readjusted and the yellowish cast disappears. Television screens observed at night from outdoors appear bluish against surrounding illumination, yet when viewed at usual distances indoors, the eye rapidly adapts to the bluish light and the screens appear colourless. Thus, adaptation acts to convey any rapid changes in the environment, but hides long-maintained conditions (Hecht, 1934). However, in certain situations, complete adaptation may not be able to keep object-colour constant. Such extreme situation occurs when the object reflectance is restricted to a narrow range of spectrum. A monochromatic light that appears yellow in daylight will appear quite greenish if surrounded by artificial light. In other words, the colour of the objects will remain constant in spite of change of the illuminant so long as the colorimetric shift (i.e. the change in light input to the eye) is less than the adaptive shift (i.e. change in output stimuli to the brain due to change in receptor sensitivities).

6.3 Physiological basis of chromatic adaptation

Chromatic adaptation invariably involves simultaneous light adaptation (Wright, 1981). There are several physiological processes that contribute to the control of the light sensitivity of the eye. When the eye is adapted to a coloured stimulus, the processes occurring, in greater or lesser degree, are reflex control of the iris, the decomposition and regeneration of the photopigments in the retinal receptors, amplification controls of rods and cones, summation and convergence in the synaptic layers in the retina, neural adaptation in the visual pathways, etc.

The initial step in the chain of reactions comprising adaptive adjustment involves photolabile pigments of the retinal rods and cones (Bartleson, 1978a). The action spectra of the photopigments are not in each case simply linear transforms of the CIE standard observer colour matching functions. Light breaks down molecules of visual pigment and thus decreases the number of molecules available to produce further visual response. At higher stimulus intensities there is less photopigment available, and photoreceptors exhibit a decreased responsivity. Considerable changes in the sensitivity may occur without appreciable bleaching or little structural rearrangement of the photopigments. Moreover, the time periods involved in rapid changes in adaptation are too brief to involve bleaching or regeneration of photopigments. The visual pigments may play an important role in the initiation of adaptation, but other factors also come into play. Ionic permeability and conductance in the outer segments of the receptors change due to absorption of photons resulting in neuro-electrical signals that pass through the axons and synapses to higher neural levels. The specific characteristics of these coded chromatic response signals vary with adaptation to illumination of different spectral selectivity. Again, not all adaptive adjustments can be attributed to the rearrangement of retinal response characteristics. It has been demonstrated that spectral sensitivities at the geniculate nucleus and occipital cortex are not simply related to receptor sensitivities. In short, adaptive effects take place at different levels throughout the visual mechanism. Non-linearities and interactions overflow throughout the visual pathways. The dynamics of chromatic adaptation is difficult to formulate. However, the problem in colorimetric study may be reduced if we consider the conditions of equality of colour appearance only.

Independent sensitivity changes in the photoreceptors are referred to as receptor gain control. It is possible to imagine a gain control that varies the relationship between the number of photons incident on the photoreceptors and corresponding electrochemical signal produced. Chromatic adaptation turns down the gain when there are many protons (high excitation of a particular cone type), and turn up the gain when photons are less readily available. These gain controls are independent in each of the three cone types.

The adaptation is thought to be caused by gain-control mechanisms at the level of the horizontal, bipolar and ganglion cells in the retina.

There is also psychophysical evidence for subtractive mechanisms of chromatic adaptation in addition to the gain-control mechanism. Physiological models of adaptation require both multiplicative (gain) and subtractive mechanisms. The subtractive mechanism takes place after a compressive non-linearity.

6.4 Measurement methods

While reviewing, Bartleson (1978a) reported that a tremendous volume of study has been made on chromatic adaptation to fulfil two different objectives – first, to analyse the physiological properties of the visual mechanism, and second, to elucidate the psychophysical relations among the colour attributes under varying illuminant and illuminance.

Chromatic adaptation may be measured in two ways:

1. Visual methods
2. Colorimetric methods

The most extensive available visual data on chromatic adaptation are corresponding colours data. Corresponding colours are defined as two stimuli viewed under different viewing conditions that match in colour appearance. For example, a stimulus specified by the tristimulus values x,y,z viewed in one set of viewing conditions might appear to be of the same colour as a second stimulus, specified by the tristimulus values x',y',z', viewed in a second set of viewing conditions – x,y,z and x',y',z', together with specifications of the two viewing conditions, represent a pair of corresponding colours. Corresponding colour data have been obtained through a wide variety of experimental techniques. The corresponding colour data can be used to test a colour appearance model by taking the set of values for the first viewing condition, using the model to predict lightness-chroma matches for the second viewing condition, and comparing the predictions with the visual results.

Various scaling methods used for measurement of colour appearance, as discussed in Section 2.16 (see Roy Choudhury, 2014, chapter 2, section 3.7, p. 130), can be used for measurement of chromatic adaptation or corresponding colours. The various methods include binocular matching under different adapting conditions (Wright, 1946; Burnham *et al.*, 1957; Jameson and Hurvich, 1972), hue cancellation (Hurvich, 1978), haploscopic matching (Breneman, 1977), short-term memory matching (Pitt and Winter, 1974), colour scaling (Padgham and Rowe, 1973) and a special scaling method called magnitude estimation (Nayatani *et al.*, 1974).

Wright (1981) explained the different methods of measuring chromatic adaptation. Various threshold methods for measuring light sensitivity can also be used for the purpose, but the relation between the two is not very clear. Threshold judgement may be absolute or incremental. The absolute thresholds method consists in determining the minimum energy or radiant power of each wavelength in the spectrum that can just be perceived, the inverse of the quantity being the sensitivity to the particular wavelength. The observation may be carried out for the dark-adapted eye, with the threshold target being viewed at the fovea or at various retinal positions. The observations may be made under different states of colour adaptation to isolate the spectral sensitivity curves of the three or more retinal colour receptor processes. The technique is based on sound principles, and a number of variations are possible in the method of presentation of test and adapting stimuli. In Boynton's experiment (Boynton, 1979), the adaptation was provided by a transient flash lasting just over half a second, with the monochromatic test flash of 0.04 s duration exposed for 0.05 s after the onset of the background flash.

In the increment thresholds method, the sensitivity is measured in terms of the amount of light that can just be perceived against a background of some defined radiance or luminance. This technique was pioneered by Stiles, who used several combinations of wavelengths of test and adapting field. Strictly speaking, the observation is a discrimination judgement.

Bartleson (1978a) classified the methods adopted by various colourists in psychophysical chromatic adaptation studies broadly into four groups, namely:

- Asymmetric matching or differential retinal conditioning and comparison
- Memory matching
- Direct scaling or magnitude estimation
- Haploscopic matching (differential ocular conditioning and comparison). The form of stimulus presentation was subdivided into two broad categories of: (a) simple fields in surface and aperture mode; and (b) complex fields of luminous, projected or reflection images.

Bartleson (1978a) discussed the merits and demerits of each method.

In asymmetric matching, two different areas of retina (left and right halves) were exposed to different adapting stimuli i.e. differential retinal conditioning (MacAdam, 1961) and then test and matching stimuli were presented in the two halves of the visual field for colour matching. It is assumed that differential adaptation of the two halves of the retina is similar to adaptation in normal viewing. This assumption is probably false, and the differential retinal conditioning has become obsolete.

One technique to avoid the assumptions of differential retinal conditioning is 'memory matching', in which observers generate a match in one set of viewing conditions to the remembered colour of a stimulus in different viewing conditions. Memory matching is mostly confined to surface mode in a simple field. The observer first studies the colour of a stimulus under some specified viewing condition. He then adapts to a second viewing condition and adjusts a stimulus to match the remembered appearance of the stimulus in the first condition. Alternately, he may select a matching stimulus from a range of choices. The experimental method poses the problem of limited capacity on the part of the observer for retaining information. Short-term memory may involve systematic distortions – saturation tends to increase in memory, lightness increases for light colours and decreases for dark colours. Braun *et al.* (1996) concluded that a short-time memory matching technique produced most reliable result.

In magnitude estimation, observers assign scale values to various attributes of appearance such as lightness, chroma and hue, or brightness, colourfulness and hue. Such experiments can provide colour appearance data as well as corresponding colours data.

The direct scaling method, or magnitude estimation technique, requires observers to estimate scale values of the various appearance attributes. For example, observers may estimate lightness on a scale that extends from 0 for black to 10 for white. The main advantage of the method is that the observers make judgements on stimuli viewed under a single and steady set of viewing conditions. Later judgements may be made for altered viewing conditions for comparison. Magnitude estimation demands extensive training for the observers for scaling the particular attribute of colour accurately. For example, they should know the difference between chroma and colourfulness. There are general problems of psychological scaling that affect precision in ways that are more difficult to assess. Inter- and intra-observer uncertainty is much larger as compared to that for memory matching. However, if the observers are merely consistent in their scaling responses, the data may be comparable to those derived by other method. Under the best conditions, more information may be available from the direct scaling method, as this method may be used for measurement of colour appearance and not merely for comparison of colour appearance under the condition of equality. To derive a realistic model, the experimental data should be reliable. Although the general characteristics of the reported experimental data are roughly similar, there are perplexing differences between them.

The low precision of memory matching and magnitude estimation technique has led to the development of the haploscopic technique. In these experiments, adapting stimuli are presented such that the left eye becomes adapted to one viewing condition while the right eye becomes adapted to a second viewing condition. Then a stimulus presented to one eye is matched to a corresponding stimulus presented to the other eye. The main advantage of the method is that it allows direct matching of colour appearance across adapting conditions. So the approach is more precise than the traditional colour matching experiments. However, the haploscopic method involves the assumption that the active mechanisms of chromatic adaptation are essentially independent for the two eyes. Precision is, therefore, increased at the expense of more realistic viewing conditions used in magnitude estimation and memory matching techniques. The assumption is valid for sensory adaptation mechanisms, but does not hold for cognitive mechanisms (i.e. based on colour knowledge or experience) that act on information after it has been synthesized from the signals from both eyes (Eastman and Brecher, 1972). Binocular rivalry occurs when the two eyes are presented with disparate (dissimilar) stimuli, and the observer tends to favour perception of one stimulus condition over the other and cannot perceive a combination of the two. This makes the haploscopic experiment more difficult, and creates annoyance to the observer.

To reduce the possible confusion of higher level visual mechanisms when different adapting stimuli are presented to both eyes simultaneously, in the successive haploscopic technique one eye is exposed to a given stimulus while the other eye is occulted. When the second eye is exposed to a second adapting stimulus, the first eye is occulted. This process is repeated as many times as necessary to complete the experiment. The method is claimed to be successful in controlling the neural interaction between the eyes and also for the binocular rivalry. However, the sensory mechanisms are likely to be in transitional state while observers alternate between eyes (generally after every 4 s), because it takes several minutes to reach equilibrium after transition from darkness.

The successive Ganzfeld haploscopic technique relies on a specific type of stimulus pattern, known as *Ganzfeld*. When such a spatially and temporally homogeneous stimulus is presented, the visual perception of light fades away after a few seconds and no signal is transmitted to higher level of the visual system, in spite of constant stimulation and response by the cone photoreceptors. The Ganzfeld was originally introduced into experimental psychology due to the experiments of the German psychologist Wolfgang Metzger (1899–1979) on the perception of a homogenous visual field (Tyson *et al*., 2011).

