# An Eye for All Seasons

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## Abstract

The human visual system is able to adapt its sensitivity so as to compensate, to a considerable extent, for changes in the level and the color of the illumination. The means whereby this adaptation is provided include: changes in the diameter of the iris; changes between cone and rod vision; bleaching of the visual pigments in the receptors; adjustments to the amplification of the electronic signals produced by the receptors; and cortical effects. The extent of the compensation is not complete, so that the color appearance of objects is only approximately constant. Because original scenes and images often involve various levels and colors of illumination, the effects of this incomplete adaptation can have important implications for producing satisfactory pictures. The recent availability of an agreed Color Appearance Model (CIECAM97s) with its included Chromatic Adaptation Transform (CAT97), and a derived Color Inconstancy Index (CON97), now make it possible to allow for these effects quantitatively.

## Introduction

The visual system has a remarkable ability to change its state in response to changes in the stimuli presented to it. For instance, if two patterns of differently spaced lines are viewed for a few seconds, subsequent viewing of two sets of lines having the same spacing will appear to have different spacings if they are seen in the parts of the field previously occupied by the sets of differently spaced lines.

In normal viewing tasks, enormous changes in the level of illumination can be encountered. It is possible to see, although not with equal facility, over a range of illumination levels of 100 million to one ($10^8$ to 1). This is possible because of the processes of *adaptation*. Typical circumstances in which various levels of illumination are encountered are as follows[1] (1 lux, the unit used for expressing measurements of the level of illumination, is the illumination provided by 1 lumen of light spread uniformly over 1 square metre):

| | | | |
|---|---|---|---|
| Bright sunlight | 100000 | lux | $10^5$ |
| Dull daylight | 10000 | lux | $10^4$ |
| Shop windows | 1000 | lux | $10^3$ |
| Living rooms | 100 | lux | $10^2$ |
| Good street lighting | 10 | lux | $10^1$ |
| Poor street lighting | 1 | lux | $10^0$ |
| Full moon | 0.1 | lux | $10^{-1}$ |
| Crescent moon | 0.01 | lux | $10^{-2}$ |
| Bright star light | 0.001 | lux | $10^{-3}$ |
| Dim star light | 0.0001 | lux | $10^{-4}$ |

The colors of illumination met with in practice can also vary considerably, and it is possible to recognize the colors of objects with remarkably good consistency over a wide range of illuminant colors. This is possible because of the process of chromatic adaptation; when there is no change in the appearance of a color it is said that *color constancy* occurs.

## Means of Adaptation

The means by which adaptation is achieved include the following five phenomena: changes in pupil diameter, changes between cone and rod vision, retinal pigment bleaching, changes in cellular activity, and cortical changes.

### Pupil Area

The adult human pupil has a maximum diameter of about 8 mm and a minimum diameter of about 2 mm (although there are variations among observers[2]). This might be expected to provide an adjustment for illumination level of the ratio of the corresponding areas, $8^2/2^2$, or 16 to 1. But the cones are less sensitive to the off-axis rays (Stiles-Crawford effect[3]); hence the effective adjustment is only about 10 to 1. This can therefore provide only a very small part of the adjustment needed over the 100 million to 1 range encountered in practice. An important function of changes in pupil diameter is to reduce the effects of sudden changes in level of illumination. Of course, changes in pupil diameter cannot compensate for changes in the colors of illuminants.

### Receptor Type

The rods are somewhat more sensitive than the cones and this provides some increased sensitivity at low levels of illumination. But a far more important factor is that there are many more rods than cones (about 100 million rods and only about 6 million cones in each eye), and, because these receptors are served by only about 1 million nerve fibres connecting them to the cortex, the outputs from many rods (on average about 100) are fed into single nerve fibres, with consequent large improvements in signal-to-noise ratios. The rod system therefore provides higher sensitivity at low levels of illumination, as required to provide compensation. The level at which the change from cones to rods takes place is such that above about 10 lux greater use is made of the cones, and below about 0.1 lux greater use is made of the rods.

### Pigment Bleaching

Bleaching of the photo-sensitive retinal pigments results in less unbleached pigment being present at high, than at low, levels of illumination, and this would reduce sensitivity at high levels, as required for compensation. However, metameric matches are not upset by changes of adaptation over the normal range of illumination levels[4]. Because metameric matches depend on the different spectral compositions resulting in equal cone signals, the changes in sensitivity caused by adaptation must not alter the shapes, but only the heights, of the cone sensitivity curves. But bleaching does alter the shapes of these curves: at high pigment concentrations the spectral sensitivity curve tends to be broad and flat-topped because most of the light is absorbed (at an infinitely high concentration the curve would be flat throughout the spectrum because all the light would be absorbed at all wavelengths); on the other hand, at low concentrations, the spectral sensitivity curve would depend markedly on the different proportions of the light absorbed by the molecules at each wavelength. Hence, because the independence of metameric matches on the state of adaptation requires the sensitivity curves to remain the same shape, it follows that the cause of adaptation cannot be mainly pigment bleaching. Some pigment bleaching does occur, but it is only significant at very high levels of illumination, probably above about 10 000 lux for cones (at which levels metameric matches do break down[5]) and above about 100 lux for rods. However, for the rods to reach maximum sensitivity in the dark requires the visual pigment to reach a very high level, and this may take up to 30 minutes[6].