In this method, one eye is exposed to a given adapting condition while the other eye is exposed to a Ganzfeld of the same luminance and chromaticity as the second adapting condition. When the observer chooses, the situation alternates such that the observer can view the second adapting condition while the first eye is exposed to Ganzfeld with the luminance and chromaticity of the first adapting condition. The result is that the sensory chromatic adaptation of both eyes is held constant, while the binocular rivalry and confusion of cognitive chromatic adaptation mechanism are eliminated by the Ganzfeld effect. For this purpose, a shutter is arranged such that one eye is blocked by a neutral diffuser while the other eye is presented with a clear aperture into the viewing booth. The main advantage of the successive Ganzfeld technique is that the state of sensory chromatic adaptation mechanism is well defined and constant for each eye, while the binocular rivalry and problems with cognitive chromatic adaptation mechanism are eliminated (Fairchild *et al.*, 1994).

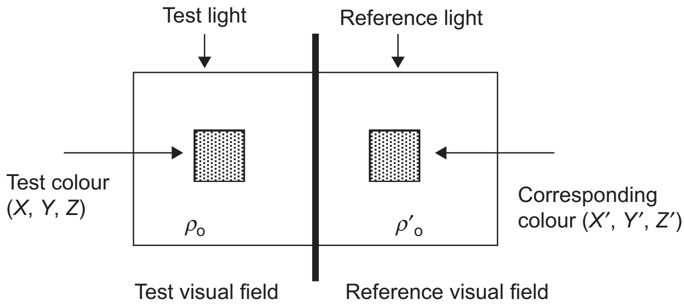
Chromatic adaptation is difficult to measure in a real visual situation that is very complex. However, under controlled viewing conditions, the colour appearance of Munsell samples under different illuminants may be calculated colorimetrically and presented in a chromaticity diagram called a colour appearance grid. As Munsell samples are equally visually spaced, constant chroma loci should appear perfectly circular under daylight illuminant. The chromaticity coordinates under different illuminants cannot be compared directly. However, using a suitable chromatic adaptation model, the chromaticity coordinates under a test illuminant can be converted into the corresponding or equal-appearing colours under a reference illuminant (mostly daylight) by mathematical transformation, and can be compared by plotting both actual and transformed chromaticities under the reference illuminant in a colour appearance grid. Bartleson (1978a) reviewed and Pointer (1982) compared the performances of different grids. Bartleson (1978b) also classified the grids into two types, namely:

1. Type I, based on the von Kries (linear) rule suitable for pseudo-surface colours,
2. Type II, based on non-von Kries types (non-linear) suitable for real surface colours.

6.5 Chromatic adaptation theory

Ordinary colour matching, which is the basis of colorimetry, may be described as *symmetric matching*, since all spatial, temporal, physical and physiological factors involved in the match are the same. However, the match involved in chromatic adaptation is asymmetric, because there exists an asymmetry over illumination and consequent differences in visual sensitivities.

The colour appearance model provides mathematical formulae to transform physical measurements of the stimulus and viewing environment into correlates of perceptual attributes of colour (e.g. lightness, chroma, hue, etc.). There are two main needs for these models – image editing, and viewing-condition transformations. Image manipulations, such as colour preference reproduction and gamut mapping, are best performed in the perceptually



6.1 Schematic diagram of experimental set-up for chromatic adaptation transform.

significant dimensions (e.g. lightness, chroma and hue) of a colour appearance model. The transformation of colorimetric coordinates from one set of viewing conditions (white point, luminance, surround, medium, etc.) to a second set of viewing conditions requires a colour appearance model.

The aim of the colour appearance model is to predict the colour appearance under different viewing conditions. Various components in a viewing field have an impact on the colour appearance of a stimulus. The experimental set-up is shown in Fig. 6.1.

Two models of chromatic adaptation, those of von Kries and Judd, have gained long-standing popularity and have also been held accountable for colour constancy (Helson *et al.*, 1952).

Helmholtz in 1866 proposed that a selective decrease in the sensitivities occurs due to *fatiguing* of the nervous system with prolonged exposure to spectrally selective illumination. On the basis of fatigue theory, von Kries (1911) proposed his famous coefficient law, which implies that the visual responses are linearly proportional to the physical stimulation of each of the three sets of colour receptors in the eye, and that only the coefficients of proportionality change from one adaptation to another. The sensitivities of the adapted visual mechanism are simply proportional to the sensitivities of the mechanism under some different conditions of adaptation, such as in Equation [6.1]:

$$S'_1 = K_1S_1, S'_2 = K_2S_2, S'_3 = K_3S_3 \qquad [6.1]$$

where S_i are the three rest state sensitivities, and S'_i are the altered sensitivities brought about by exposure to spectrally selective illumination. The coefficients K_i are inversely proportional to the relative strength of activation of S_i by the spectral power of illumination. However, the above proportionality rule considers the independence of three sensitivity functions, which has not been supported by much experimental evidence. However, if the persistence law is nearly correct at some moderate levels of adapting intensities, then we may assume a first-order approximation to validity for proportionality. Although there is poor experimental support for the von Kries coefficient law, its use persists as a rough approximation to the general trend of adaptation-induced colour shifts due to simplicity.

Judd (1940) proposed discounting the colour of the illuminant due to adaptation by subtracting tristimulus values of a reference white from those of the object colour (Equation [6.2]):

$$X' = X - X_0,\ Y' = Y - Y_0,\ Z' = Z - Z_0 \qquad [6.2]$$

where X, Y, Z and X', Y', Z' are the pre-adapted and adapted tristimulus values of the object, and X_0, Y_0, Z_0 are the tristimulus values of the reference white. The Judd adaptation, in its simplest form, translates object-colour chromaticities to compensate for the shift of the white point when the illuminant changes. Judd's chromatic adaptation is incorporated in the CIELUV space for colour specification, while the von Kries adaptation is incorporated in the CIELAB specification.

Brill and West (1983–84) proposed a group theory of chromatic adaptation with higher associability between transformations of colour appearances in different adaptation states.

It is important to note that CIELAB is a uniform colour space developed to specify colour difference. It is not a colour appearance model. The positive aspects of CIELAB system are that:

- It accounts for chromatic adaptation
- It works well for near-daylight illuminants for medium grey background and surround and moderate illuminance levels. The surround is defined as the field outside background. It is the area outside the image display filling the rest of visual field. In practical situations, the surround can be considered as the entire room, or the environment in which the image (or other stimuli) is viewed.

The limitations of the CIELAB system are:

- It does not account for changes in background, surround, luminance and cognition.
- It cannot predict brightness and colourfulness.
- 'Wrong' von Kries transform used in the CIELAB system works poorly for large changes from daylight.
- Constant-hue predictions could be improved further, especially blue.

CIELAB makes a good, simple baseline for comparison. However, there are several aspects of colour appearance that CIELAB is incapable of predicting. CIELAB incorporates no luminance-level dependency and no background or surround dependency. CIELAB also has no mechanism for modelling cognitive effects, such as discounting the illuminant, which may be important in cross-media colour reproduction applications (e.g. the reproduction of an image on a display, on a projection screen or as hard copy). The CIELAB system does not provide correlates for the absolute colour appearance attributes of brightness and colourfulness.

Non-linear models, such as Hunt, Nayatani, CIECAM97s, CIECAM02, and a few less known models, have been developed beyond CIELAB and they provide more accurate adaptation transform to calculate hue, brightness and colourfulness considering luminance and surround dependencies.

6.6 Non-linear models

There is considerable evidence that in the receptors stage, the visual signal is largely a linear function of the three variables. But while transmitting from cones through optic nerves (i.e. neural system), the signals are compressed non-linearly, i.e. when the intensities of the stimuli are changed in a certain ratio, the resulting signals are changed in a smaller ratio.

MacAdam (1961) first proposed a non-linear power function. Subsequently, a number of two-stage models were proposed. Hunt's model is the most extensive, complete and complex colour appearance model that has been developed. The root of the model lies in the Hunt's early chromatic adaptation studies (Hunt, 1952) through its rigorous development in the 1980s and 1990s (Hunt, 1982, 1985, 1994, 1995).

Nayatani *et al.* (1982) also developed one of the most important early colorimetry-based colour appearance models. They subsequently calculated the exponents for a light background (Nayatani *et al.*, 1982) under different adapting conditions (Nayatani *et al.*, 1986) using Estévez-Hunt-Pointer primaries (Nayatani *et al.*, 1987). Among them, the two most important models are those of Hunt (1961) and Nayatani. The two models differ significantly in their formulations. Hunt's model was also revised several times (Hunt, 1991).

Both the models attempt to predict the chromaticity of a corresponding colour (i.e. colour of equivalent appearance) under one illuminant from those under another illuminant using a set of mathematical transformations.

6.7 Nayatani's model

The colour appearance model of Nayatani *et al.* evolved as a natural extension of their chromatic adaptation. It is important to note the context in which the Nayatani *et al.* model was formulated. The researchers came from the field of illumination engineering, in which the critical application of the model is the specification of the colour rendering properties of light sources. This provides significantly different challenges from those encountered in the field of image reproduction. Those interested in image reproduction might find some aspects of Nayatani's model inappropriate for their needs. The reverse is also true. Though Nayatani's model was not designed for imaging applications, it is certainly worthy of evaluation in any application that might require a colour appearance model. The model attempts to predict various colour appearance phenomena, such as the Stevens effect, the Hunt effect and the Helson-Judd effects in addition to the effects of chromatic adaptation. It is designed to predict the colour appearance of simple patches on uniform mid-to-light grey backgrounds. It is not designed for complex stimuli or changes in background or surround. The output of the model includes all important colour appearance attributes including brightness, lightness, colourfulness, chroma and hue. The model designs for simple stimuli on uniform backgrounds, while models such as Hunt's, RLAB and CIECAM02 were designed with specific attributes for imaging applications.

The input data for Nayatani's model are:

1. Luminance factor of the achromatic background, ρ_0 ($\geq$18%).
2. Chromaticity (x_0. y_0 for 1931 standard colorimetric observer) of the illumination.
3. Chromaticity coordinate (x, y) of the test stimulus and its luminance factor, Y.
4. The absolute luminance of the stimulus and adapting field defined by the illuminance of the viewing field, E_0, expressed in lux.
5. The normalizing illuminance E in lux (1000–3000 lux).
6. Noise, n, used in non-linear chromatic adaptation, usually considered to be 1.

The steps involved in the Nayatani's chromatic adaptation transformation (CAT) are as follows (Nayatani *et al.*, 1984; Nayatani *et al.*, 1987):

Step 1. Transformation of tristimulus values into the fundamental primary system (R, G, B) using Estévez-Hunt-Pointer primaries (Equation [6.3]):

$$\begin{aligned} R &= 0.40024X + 0.70760Y - 0.08081Z \\ G &= -0.22630X + 1.16532Y + 0.04570Z \\ B &= 0.91822Z \end{aligned} \quad [6.3]$$

Step 2. Calculation of respective values for the non-selective background (R_0, G_0, B_0) from those of the illuminant.

In Nayatani's model, the transformation, from CIE tristimulus values to cone responsivities for the adaptive field, is expressed in terms of chromaticity coordinates rather than tristimulus values. At first, transformed values ξ, η, ζ (equivalent to tristimulus values) under fundamental primary system for the light source illuminating the field are calculated from its chromaticity coordinates (x, y), by the following equation derived from Equation [6.3].

$$\begin{aligned} \xi &= (0.48105x + 0.78841y - 0.08081)/y \\ \eta &= (-0.27200x + 1.11965y + 0.04570)/y \\ \zeta &= 0.91822(1 - x - y)/y \end{aligned} \qquad [6.4]$$

Then R_0, G_0, B_0 values are calculated by multiplying the transformed values with the adapting illuminance and the reflectance of the background (Equation [6.5]):

$$\begin{bmatrix} R_0 \\ G_0 \\ B_0 \end{bmatrix} = \left[\frac{\rho_0 E}{100\ \pi} \right] \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} \qquad [6.5]$$

'E' denotes illuminance of the illuminant. ρ_0 and ρ_0' are the reflectances of the background in the test and reference fields, respectively. The values ξ, η, ζ and R_0, G_0, B_0 are calculated for the test illuminant, and the values ξ', η', ζ' and R_0', G_0', B_0' for the reference illuminant (generally D65).

Step 3. Calculation of adapted cone response functions in the reference illuminant (R', G', B') from R, G, B by mathematical transformations. The adaptation occurs in two stages.

In the first stage, the receptors send out responses R^*, G^*, B^* by the incidence of the test stimulus. The values can be calculated from the R, G and B values of the test colour and those of the background by a linear function, *modified von Kries law*, as follows (Equation [6.6]):

$$\begin{aligned} R^* &= \frac{R + R_n}{R_0 + R_n} \\ G^* &= \frac{G + G_n}{G_0 + G_n} \\ B^* &= \frac{B + B_n}{B_0 + B_n} \end{aligned} \qquad [6.6]$$

The values R_n, G_n, B_n are the noise components of the receptors, proposed by Helmholtz to correct the Weber-Fechner law at a low luminance level. These are independent of the test stimulus.

The second stage non-linear transformation proposed by Nayatani corresponding to a compression of response of each mechanism transmitted from receptor to brain (Equation [6.7]) is:

$$
\begin{aligned}
R^{**} &= a_r\left(R^{*}\right)^{\beta_r(R_0)}\\
G^{**} &= a_g\left(G^{*}\right)^{\beta_r(G_0)}\\
B^{**} &= a_b\left(B^{*}\right)^{\beta_r(B_0)}
\end{aligned}
\qquad [6.7]
$$

The above coefficients are calculated as follows (Equation [6.8]):

$$
\begin{aligned}
\beta_r(R_0) &= \left(\frac{6.469+6.362R_0^{0.4495}}{6.469+R_0^{0.4495}}\right)\\
\beta_G(G_0) &= \left(\frac{6.469+6.362G_0^{0.4495}}{6.469+G_0^{0.4495}}\right)\\
\beta_B(B_0) &= \left(\frac{8.414+8.091B_0^{0.5128}}{8.414+B_0^{0.5128}}\right)
\end{aligned}
\qquad [6.8]
$$

In this formulation, the exponent for the short-wavelength sensitive cones (B in Nayatani's model) differs from the exponents for the middle (G) and long (R) wavelength-sensitive cones.

Step 4. For equal colour appearances, the adapted responses should be equal under both illuminants (Equation [6.9]) i.e.

$$R^{**} = R'^{**},\ G^{**} = G'^{**},\ B^{**} = B'^{**} \qquad [6.9]$$

Step 5. The values R', G', B' under the reference illuminant can be calculated from R'^{**}, G'^{**}, B'^{**} using equations inverse to [6.6] and [6.7].

All the above stages are combined and expressed by a single set of equations, as follows (Equation [6.10]):

$$
\begin{aligned}
R' &= \left(100\rho'_0\xi' + 1\right)\left(\frac{R+1}{100\rho_0\xi+1}\right)^{P_r} - 1\\
G' &= \left(100\rho'_0\eta' + 1\right)\left(\frac{G+1}{100\rho_0\eta+1}\right)^{P_g} - 1\\
B' &= \left(100\rho'_0\zeta' + 1\right)\left(\frac{B+1}{100\rho_0\zeta+1}\right)^{P_b} - 1
\end{aligned}
\qquad [6.10]
$$

The exponents P_r, P_g, P_b depend on the effective adapting levels R_0, G_0, B_0 and R'_0, G'_0, B'_0 and are calculated as follows (Equation [6.11]):

$$
\begin{aligned}
P_r &= \frac{\beta_r(R_0)}{\beta_r(R_0')} = \left(\frac{6.469 + 6.362R_0^{0.4495}}{6.469 + R_0^{0.4495}}\right) \Big/ \left(\frac{6.469 + 6.362R_0'^{\,0.4495}}{6.469 + R_0'^{\,0.4495}}\right)\\
P_g &= \frac{\beta_g(G_0)}{\beta_g(G_0')} = \left(\frac{6.469 + 6.362G_0^{0.4495}}{6.469 + G_0^{0.4495}}\right) \Big/ \left(\frac{6.469 + 6.362G_0'^{\,0.4495}}{6.469 + G_0'^{\,0.4495}}\right)\\
P_b &= \frac{\beta_b(B_0)}{\beta_b(B_0')} = \left(\frac{8.414 + 8.091B_0^{0.5128}}{8.414 + B_0^{0.5128}}\right) \Big/ \left(\frac{8.414 + 8.091B_0'^{\,0.5128}}{8.414 + B_0'^{\,0.5128}}\right)
\end{aligned}
\qquad [6.11]
$$

Step 6. Reference cone response functions, so derived, are transformed to tristimulus values under the reference illuminant using Equation [6.12]:

$$
\begin{aligned}
X' &= 1.85995R' - 1.12939G' + 0.21990B'\\
Y' &= 0.36119R' + 0.63881G'\\
Z' &= 1.08906B'
\end{aligned}
\qquad [6.12]
$$

X', Y', Z' are the tristimulus values under the reference illuminant having equal colour appearance to that under the test illuminant.

Berns (1986) developed a computer program based on Nayatani's non-linear model. Nayatani and co-workers conducted field trials of their non-linear model on the colour appearance of chromatic colours by changing adapting-illuminance levels while using the same illuminant (Nayatani *et al.*, 1988a) and under various artificial light sources (Nayatani *et al.*, 1988b). The model is claimed to give reasonably good predictions on the perception of lightness, chroma, brightness and colourfulness for different levels of adapting illuminance, on the effect of chromatic adaptation between illuminants C and A and also on the visual subjective estimation by Fuchida and Mori (1982) of eight highly saturated colours under five fluorescent lamps.

The model further provides colour appearance attributes such as opponent colour dimensions, brightness, lightness, hue, saturation, chroma colourfulness, etc. (Fairchild, 2006).

Nayatani's model is a complete model in terms of output correlates. It is fairly straightforward and analytically invertible. However, it cannot account for changes in background, surround or cognitive effects. Surround and cognitive effects are critical in image reproduction applications. It does not predict adaptation level, which is also important in cross-media reproduction applications. It is derived and tested mainly for simple patches, which might limit its usefulness in complex viewing situations. This model cannot, therefore, provide the ultimate answer as a single colour appearance model.

6.8 Hunt's models for chromatic adaptation

Hunt's model is designed to predict the appearance of stimuli in a variety of backgrounds and surrounds at luminance levels, ranging from the absolute threshold to cone bleaching. It can be used for related and unrelated stimuli. It predicts a wide range of colour appearance phenomena, including Bezold-Brücke Hue Shift, Abney Effect, Helmholtz-Kohlrausch Effect, Hunt Effect, simultaneous contrast, Helson-Judd Effect, Stevens Effect and Bartleson-Breneman observations. It predicts changes in colour appearance due to light and chromatic adaptation and cognitive discounting the illuminant. It also includes the contributions of rod photoreceptors.

Two-way proposals of Hunt (1987, 1991) are:

1. The first method proposes transformation of tristimulus values from one adapting illuminant to another following von Kries coefficient law.
2. In the second method unadapted cone response functions are converted into adapted cone response function under a single illuminant.

6.8.1 Hunt's first method

CIE tristimulus values (X, Y, Z) are in imaginary space and are first converted to fundamental primary system or cone response functions (ρ, γ, β) using Estévez-Hunt-Pointer primaries (E-H-P) (Estévez, 1979) as follows (Equation [6.13]:

$$\begin{aligned}\rho &= 0.40024X + 0.70760Y - 0.08081Z\\ \gamma &= -0.22630X + 1.16532Y + 0.04570Z\\ \beta &= 0.91822Z\end{aligned} \qquad [6.13]$$

Step 1. Conversion as above for reference white under reference illuminant (Equation [6.14]).

$$X_w, Y_w, Z_w \rightarrow \grave{a} r_w, g_w, b_w \qquad [6.14]$$

Step 2. Similar conversion for reference white under test illuminant (Equation [6.15].

$$X'_w, Y'_w, Z'_w \rightarrow \grave{a} r'_w, g'_w, b'_w \qquad [6.15]$$

Step 3. Similar conversion for test colour under reference illuminant (Equation [6.16].

$$X, Y, Z \rightarrow \grave{a}r, g, b'_w \qquad [6.16]$$

Step 4. According to the von Kries coefficient law, for equal colour appearance under reference and test illuminant it is necessary that the response ratios are equal (Equation [6.17]), i.e.

$$\frac{\rho}{\rho_w} = \frac{\rho'}{\rho'_w}, \quad \frac{\gamma}{\gamma_w} = \frac{\gamma'}{\gamma'_w}, \quad \frac{\beta}{\beta_w} = \frac{\beta'}{\beta'_w} \qquad [6.17]$$

From the above equations, ρ', γ', β' are calculated. These are cone response functions of corresponding colours under reference illuminant having same colour appearance as under the test illuminant.

Step 5. From ρ', γ', β' values, X', Y', Z' are calculated.

6.8.2 Hunt's second method

Step 1. E-H-P primaries are normalized under illuminant D65. Hence for other illuminants in the revised model, the primaries normalized for an equal-energy stimulus is used (Equation [6.18]).

$$\begin{aligned} \rho &= 0.38971X + 0.68898Y - 0.07868Z \\ \gamma &= -0.22981X + 1.18340Y + 0.04641Z \\ \beta &= 1.00000Z \end{aligned} \qquad [6.18]$$

Step 2. Calculation of luminance-level adaptation (Equations [6.19]) and [6.20]),

$$\begin{aligned} F_L &= f(L_A) \text{ or } f(5L_A) \\ F_L &= 0.2K^4(5L_A) + 0.1(1 - K^4)^2(5L_A)^{1/3} \end{aligned} \qquad [6.19]$$

$$K = \frac{1}{5L_A + 1} \qquad [6.20]$$

while L_A denotes luminance of the adapting field, $5L_A$ denotes approximately. luminance of a reference white.

Step 3. Calculation of chromatic adaptation factors, $F_\rho, F_\gamma, F_\beta$. These depend on the luminance of the adapting field (L_A) and the respective ρ, γ, β values of the reference white (Equation [6.21]).

$$F_\rho = \frac{(1 + L_A^{1/3} + h_\rho)}{(1 + L_A^{1/3} + 1/h_\rho)}$$
$$\text{where,} \quad h_\rho = \frac{3\rho_w}{(\rho_w + \gamma_w + \beta_w)} \qquad [6.21]$$

The same equations may be used for calculation of F_γ and F_β, by replacing ρ with γ and β, respectively.

Step 4. Calculation of ρ_D, γ_D, β_D to adjust the Helson-Judd effect (Equation [6.22]). The values depend on the ratio of luminance factor of background Y_B and that of reference white Y_W, luminance-level factor F_L and respective chromatic adaptation factor F_ρ, F_γ or F_β. γ_D is set to zero.

$$\begin{aligned}
\rho_D &= f_n\left[(Y_b / Y_w) F_L Fg\right] - f_n\left[(Y_b / Y_w) F_L Fr\right] \\
\gamma_D &= 0 \\
\beta_D &= f_n\left[(Y_b / Y_w) F_L Fg\right] - f_n\left[(Y_b / Y_w) F_L F_b\right]
\end{aligned} \qquad [6.22]$$

The Helson-Judd effect does not occur in most typical viewing conditions. In those cases, and when the colour of the illuminant is discounted, $\rho_D = \gamma_D = \beta_D = 0$.

$$\mathrm{B}_\rho = \frac{10^7}{10^7 + 5\mathrm{L_A}\left(\dfrac{\rho_\omega}{100}\right)} \qquad [6.23]$$

Step 5. Calculation of cone bleaching factors, B_ρ, B_γ, B_β (Equation [6.23]).

The same equation may be used for calculation of B_γ and B_β, by replacing ρ with γ and β, respectively.

These factors influence cone response functions only at a high level of illumination ($5L_A \geq 10^6$ cd/m^2) when the values are less than unity, otherwise the values are unity.

Step 6. The chromatic adaptation model embedded in Hunt's model is a modified form of the von Kries hypothesis. The cone responses after adaptation (ρ_a, γ_a, β_a) are determined from the cone responses for the stimulus (ρ, γ, β) and those for reference white (ρ_w, γ_w, β_w) (Equation [6.24]):

$$\begin{aligned}
\rho_a &= B_\rho\left[f_n\left(F_L F_\rho \rho / \rho_w\right) + \rho_D\right] + 1 \\
\gamma_a &= B_\gamma\left[f_n\left(F_L F_\gamma \gamma / \gamma_w\right) + \gamma_D\right] + 1 \\
\beta_a &= B_\beta\left[f_n\left(F_L F_\beta \beta / \beta_w\right) + \beta_D\right] + 1
\end{aligned} \qquad [6.24]$$

where W.No.-14-15-2236 f () is a general hyperbolic function given by Equation [6.25].

$$f_n\,(I) = 40\,[I^{0.73}/(I^{0.73} + 2)] \qquad [6.25]$$

When the adapted cone responses are equal, i.e. $\rho_a = \gamma_a = \beta_a$, the colour predicted is achromatic.

Step 7. Conversion of $\rho_a, \gamma_a, \beta_a$ to adapted tristimulus values, X_a, Y_a, Z_a.

When the adapted cone signals are available, it is possible to calculate the opponent responses and colour appearance correlates, such as hue, saturation, lightness, brightness, chroma, colourfulness, etc. The rod signals and their adaptation may be treated as they are incorporated in the achromatic response.

The Hunt colour appearance model is the most complex to implement of the traditional colour appearance models.

6.9 CIECAM97s model

CIE held an expert symposium on Colour Standards for Image Technology in Vienna in March, 1996 (CIE, 1996). Industrial participants requested guidance from the CIE in establishing a single colour appearance model that can be used throughout the industry to promote uniformity of practice and compatibility between various components in modern open imaging systems. Hunt reviewed the current status and presented 12 principles for consideration in establishing a single model, as follows (CIE, 1998):

1. The model can be used under a variety of applications. However, initially only static adaptation may be considered, because dynamic adaptation is highly complex.
2. The model should cover a wide range of stimulus intensities, from dark object colours to very bright self-luminous colours. This means the dynamic response function must have a maximum, and cannot be simply logarithmic or a power function.
3. The model should cover a wide range of adapting intensities, from very low scotopic levels, as in starlight, to very high photopic levels, such as in sunlight. Therefore, rod vision should be included in the model, but there should be the option to exclude this for applications where rod vision is negligible.
4. A wide range of viewing conditions should be covered, including backgrounds of different luminance factors and dark, dim and average surrounds.
5. For simplicity, the spectral sensitivities of the cones should be a linear transformation of CIE $\bar{x}$, $\bar{y}$, $\bar{z}$ or $\bar{x}_{10}$, $\bar{y}_{10}$, $\bar{z}_{10}$ functions and the $V'(\lambda)$ functions should be used for spectral sensitivity of the rods. As scotopic

photometric data are often unknown, the methods of providing approximate scotopic values should be provided.

6. The model should be applicable for any degree of adaptation from complete to none, for cognitive factors and Helson-Judd effect as options.
7. The model should be able to predict hue (hue angle and hue quadrature), brightness, lightness, saturation, chroma and colourfulness.
8. The model should also operate in reverse mode.
9. The model should be as uncomplicated as possible.
10. Any simplified version for a particular application should give same prediction as the complete model for the same specified set of conditions.
11. The model should give best prediction in each application.
12. The model should provide a version for unrelated colours (colours seen in isolation in dark surrounds).

In CIECAM97s and CIECAM02 models, hue appearance is denoted by a system similar to that of the Natural Colour order system (Hård and Sivik, 1981). The hue circle is divided into four quadrants separated by the unique hues, red, yellow, green and blue. Hues are denoted by a quantity called hue quadrature (H), varying from 0 to 400 – H = 0 (or 400) for unique red, 100 for unique yellow, 200 for green, 300 for blue. The intermediate hues are uniformly spaced within the four quadrants. The eccentricity factor (e) accounts for the empirical fact that achromatic colours are not located at the centre of contours of low saturation.

Input Data for CIECAM97 Model

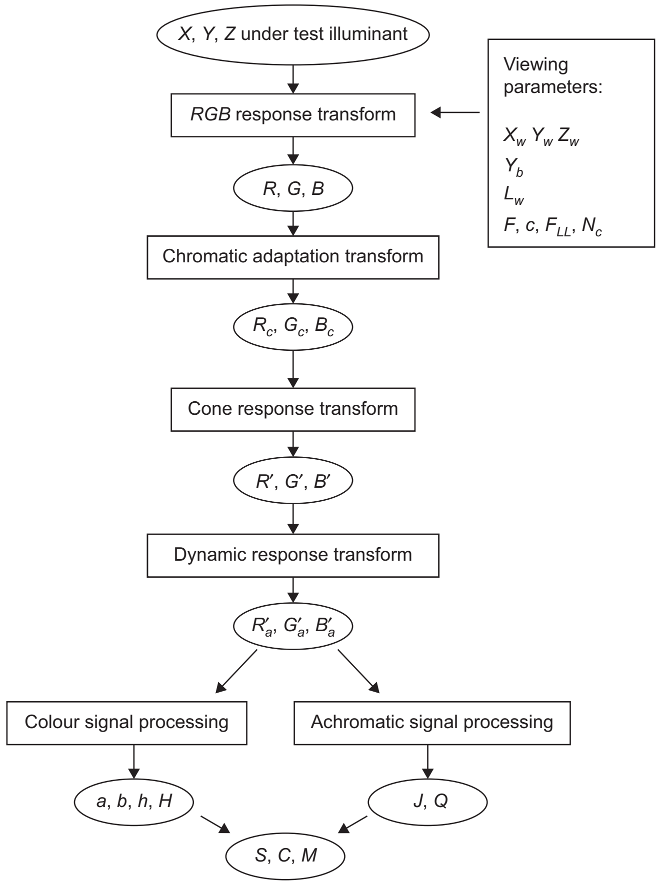
- XYZ: Relative tristimulus values of colour stimulus
- L_a: Luminance of the adapting field (cd/m*m)
- $X_w Y_w Z_w$: Relative tristimulus values of white
- Y_b: Relative luminance of the background

Viewing Condition Parameters

- c: Impact of surround
- N_c: Chromatic induction factor
- F_{LL}: Lightness contrast factor
- F: Degree of adaptation factor

Output Data

- J: Lightness: Overall illumination of the colour, related to brightness
- C: Chroma: Richness of the colour, related to colourfulness
- h: Hue: Classifies the colour as an angle, in degrees, around a colour wheel



6.2 The structure of CIECAM97s model.

The structure of the CIECAM97s model is shown in Fig. 6.2.

At the meeting held at Kyoto in May 1997, CIE Technical committee TC 1–34 agreed to adopt a simple colour appearance model, CIECAM97s, based on the work of several investigators (CIE, 1998).

The CIECAM97s model is based on the Bradford CAT, which uses as in input the ratios X/Y, Y/Y and Z/Y instead of X, Y, Z. The input data to the model include the luminance, L_A, of the test adapting field in cd/m^2. It is also necessary to know whether the surround conditions are average, dim, dark or 'cut-sheet' (i.e. typical condition for viewing cut-sheet film on light boxes and according four parameters, F, c, F_{LL} and N_c are chosen).

The values of the parameters under different surround conditions are given in Table 6.1.

It is also necessary to know if the colour of the illuminant is being completely discounted, partially discounted, or there is no chromatic adap-

Table 6.1 The values of the parameters under different surround conditions in CIECAM97s model

Surround conditions	F	c	F_{LL}	N_c
Average (if the samples subtend more than 4° on eye)	1.0	0.69	0	1.0
Average	1.0	0.69	1.0	1.0
Dim	0.9	0.59	1.0	1.1
Dark	0.9	0.525	1.0	0.8
Cut-sheet	0.9	0.41	1.0	0.8

tation and accordingly 'D' value is set to 1.0, intermediate value or zero, respectively.

It is assumed that the amount of cone pigment bleaching is negligible and there is no significant contribution from the rods.

Step 1. At first tristimulus values for both the sample (b) and white (w) are normalized and transformed to cone response functions (R, G, B) using the Bradford transformation as given in Equation [6.26]:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{BFD} \begin{bmatrix} X/Y \\ Y/Y \\ z/Y \end{bmatrix}$$
$$M_{BFD} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \quad [6.26]$$

Step 2. Various factors must be calculated prior to further calculations.
Background parameters:

$$\text{Background induction factor} = n = Y_b/Y_w \quad [6.27]$$

$$\text{Background brightness induction factor} = N_{bb} = 0.725\,(1/n)^{0.2} \quad [6.28]$$

$$\text{Chromatic brightness induction factor} = N_{cb} = N_{bb}$$

$$\text{Base exponential non-linearity, } z = 1 + F_{LL} n^{0.5} \quad [6.29]$$

F_L is the luminance-level adaptation, L_A denotes luminance of the adapting field, $5L_A$ denotes approximately luminance of a reference white as in the case of Hunt's model (Equation [6.19]).

$$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)(5L_A)^{1/3} \quad [6.30]$$

where $k = 1/(5L_A + 1)$

Step 3. Calculation of the corresponding tristimulus values R_c, G_c, B_c for the sample under the reference conditions. The CAT is a modified von Kries-type transformation with an exponential non-linearity on the short-wavelength-sensitive channel as given in Equations [6.31]–[6.33]. In addition, the variable D is used to specify the degree of adaptation. D is set to 1.0 for complete adaptation or discounting the illuminant (as is typically the case for reflecting materials). D is set to 0.0 for no adaptation. D takes on intermediate values for various degrees of incomplete chromatic adaptation. Equation [6.34] allows calculation of such intermediate D values for various luminance levels and surround conditions.

$$R_c = [D(1.0/R_w) + 1 - D]R \qquad [6.31]$$

$$G_c = [D(1.0/G_w) + 1 - D]G \qquad [6.32]$$

$$B_c = [D(1.0/B^{p}{}_{w}) + 1 - D]\,|B|^p \qquad [6.33]$$

where $p = (B_w/1.0)^{0.0834}$

$$D = F - F/[1 + 2(L_A{}^{0.25}) + (L_A{}^2/300)] \qquad [6.34]$$

If B is negative, then B_c is also set to be negative. Similar transformations are also made for the source white, since they are required in later calculations.

Step 4. The post-adaptation signals for both the sample and the source white are then transformed from the sharpened cone responses to the Hunt-Pointer-Estevez cone responses, as shown in Equation [6.35], prior to application of a non-linear response compression.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M_{BFD}^{-1} \begin{bmatrix} R_C Y \\ G_C Y \\ B_C Y \end{bmatrix}$$

$$M_H = \begin{matrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{matrix} \qquad [6.35]$$

$$M^{-1}{}_{BFD} = \begin{matrix} 0.98699 & -0.14705 & 0.15996 \\ 0.43231 & 0.51836 & 0.04929 \\ -0.00853 & 0.04004 & 0.96849 \end{matrix}$$

Step 5. The post-adaptation cone responses (for both the sample and the white) are then calculated using Equation [6.36]–[6.38].

$$R'_a = 40[(F_L R'/100)]^{0.73}/[(F_L R'/100)^{0.73} + 2] + 1 \quad [6.36]$$

$$G'_a = 40[(F_L G'/100)]^{0.73}/[(F_L G'/100)^{0.73} + 2] + 1 \quad [6.37]$$

$$B'_a = 40[(F_L B'/100)]^{0.73}/[(F_L B'/100)^{0.73} + 2] + 1 \quad [6.38]$$

Step 6. Calculation of appearance correlates

Redness-greenness, $a = R'_a - 12\, G'_a/11 + B'_a/11$ [6.39]

Yellowness-blueness, $b = (1/9)(R'_a + G'_a - 2B'_a)$ [6.40]

Hue angle, $h = \tan^{-1}(b/a)$ [6.41]

Step 7. Hue quadrature, H, and eccentricity factors, e, are calculated from the following unique hue data via linear interpolation between the following values for the unique hues:

Red: $h = 20.14$, $e = 0.8$, $H = 0$ or 400
Yellow: $h = 90.00$, $e = 0.7$, $H = 100$
Green: $h = 164.25$, $e = 1.0$, $H = 200$
Blue: $h = 237.53$, $e = 1.2$, $H = 300$

Equations [6.42] and [6.43] illustrate calculation of e and H for arbitrary hue angles where the quantities subscripted 1 and 2 refer to the unique hues with hue angles just below and just above the hue angle of interest.

$$e = e_1 + (e_2 - e_1)(h - h_1)/(h_2 - h_1) \quad [6.42]$$

where e_1 and h_1 are the values of e and h, respectively, for the unique hues having the nearest lower value of h; and e_2 and h_2 are the values having the nearest higher value of h, respectively.

Hue quadrature, $H = H_1 + 100[(h - h_1)/e_1]/[(h - h_1)/e_1 + (h_1 - h)/c_2]$ [6.43]

where H is 0, 100, 200 or 300 according to whether red, yellow, green or blue, respectively, is the hue having the nearest lower value of h.

The achromatic response is calculated as shown in Equation [6.44] for both the sample and the white.

$$A = [2R'a + G'a + (1/20)B'a - 2.05]N_{bb} \quad [6.44]$$

Step 8. Calculation of

$$\text{Lightness, } J = 100(A/A_w)^{cz}, \text{ where } z = 1 + F_{LL}n^{0.5} \quad [6.45]$$

$$\text{Brightness, } Q = (1.24/c)(J/100)^{0.67}(A_w + 3)^{0.9} \quad [6.46]$$

$$\text{Saturation, } s = [50(a^2 + b^2)^{0.5}100e(10/13)N_cN_{cb}]/[R'_a + G'_a + (21/20)B'_a] \quad [6.47]$$

$$\text{Chroma, } C = 2.44s^{0.69}(J/100)^{0.67n}(1.64 - 0.29^n) \quad [6.48]$$

$$\text{Colourfulness, } M = CF_L^{0.15} \quad [6.49]$$

where

$$A = [2R'_a + G'_a + (1/20)B'_a - 2.05]N_{bb}$$

$$A_w = [2R'_{aw} + G'_{aw} + (1/20)B'_{aw} - 2.05]N_{bb}$$

Steps for using the CIECAM97s model in reverse mode are also given (Luo and Hunt, 1998a).

CIE (1998) TC1–34 recommends that the CIECAM97s model be evaluated as an interim solution to the problem of colour appearance specification. This model should help to address industrial needs by providing a single, CIE-recognized colour appearance model more sophisticated than those provided by the CIELAB colour space.

It does not allow for predictions of the influence of rod photoreceptors on colour appearance, the Helson-Judd effect, the Helmholtz-Kohlrausch effect, or the appearance of unrelated colours. A more comprehensive model, such as the planned CIECAM97c model should be considered when such phenomena are important. It is reasonable to expect that, at some future date, a more accurate and/or theoretically-based model might be developed.

6.10 CIECAM02 model

A number of potential improvements to CIECAM1987s were suggested, and these were compiled into a single publication on behalf of TC8–01 by Fairchild (2001). The adjustments considered, and ultimately included in CIECAM02 in some form, included:

- The use of a linear, von Kries-type CAT resulting in a simpler model with equivalent performance and allowing for a simple analytical inversion of CIECAM02,
- Correlation of anomalous surround compensation,
- Correction of the lightness scale for perfect stimuli,
- Correction of chroma scale expansion for colour of low chroma,

- Inclusion of a continuously variable surround compensation,
- Improved response compression function to facilitate an improved saturation correlate.

The proximal field is the immediate environment of the colour element considered, extending typically for about 20 from the edge of that colour element in all or most directions. Currently, the proximal field is not used in CIECAM02.

The background is defined as the environment of the colour element considered, extending typically for about 100 from the edge of the proximal field, in all or most directions. When the proximal field is the same colour as the background, the latter is regarded as extending from the edge of the colour element considered. Background is measured by a TSR to define background luminance, L_b.

In CIECAM02, background is defined by the luminous factor, $Y_b = 100 \times L_b/L_W$.

A surround is a field outside the background and outside the white border (reference white). Surround includes the entire room or the environment. Surround is not measured directly, but rather the surround ratio SR is determined and used to assign a surround. If SR is less than 0.2, then a dim surround should be used, while an SR of greater than or equal to 0.2 corresponds to an average surround. Different surround 'average', 'dim', 'dark' lead to different parameters (F: incomplete adaptation factor; Nc: chromatic induction factor; and c: impact of surround) used in CIECAM02. The adapting field is the total environment of the colour element considered, including the proximal field, the background and the surround, and extending to the limit of vision in all directions.

Inputs are same as those in the case of CIECAM02, and are as follows:

L_A:	Adapting field luminance in cd/m^2 (often 20% of the luminance of white)
XYZ:	Relative tristimulus values of the sample
$X_wY_wZ_w$:	Relative tristimulus values of the white
Y_b:	Relative luminance of the background
D:	Specifies the degree of adaptation:

Surround Parameters:

c:	Impact of surround
N_c:	Chromatic induction factor
F:	Factor for degree of adaptation
F_{LL}	Always 1.0

The values of the parameters in CIECAM02 model under different surround conditions are given in Table 6.2. The two conditions, large samples

Table 6.2 The values of the parameters under different surround conditions in CIECAM02 model

Surround condition	F	c	N_c
Average surround	1.0	0.69	1.0
Dim surround	0.9	0.59	0.9
Dark surround	0.8	0.525	0.8

and cut-sheet, considered in CIECAM97s, are removed i.e. not considered in the newer model.

Step 1. CIE tristimulus values are normally calculated using the CIE 1931 standard colorimetric observer (2°) and are converted to RGB responses based on the optimized transform matrix M_{CAT02} as shown in Equation [6.50].

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{\mathrm{CAT02}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$
$$\text{where } M_{\mathrm{CAT02}} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad [6.50]$$

The transformation to cone responses is the same as that used in the Hunt model. Matrix M_{CAT02} is normalized such that the tristimulus values for the equal-energy illuminant ($X=Y=Z=100$) produce equal cone responses ($L = M = S = 100$).

The degree of adaptation, D, is computed as a function of the adapting luminance, L_A, and surround, F (Equation [6.51]):

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{\left(\frac{-(L_A+42)}{92}\right)}\right] \quad [6.51]$$

$D = 1.0$ for complete adaptation or discounting the illuminant

$D = 0.0$ for no adaptation

The value of D is in between for various degrees of incomplete adaptation. As a practical limitation, it will rarely go below 0.6.

Step 2. The tristimulus responses for the stimulus colour are converted to adapted tristimulus responses, $R_cG_cB_c$ representing corresponding colours for an implied equal-energy illuminant reference condition using Equations [6.52]–[6.54]. $R_wG_wB_w$ are the tristimulus responses for the adapting white.

$$R_c = [(100D/R_w) + (1 - D)]R \quad [6.52]$$

$$G_c = [(100D/G_w) + (1 - D)]G \quad [6.53]$$

$$B_c = [(100D/B_w) + (1 - D)]B \quad [6.54]$$

The above equations represent the most general form of CIECAM02 CAT as a simple von Kries transform to implicit equal-energy reference conditions with incomplete adaptation. These can be used in all applications to maximize generality and minimize confusion.

Step 3. For further computations, a number of viewing-condition-dependent components are computed as intermediate values in similar way to the CIECAM1997s model. These include:

- Background induction factor, n, as in Equation [6.27]
- Induction factors, N_{cb} and N_{bb}, as in Equation [6.28]
- Luminance-level adaptation, F_L, as in Equation [6.29]

The equation for base exponential non-linearity, z, is different from that in the CIECAM1997s model.

$$\text{Base exponential non-linearity, } z_{\text{CIECAM02}} = 1.48 + n^{0.5} \quad [6.55]$$

Step 4. The adapted RGB responses are first converted from the MCAT02 specification to Hunt-Pointer-Estevez fundamentals, which more closely represent cone responsivity. This transformation is represented by Equation [6.56].

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M^{-1}_{\text{CAT02}} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix}$$

where

$$[M_H] = \begin{matrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{matrix} \quad [6.56]$$

$$M^{-1}{}_{\text{CAT02}} = \begin{matrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.05698 & 1.015326 \end{matrix}$$

Matrix M_H is same as in the case of the CIECAM97s model.

Step 5. Post-adaptation non-linearities are similar to those in the case of the CIECAM97s model, slightly modified to produce a simple power function response over a larger dynamic range. These non-linearities are given in Equations [6. 57]–[6.59].

$$R'_a = 400(F_L R'/100)^{0.42}/[27.13 + (F_L R'/100)^{0.42}] + 0.1 \qquad [6.57]$$

$$G'_a = 400(F_L G'/100)^{0.42}/[27.13 + (F_L G'/100)^{0.42}] + 0.1 \qquad [6.58]$$

$$B'_a = 400(F_L B'/100)^{0.42}/[27.13 + (F_L B'/100)^{0.42}] + 0.1 \qquad [6.59]$$

These values are then used to create opponent colour responses and formulate correlates of colour appearance. Redness-greenness (a), yellowness-blueness (b) and hue angle may be computed using same equations (Equations [6.39]–[6.41] as in the case of the CIECAM97s model.

The eccentricity factor e_t is similar to that in the CIECAM97s, but has been calculated analytically as in Equation [6.60]:

$$e_t = \frac{1}{4}\left[\cos\left(h\frac{\pi}{180}+2\right)+3.8\right] \qquad [6.60]$$

Hue quadrature, H, and hue composition, H_c, can be determined through linear interpolation of the unique hue data given in Table 6.3 using Equation [6.61].

$$H = H_i + \frac{100(h-h_i)/e_i}{(h-h_i)/e_i+(h_{i+1}-h)/e_{i+1}} \qquad [6.61]$$

The achromatic response is calculated as shown in Equation [6.62] (the same as CIECAM97s except with constant 3.05 instead of 2.05 in the case CIECAM97s) for both the sample and the white.

$$A = [2R'a + G'a + (1/20)B'a - 3.05]N_{bb} \qquad [6.62]$$

Lightness J is calculated from the achromatic response of the sample, A, that of white, A_w, the surround factor, c and the base exponent z as shown in Equation [6.45].

Brightness equation is somewhat different from that of CIECAM97s, as shown in Equation [6.63].

$$\text{Brightness, } Q = (4/c)(J/100)^{0.5}(A_w + 4)F_L^{0.25} \qquad [6.63]$$

A temporary quantity t, is computed, as in Equation [6.64].

Table 6.3 Unique hue data for conversion from hue angle to hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_t	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
Ht	*0*	*100*	*200*	*300*	*400*

$$t = \frac{e(a^2 + b^2)^{0.5}}{R_a' + G_a' + (21/20)B_a'} \qquad [6.64]$$

The CIECAM02 chroma, C, is then computed by multiplying the slightly non-linear form of t by the square-root of lightness, J, with some adjustment for background n, as shown in Equation [6.65].

$$\text{Chroma, } C = t^{0.9}(J/100)^{0.5}(1.64 - 0.29^n)^{0.73} \qquad [6.65]$$

$$\text{Colourfulness, } M = CF_L{}^{0.25} \qquad [6.66]$$

A simple and logical predictor of saturation s is defined in CIECAM02 as the square-root of colourfulness relative to brightness (analogous to CIE saturation), as in Equation [6.67].

$$S = 100\,(M/Q)^{0.5} \qquad [6.67]$$

CIECAM02 can predict all the phenomena that can be predicted by CIECAM97s – in fact it is a simpler and better version of CIECAM97s. CIECAM02 is an internationally accepted colour appearance model with a relatively simple formulation with reasonable accuracy.

Overall, the CIECAM02 is capable of accurately predicting colour appearance under a wide range of viewing conditions. It has been proved to achieve successful cross-media colour reproduction, and is adopted by the Microsoft Company in their latest colour management system, Windows Color System (WCS). With the addition of CAM02-UCS uniform colour space, size effect and unrelated colours, it will become a comprehensive colour appearance model to serve most applications.

Many researchers are turning to more complex viewing situations, including computational prediction of special and temporal effects, and are deriving more new colour appearance models with different capabilities.

Colour spaces related to appearance models are normally specified in terms of cylindrical coordinates of lightness, chroma and hue (J, C, h) or brightness, colourfulness and hue (Q, M, h). However, in some applications, such as colour reproduction application, it is useful to have equivalent Cartesian coordinates (X, Y, Z). While this computation is a simple coordinate transformation, it was never explicitly defined in CIECAM97s. CIECAM02 is a significant improvement over CIECAM97s in terms of simplicity of inversion. This is largely due to the adaptation of a simple linear chromatic adaptation. The CIE technical report on CIECAM02 includes a detailed explanation of the model inversion, and worked example (CIE, 2004).

6.11 Evaluation of the models

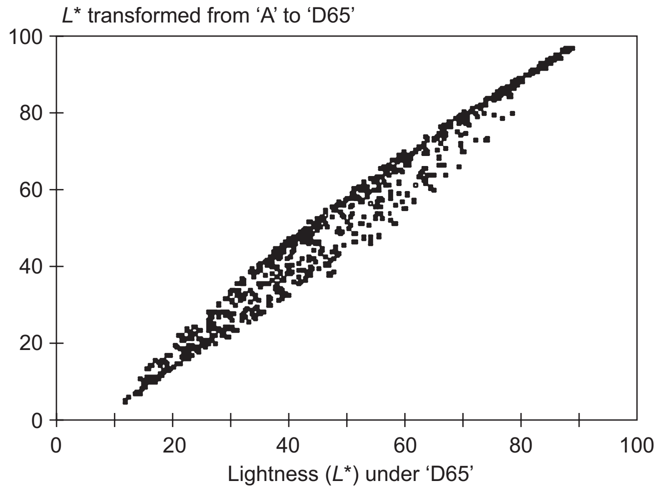
A large-scale psychophysical experiment was conducted in which appearance was assessed under a wide range of viewing conditions. The results are accumulated to form the LUTCHI colour appearance data (Luo, 1996). A number of colours were scaled by a panel of observers under a set of viewing conditions in which parameters such as light sources, luminance level, background and media (e.g. reflection prints, transparent cut sheets, 35 mm transparencies and monitor) are specified. In the viewing field, the test pattern is surrounded by a few decorating colours to form a complex pattern. In addition, white reference and colourful samples are presented as anchor points for scaling lightness and colourfulness. Following magnitude estimation technique, the observers were asked to scale lightness, colourfulness and hue attributes for each test colour. The coefficient of variation among observers showed that the observers scaled hue most accurately, followed by lightness, with colourfulness being the worst. The colour appearance models of Nayatani and Hunt, tested with the LUTCHI colour appearance data and the Hunt 91 model (second method), along with his revised predictors for chroma, C_{94}, and colourfulness, M_{94},was found to predict LUTCHI colour scaling most successfully. The revised predictor for chroma, C_{94}, which predicted the colourfulness of related colours of modest ranges of luminance level, is as in Equation [6.68] (Hunt, 1994):

$$C_{94} = 2.44 s^{0.69} \left(\frac{Q}{Q_w} \right)^{\frac{Y_b}{Y_w}} \left(1.64 - 0.29^{\frac{Y_b}{Y_w}}\right) \qquad [6.68]$$

where Q and Q_w are the predictors for brightness for the colours considered and for the reference white, respectively, and Y_b and Y_w are the luminance factors of the background and of reference white, respectively. s is the predicted saturation.

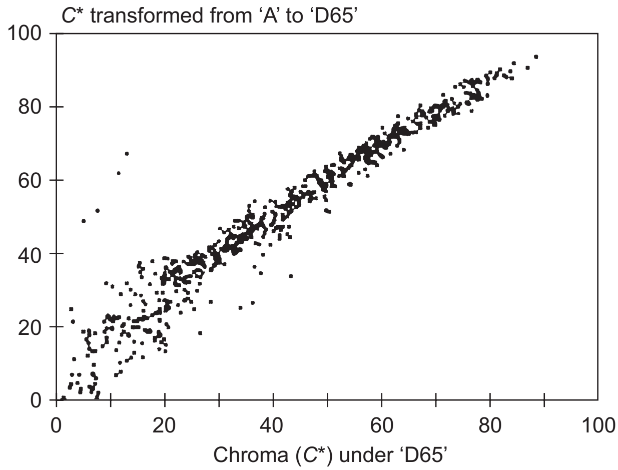
6.12 Effect of changing illuminant on colour appearance

In a study made by Roy Choudhury and Chatterjee (1997), thick knitted cotton materials were dyed into 660 self-shades using 160 dyes belonging

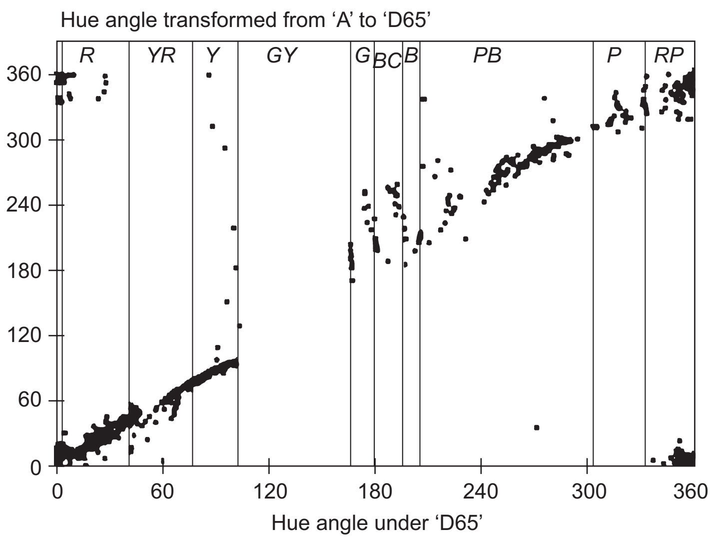


6.3 Comparison of lightness (L^*) of 660 dyed samples under the illuminant D65 and those transformed to 'D65' from 'A' by Nayatani chromatic adaptation transform.

to the azoic, vat, reactive and direct class of dyes. The dye concentration (i.e. depth of dyeing) ranges were so chosen as to cover approximately the whole colour gamut commonly encountered in cotton (cellulosic) textile dyeing processes. The samples were sorted under illuminant D65 to nine Munsell hue groups and a hueless group, and there were no samples belonging to hue-group GY (Hue no. 33–41). The comparison of colour appearance parameters of 660 dyed samples under a pair of illuminants was made by considering metric parameters namely lightness, chroma and hue angle separately. As the colour space varies with the illuminant, the parameters under test illuminant were transformed to reference illuminant (D65) by the CAT proposed by Nayatani. The transformed values represent corresponding colours under reference illuminant, and are expected to have equal colour appearance as under test illuminant. Figures 6.3–6.5 show the correlation curves for CIE lightness (L^*), chroma (C^*) and hue angle (h^0), respectively, of the 660 dyed samples under the illuminant D65 and those transformed to 'D65' from 'A'. Figure 6.5 also shows the approximate zones of hue angle for various Munsell hue groups. For lightness and chroma, the correlations were very high – R^2 values were 0.97 and 0.93, respectively. For a three-band fluorescent lamp TL84 of correlated colour temperatures 4400 K, called a departmental store lamp, the correlations were still better – 0.99 and 0.96, respectively. The hue angle values under two illuminants, reference illuminant 'D65' and a test illuminant '*A*' or 'TL84', showed poor correlations and the R^2 values were 0.44 and 0.71 for the test illuminant '*A*' and 'TL84', respectively. In other words, the colour appearances of many samples under test illuminant differ distinctly from



6.4 Comparison of chroma (C^*) of 660 dyed samples under the illuminant D65 and those transformed to 'D65' from '*A*' by Nayatani chromatic adaptation transform.



6.5 Comparison of hue angle ($h°$) of 660 dyed samples under the illuminant D65 and those transformed to 'D65' from '*A*' by Nayatani chromatic adaptation transform.

those under reference illuminant (D65), when the test illuminant is '*A*'. In case of test illuminant 'TL84', the deviation in the hue angles from those under reference illuminant are less random, probably because of the similarity in spectral power distributions (SPD) of the two fluorescent lights

'TL84' and 'D65'. The study shows that the change of lightness (L^*) with the change of illuminant is less random for most of the samples, while the change of chroma is moderately random and the change of hue angles is highly random among the samples.

6.13 Colour constancy

Colour constancy is an example of subjective constancy and a feature of the human colour perception system that ensures that the perceived colour of objects remains relatively constant under varying illumination conditions. A green apple, for instance, looks green to us at midday, when the main illumination is white sunlight, and also at sunset, when the main illumination is red. This helps us to identify objects. Colour is one of the most important aids for recognition of objects. But the level and colour of the illumination may vary widely. The human vision system is highly efficient at compensating such changes and, as a result of this adaptation, the perceived colour of the object remains approximately constant. Colour constancy is the invariance of an object's colour under a situation of changing illuminance. Colour constancy phenomena are largely confined to surface or object modes of colour perception. When the illuminant is changed, a colorimetric colour shift occurs due to change in the spectral radiant power of the illuminant. For colour-constant substances, the shift is negligible. After a short period, the colour of the object reverses more or less to its original colour. This reversal is termed an *adaptive shift* and, if it is incomplete, the difference between the perceived colours after complete adaptation is termed a resultant shift (McLaren, 1983). Colour constancy always involves only one object at a time. Perhaps for evolutionary reasons, or for reasons of particular reflectance properties, natural colours appear more colour constant than artificial ones (Berns, 1983). Coal continues to look black and snow white, even when the luminance of the coal is greater than that of snow. Moreover, snow continues to look white, whether the illumination is skylight, lamplight or firelight. Similarly, green grass nearly always looks green, and red roses red. Colour constancy is only approximate, and considerable change in colour appearance may sometimes occur. Constancy is maintained in a complex visual scene by comparison with the surrounding objects of relatively high reflectance (MacDonald, 1987).

Colour constancy fails when:

1. The illuminant is monochromatic (e.g. sodium vapour lamp).
2. The illumination varies remarkably across the visual scene.
3. The objects are viewed against a black background, and therefore no comparison is possible with the surrounding objects.

Colour constancy is improved by maximizing reflectance at 450, 530 and 610 nm (Thornton, 1986). Colour constancy also depends in part on the tolerance of memory-colours of familiar objects (OSA, 1953). The changes in colour perception due to change in illumination may pass unmarked because they do not exceed the individual's memory colour latitude or tolerance. If a direct perceptual comparison is made later, the observer is likely to be startled by the amount of change that he has tolerated. Coal usually looks black and snow looks white, even when the illuminance of the former is greater than the latter. In practical work, such as design and selection of light sources, it is desirable to know the net effect of a lighting change on the colours perceived in a scene.

Brill and West (1986) commented that chromatic adaptation and colour constancy are different phenomena, as the former requires a little time (a few seconds) while the latter is instantaneous. Hunt (1981) demonstrated that the colour of the objects of a room in a colour slide can be recognized immediately (i.e. colour constancy) even when the slide is covered with a blue filter, but it takes little time for the bluish overcast to disappear (i.e. chromatic adaptation). Chromatic adaptation is measured by asymmetric matching experiment in which two eyes are adapted to different adaptation state and both fields are seen on a spatially uniform background. Such conditions are not favourable for good colour constancy. Colour constancy is best seen in complex scenes in which many reflecting areas retain their colour relationship when the illumination changes.

However, the principles that need to be followed to achieve colour constancy have not been well understood. It is not known whether colour constancy is associated with the presence or absence of certain colourants or whether it depends on specific criteria for the spectral reflectance curves of the objects. Using Nayatani's non-linear model of chromatic adaptation, approximately colour-constant 1931 CIE tristimulus values for the notations of the Munsell book of colours were calculated by Berns and others (1985) for a variety of illuminants. As the relation between colour constancy and chromatic adaptation is disputed, a number of models for colour constancy, both dependent and independent of chromatic adaptation, are proposed.

6.14 Visual assessment of colour constancy

In colour constancy study by McCann and others (1976), called a quantitative-retinex experiment, a complex reflecting background or *Mondrian* is introduced on one side of the asymmetric match. A large number (precisely 18 nos. used by McCann) of coloured papers of various Munsell designations and various size and shapes are pasted on the Mondrian. The Mondrian is illuminated by a mixture of three independently variable narrow-band lights of wavelength 630, 530 and 450 nm. In a second box, a Munsell book of colour is illuminated by a constant mixture of the above three lights. With one eye, the observer views the Mondrian. A short time later, the observer views the Munsell samples against grey background with the other eye, and chooses the paper from the Munsell book that closely matches one of the papers in the Mondrian and subsequently the others. The array of papers remains constant in the Mondrian, but the lighting varies. On the other box, the lighting is constant and the observer chooses one paper from a large set of Munsell colours. If perfect colour constancy holds, then the papers chosen to match a given area of Mondrian should vary little, though the chromaticity and luminance of the area are varied.

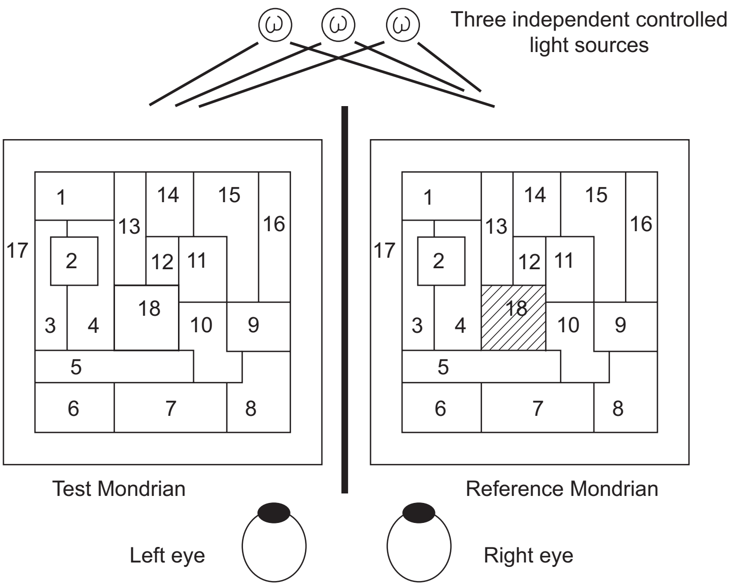
From quantitative-retinex experiment, Worthey (1985) concluded that:

1. The eye can discount certain features of the illuminant but not the others.
2. The eye discounts illuminant effects on object luminance well.
3. When a change in illuminant spectral composition affects object luminance well, this too is discounted well.
4. The eye tends to discount the colour of the illuminant. Blue-yellow shifts are discounted well and red-green shifts less well.
5. The eye does not discount those features of the illuminant that govern colour contrast. Commercial light sources vary considerably in their tendency to reduce or enhance the red-green contrasts of objects in the lit space. Often they create a partial loss of red-green contrast.

Brill and West (1983–84) suggested certain modifications because, in McCann's experiment, the spatial (reflectance) context in both test and reference fields is different. Figure 6.6 shows schematic arrangements for modified method of testing colour constancy. The same Mondrian may be used for both the test and reference fields. The figure shows the Mondrians, each consisting of 18 reflecting patches of various Munsell specifications. The test colour is placed in the position marked '18'. In the reference field, a vacant place (hatched lined area in the figure) is left in the identical position of the Mondrian, where reference samples can be placed one after another to check exact matching against the test colour. Both the fields are illuminated by a mixture of the same three monochromatic light sources with controls – the reference field is illuminated with a constant mixture, while the test field with a varying mixture.

6.15 Colour constancy models

The models for generating colour constant (i.e. illuminant invariant) reflectances may be classified into two groups (Brill and West, 1986), as follows:



6.6 Experimental set-up for colour constancy experiment.

1. Models based on chromatic adaptation models of von Kries, Judd, Hunt or Nayatani,
2. Models independent of chromatic adaptation, which may be further classified into two groups namely:
   a. Inversion models, involving simultaneous estimation of the illuminant and reflectance spectra.
   b. Non-inversion models, which do not estimate the illuminant SPD but make use of illuminant invariance to estimate reflectance directly.

6.15.1 Adaptation models

The spectral reflectances of the objects illuminated under a light source can be represented as points in tristimulus space. With the change of illumination, the locations of the points change. Due to chromatic adaptation, these pre-adapted locations further change into new adapted locations. If perfect colour constancy is retained by the chromatic adaptation, a coordinate transformation in tristimulus space restores all object-colour points to their original positions when the illumination changes. Chromatic adaptation models depend only on the tristimulus values of the initial and final illuminations estimated as reflection of a white surface or as a spatial average over a visual scene. However, some reflectances are metameric, i.e.

they have identical tristimulus values under one light, and different values under a second light. Therefore, for a given model of chromatic adaptation, it is necessary to know what conditions on reflectance and illumination are required to insure colour constancy.

Both von Kries' and Judd's models of chromatic adaptation have been held accountable for colour constancy. The adapted tristimulus values in both models have, in common, invariance to changing S_λ by a scale factor (kS_λ). This property, called *scale invariance*, is a convenient feature of these models. As one aspect of the illuminant invariance is incorporated, the models assure colour constancy. Moreover, the exchange of illumination incident on a spectral reflectance can be represented as wavelength by wavelength multiplication by the ratio of new to old illuminant SPDs. As multiplication is commutative or exchangeable, the transformations by both von Kries and Judd are commutative. Brill and West (1986) have enumerated the spectral conditions for illuminant invariance under both the models. In both cases, the illuminant SPD are considered to be linear combinations of N principal components and the illuminant invariance holds when the reflectances are orthogonal to a forbidden subspace of at most $3(N-1)$ dimensions. In other words, if there is a set of at most $3(N-1)$ functions $f_k(\lambda)$, each linear combination of $f_k(\lambda)$ constant reflectance $\rho(\lambda)$ is orthogonal to each $f_k(\lambda)$ (Equation [6.69]) i.e.

$$\int \rho(\lambda) f_k(\lambda) d\lambda = 0 \qquad [6.69]$$

Least-squares-best-fit colour-constant reflectances can be obtained by subtracting the forbidden component of a real reflectance. The colour-constant reflectances are insensitive to the choice of chromaticity space. For both von Kries and Judd adaptations, the colour-constant reflectances for $N = 3$ are unrealistically jagged – such reflectances give rise to unsaturated object colours, and hence the colour gamut is restricted. Invoking weak invariance by allowing limited variation in the coefficients of the illuminant principal components and less than 10% departure from illuminant invariance and optimizing the fit of the approximate colour-constant reflectance spectra with real reflectance, more realistic spectra were obtained. The colour-constant reflectances are still far from the real reflectance from which it is derived.

Berns *et al*. (1985) used a linear programming approach to test the colour constancy of Nayatani's non-linear chromatic adaptation model. The derived reflectances of Munsell colours had more extrema than usual for real pigments. Moreover, the model does have the scale-invariant property of von Kries and Judd and, therefore, is unable to normalize the illuminant intensity completely.

The colour constancy indices (CCI), the measures of the degree of colour constancy, reported in the literature are all based on Nayatani's non-linear chromatic adaptation model (Berns and Billmeyer, 1983).

A simple colour constancy index based on CAT is as in Equation [6.70] (Berns *et al.*, 1985):

$$CCI(XYZ) = \left[\left(X - X'^{J}\right)^2 + \left(Y - Y'^{J}\right)^2 + \left(Z - Z'^{J}\right)^2 \right]^{1/2} \qquad [6.70]$$

where X, Y, Z are the tristimulus values under reference illuminant and X'^{J}, Y'^{J}, Z'^{J} are the theoretical tristimulus values under the same illuminant obtained by the non-linear CAT proposed by Nayatani *et al.* (1981) from the test illuminant '*J*' having equal appearance as under the test illuminant. Considering a visually uniform CIELAB colour space, hue weighting and normalizing chroma in terms of distance from the neutral point as in McLaren's (1976) optimized colour difference equation, the equation was further modified as follows (Equation [6.71]):

$$CCI(MC) = \frac{\left[\left(\Delta L^*\right)^2 + \left(\Delta C^*\right)^2 + \left(2\Delta H^*\right)^2 \right]^{1/2}}{\left(1 + 0.02C^*\right)} \qquad [6.71]$$

where Δ indicates the difference in respective values of the test colour under the reference illuminant from those derived by non-linear CAT from the test illuminant.

The indices will be higher if there is considerable change in the colour parameters (e.g. hue, chroma or lightness) with the change of illuminant. The indices, therefore, measure colour inconsistency, and not colour constancy.

6.15.2 Inversion models

Inversion models involve simultaneous estimation of the illuminant and reflectance spectra. The first inversion model of colour constancy was proposed by Sällström and detailed by Buchsbaum (1980).

To achieve colour constancy, the model considers both illuminant and reflectance spectra as linear combinations of three known spectra, such as Equations [6.72] and [6.73]:

$$S(\lambda) = \sum_{i=1}^{3} a_i s_i(\lambda) \qquad [6.72]$$

$$\rho(\lambda)=\sum_{k=1}^{3} b_k \rho_k(\lambda) \quad [6.73]$$

The coefficient b_k is estimated from the tristimulus values of a reference white object in the visual field having reflectance $\rho_o(\lambda)$.

A similar inversion model of Weinberg (1976) uses three illuminant spectra which generate Gaussian spectra. The model can be represented as in Equations [6.74] and [6.75]:

$$S(\lambda)=\exp\left[\sum_{i=1}^{3} a_i s_i(\lambda)\right] \quad [6.74]$$

$$\rho(\lambda)=\exp\left[\sum_{j=1}^{3} b_k s_k(\lambda)\right] \quad [6.75]$$

6.15.3 Non-inversion models

As no estimate of the illuminant is necessary, non-inversion models have the potential for greater illuminant invariance than the inversion models. A simple non-inversion model, the volumetric model, is based on the illuminant invariance of tristimulus volume ratios under fairly general spectral conditions (Brill, 1979). The illuminant spectra are a linear combination of N functions, and the reflectance spectra are a linear combination of three known spectra plus a residual term $R(\lambda)$ (Equations [6.76] and [6.77]):

$$S(\lambda)=\sum_{i=1}^{N} a_i S_i(\lambda) \quad [6.76]$$

$$\rho(\lambda)=\sum_{k=1}^{3} b_k \rho_k(\lambda)+R(\lambda) \quad [6.77]$$

$R(\lambda)$ must be orthogonal to the $3N$ product $s_i(\lambda)q_j(\lambda)$ so that

$$\int R(\lambda)\, S_i(\lambda) q_j(\lambda) d\lambda = 0 \quad [6.78]$$

The tristimulus values, Q_j of a test reflectance $\rho(\lambda)$ and P_{jk}, three reference reflectances $\rho_k(\lambda)$ under illuminant $S(\lambda)$ are given by Equations [6.79] and [6.80]:

$$Q_j = \int d\lambda\, S(\lambda)\, \rho(\lambda)\, q_j(\lambda) \tag{6.79}$$

$$P_{jk} = \int d\lambda\, S(\lambda)\, \rho_k(\lambda)\, q_j(\lambda) \tag{6.80}$$

It then follows (Equation [6.81]):

$$Q_j = \sum_{k=1}^{3} P_{jk} b_k \tag{6.81}$$

In vector notation, $Q = Pb$, or $b = P^{-1} Q$, where P is 3×3 matrix and Q and b are column 3 vectors.

The advantages of the volumetric model are:

1. Unlike the von Kries and Judd models, it has the advantages of realistic spectral assumptions
2. Computation is easier, as compared to the Weinberg model
3. For $N = 3$, it invokes spectral constraints sufficient for the Sällström-Buchsbaum model as $R(\lambda)$ does not affect computation.
4. For a large value of N, a high degree of illuminant invariance is achieved.

The volumetric model, however, requires three reference reflectances, as compared to one reference for the other models.

In all the non-inversion models, the relations between multiple objects are hypothesized as the basis for colour constancy, because colour constancy is more powerful in complex visual scenes.

Brill (1987) further showed that most of the non-adaptation model can be put into an adaptation framework. In a volumetric model, the following equation may be written for the two illuminant spectra $S_\alpha(\lambda)$ and $S_\beta(\lambda)$ (Equation [6.82]):

$$b = P_\alpha^{-1} Q_\alpha = P_\beta^{-1} Q_\beta \tag{6.82}$$

where the subscripts α and β refer to the two illuminants, and b is illuminant invariant. The corresponding adaptation model is (Equation [6.83]):

$$Q_\beta = P_\beta P_\alpha^{-1} Q_\alpha \tag{6.83}$$

The transformation between adaptation states depends on the reference reflectances and on the two illuminants, but not on the test reflectance (Equation [6.84]), i.e.

$$T_{\beta\alpha} = P_\beta P_\alpha^{-1} \qquad [6.84]$$

Although linear models of colour constancy are convenient for representing illuminant and reflectance spectra, non-linear models may more accurately represent visual physiology. Two models exist at present – one by Brill and another by Weinberg. Brill (1988) proposed a logarithmic relation of response to stimulus intensity. The cooperation between lighting and reflectance design may strive for several goals, provided the colour stability under change of illumination is precisely dictated. Colour constancy is difficult to define and measure perfectly, but awareness of its subtleties should bring rewards. In spite of the fact that a vast amount of experimental and theoretical information is available on chromatic adaptation, the underlying physiological mechanisms are not yet obvious. The colour constancy was earlier thought to be a part of the adaptation process, but some differences between the two phenomena have created confusion about their inter-relation.

Visual systems do not achieve perfect colour constancy, and colour constancy models should be able to predict how long colour constancy persists in a given varying illuminating environment. Suitable constraints are still missing for most of the models for predicting the above phenomenon. Influence Theory (Stine and Sparrow, 1989) has been proposed to predict the failure of colour constancy, by emphasizing the effects of the distribution of reflectances on the colour appearance of a scene.

6.15.4 Colour inconstancy index CMCCON02

In 1997, the Colour Measurement Committee (CMC) of the SDC proposed a method for predicting the degree of colour inconstancy, named CMCCON97, based on a particular CAT, CMCCAT97 and a suitably chosen colour difference equation. Since the publication of the work on CMCCON97 (Luo *et al.*,1999), the concept of predicting colour inconstancy has been well received. Many colourists have realized that minimizing the metamerism between a standard and a sample may not be as important in many cases as producing a sample with a high degree of colour constancy. As demonstrated by the earlier example, if there is large colour inconstancy in the standard used, any matching sample produced will also be colour inconstant if it has low metamerism. Hence, computer system developers for colour quality control and recipe formulation have implemented CMCCON97 for evaluating colour inconstancy.

A reliable colour inconstancy index depends upon an accurate CAT, which is used to predict corresponding colours (a pair of colours having same colour appearance when viewed under a reference and a test illuminant). In 2000, CMCCAT97 was modified to become MCCAT2000 (Li *et al.*, 2002). It was refined to fit all available experimental data sets (Luo and Hunt, 1998b), rather than only the Lam and Rigg data which were used to derive CMCCAT97 (although CMCCAT97 had been tested with all the available experimental data and found to give better agreement than alternative CATs then available). This resulted in an overall improvement to fit almost all data sets. More importantly, in many applications there is a need to use the reverse mode of the transform for obtaining corresponding colours from the D65 reference illuminant to the other illuminants. (The forward mode of transform can only transform coordinates from other illuminants to D65.) The CMCCAT97 formula includes a power factor applied to the blue channel. It can only be solved iteratively in the reverse mode of the transform (Li *et al.*, 2000). The CMCCAT2000 formula removes this problem by simplifying its structure. Sobagaki *et al.* (1999) showed that the CMCCAT97 gives large errors for predicting corresponding colours under the very dim saturated yellow illumination used in one of the McCann experimental phases. Later, a new model, the CAT02 model (Fairchild, 2001), was developed by fitting all available datasets except the McCann data with the same structure as CMCCAT2000. It is now included in the CIECAM02 adopted by the CIE (Luo *et al.*, 2003).

The procedure followed step by step to calculate the colour inconstancy index CMCCON02 (Safi, 2014) is as follows:

1. Determination of the tristimulus values of the sample under the illuminant D65 (Xr, Yr, Zr) and under the agreed test illuminant (X, Y, Z).
2. Calculation of the RGB cone responses to the sample (R,G,B) and to the reference white or the perfect reflecting diffuser under the test illuminant (Rw, Gw, Bw) and the illuminant D65 (Rwr, Gwr, Bwr) according to Equation [6.50]. The values of Y_W, Y_{Wr} are also adjusted to 100.
3. Calculation of the corresponding RGB cone responses by Equation [6.85]:

$$\begin{aligned} R_c &= R\left[D(R_{Wr}/R_W)+1-D\right] \\ G_c &= G\left[D(G_{Wr}/G_W)+1-D\right] \\ B_c &= B\left[D(B_{Wr}/B_W)+1-D\right] \end{aligned} \qquad [6.85]$$

4. Calculation of the tristimulus values of the corresponding colour under the illuminant D65 by Equation [6.86].

$$\begin{bmatrix} X_C \\ Y_C \\ B_C \end{bmatrix} = M^{-1}_{\text{CAT02}} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix}$$

$$M^{-1}{}_{\text{CAT02}} = \begin{matrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.05698 & 1.015326 \end{matrix} \qquad [6.86]$$

5. Calculation of the colour difference between the tristimulus values of the corresponding colour under the illuminant D65 (Xc,Yc,Zc) and those measured for the sample under the illuminant D65 (Xr,Yr,Zr) as the reference illuminant. Commonly, the colour difference equation ΔE^*_{ab} is applied (Equation [6.87]).

$$\Delta E^*_{ab} = [(L^*_C - L^*_r)^2 + (a^*_C - a^*_r)^2 + (b^*_C - b^*_r)^2]^{0.5} \qquad [6.87]$$

where L^*, a^* and b^* are the tristimulus values, or the colour parameters in the CIELAB colour system. The ΔE^*_{ab} value obtained from Equation [6.87] shows CMCCON02 colour inconstancy index (CII).

6.16 Conclusion and future trends

It has been recognized that there are significant aspects of colour appearance phenomena that are not described well, if at all, by models such as CIECAM97s or CIECAM02. These aspects include accurate metrics of colour differences, spatial aspects of vision and adaptation, temporal appearance phenomena, image quality assessment (or differences in appearance of complex stimuli) and image processing requirements.

Colour difference measurement has been treated separately from colour appearance modelling through the formulation of complex colour difference equations, such as CIE94 and CIEDE2000, built upon the foundation of CIELAB. These equations represent a significant improvement in colour tolerance prediction relative to the Euclidean DE^*_{ab} metric, but might be more complex than warranted by available data or useful in practical situations (in the case of CIEDE2000). A next generation colour difference formula will almost certainly be based on fundamental improvements in the colour space itself, and that provides an opportunity to bring together the colour appearance and colour difference models and formulae.

It is clear that many ideas for improved types of colour appearance models have been outlined, and that the time might be appropriate for a revolutionary change in the way colour appearance models for cross-media image reproduction are formulated. The requirements for such a model include simple implementation for images, spatially localized adaptation and tone mapping for high-dynamic-range images and other spatial phenomena, accurate colour appearance scales for gamut mapping and other image editing procedures, spatial filtering for visibility of artefacts, and colour difference metrics for image quality assessment. While various models or algorithms are available to address each of these aspects individually, none exist with all of these capabilities simultaneously. Such a model might well represent the next logical progression in colour appearance modelling. The framework and implementation of a model of this type, called iCAM, has been described by

Fairchild and Johnson (2014). The process is to start with tristimulus values for the stimulus and adapting white point and luminance values for the adapting level and surround. The tristimulus values are transformed to RGB values that are utilized in a linear, von Kries adaptation transform identical to that proposed for CIECAM02. The adapted signals are then transformed into the Image Processing Transform (IPT) colour space to take advantage of its accurate constant-hue contours and lightness and chroma dimensions similar to CIELAB. Ebner and Fairchild (1998) described a colour space, IPT, for image processing applications in which constant-hue lines represent perceived constant hue to a high degree of accuracy.

The adapting and surround luminance levels are used to modulate the non-linearity in the IPT transform to allow for the prediction of various appearance phenomena. A rectangular-to-cylindrical transformation is performed on the IPT coordinates to derive lightness, chroma, and hue predictors and the adapting luminance information is then used to convert these to brightness and colourfulness predictors. Saturation can be easily derived from these. Colour difference metrics are then built upon the appearance correlates. While the iCAM framework is in place and its performance for various tasks is already quite good, there is clearly much room for improvement and enhancement through the collection and analysis of new types of visual image appearance data (Fairchild and Johnson, 2014).

For colour matching, it is desirable to produce colour-constant samples, i.e. samples which maintain the same colour appearance under a wide range of illuminants. The recommended CII, CMCCON02, is an improvement over the earlier CMCCAT97 method and will provide a good measure for indicating the degree of colour inconstancy. The CMCCON02 index is in the process of becoming part of the ISO 105-J series on colour fastness test standards (Luo *et al.*, 2003).

6.17 References

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