### Cellular Changes

Most of the changes in sensitivity in the visual system seem to be cellular in origin[7]. The electrical potentials generated by the receptors, as a result of stimulation by light, are relayed by a series of neurons to the ganglion cells where signals consisting of nerve impulses are generated for passage up the optic nerve to the cortex. These neurons are apparently able to adjust the magnitudes of their output signals in such a way as to compensate for large changes in the stimuli viewed by the eye. Overall adjustments provide compensation for changes in illumination levels, and different adjustments of the outputs of the three different types of cone provide compensation for changes in illuminant colors.

### Cortical Changes

Some changes in color appearance occur so rapidly, and are so dependent on interpretive factors, that it seems likely that they are cortical in origin. For instance, a cyan filter can be used to cover a yellow object on a slide so that, when projected, the object looks green; but if the same filter is put, not just over the object on the slide, but over the whole of the slide, then, when it is projected, the same object looks yellow not green. The same filtering of the object has occurred in both cases; but the overall cyan cast of the slide in the second case is compensated by the visual system with the result that the object still looks yellow. The effect is so rapid that it is likely that it is cortical in nature. This type of effect is sometimes referred to as *cognitive* or *discounting the color of the illuminant*.

## Color Constancy in Practice

Over the range of illumination levels at which vision is mainly mediated by the cones (from about 10 to about 100 000 lux), and for illuminants that contain a significant amount of light throughout the spectrum, the colors of objects can be recognized with considerable precision. This color constancy, although only approximate, is extremely useful. It means that colors can be identified more or less independently of the level or the color of the illumination. Without the phenomenon of color constancy our ability to recognize objects by their colors would be greatly handicapped. In imaging, illuminants of many different levels and colors are encountered, and hence an understanding of color constancy is very necessary.

### The Extent of Color Constancy

Color constancy is only an approximate phenomenon. The following are some of the departures from color constancy that occur in practice:

As the level of illumination falls:

1. There is a progressive reduction in brightness and in colourfulness (this could be caused by lower and lower parts of S-shape response functions being used).
2. Below about 0.1 lux, complete loss of color vision occurs (rod vision).

As the color of the illumination becomes increasingly different from daylight:

3. There is progressive loss of color compensation (e.g. objects look yellower in candle light).
4. There are obvious changes in some colors (e.g. purples).
5. There are large changes in most colors if the illuminant contains only some parts of the spectrum (e.g. low pressure sodium street lights, which contain only yellow light).

As the field size is reduced:

6. There is progressive reduction in adaptation (e.g. projected films, or pictures printed on colored papers).

## Color Appearance Model (CIECAM97s)

The Color Appearance Model recently approved by the CIE (CIECAM97s[8]) has features built into it that represent adaptation by the cones (but not by the rods) to changes in the level and the color of the illumination; S-shape dynamic response functions that result in reduced brightness and colourfulness as the level of the illumination is reduced; the effects of the luminance factor of the background; and the effects of the surround being either *average*, *dim*, or *dark*. By 'average' is meant that the luminance of the surround is approximately the same as that of the average luminance of the displayed colors; by 'dim' is meant that the viewing conditions are typical of those used for viewing broadcast television, where the picture fills the whole of the display which is surrounded by areas of substantially lower luminances; by 'dark' is meant that the viewing conditions are typical of those used for projecting film, either slides or motion pictures, in good conditions where the projected image is seen in an environment where the surrounding luminances are extremely low. When images are seen on monitors, the surround may not be effectively 'dim'; this is particularly true if the images are surrounded on the monitor by a narrow white border beyond which is a larger gray border extending to the edge of the display device[9]; in this case, the appearance of the image can often be very similar to that of a reflection print, so that the average surround may be the appropriate one to select for the Color Appearance Model.

## 1997 Color Inconstancy Index

In various industries, particularly the colorant industries, an important issue is the degree to which colors change in appearance when the color of the illuminant is changed. This can be checked visually by observing samples under various light sources, but this is not easy to do. If the sources are changed rapidly, the eye does not adapt properly. If enough time is allowed for full adaptation, it is difficult to remember the color seen under the previous light source. This problem arises in imaging when making reflection prints which are likely to be viewed under illuminants having a wide range of spectral power distributions. An instrumental method is therefore desirable, and is essential in colorant-recipe prediction where many possible dye combinations might be considered, but no samples made for visual inspection; a similar situation can arise in selecting inks for printing systems in imaging.

An instrumental method must be based on a chromatic adaptation transform, and one that performs very well is the one that has been incorporated into the CIECAM97s Color Appearance Model[10]. Such a transform allows the tristimulus values for corresponding colors to be calculated. These are colors which look the same under two different illuminants. For example, if measurements have been made of the values of $X$, $Y$, and $Z$, for a sample under a test illuminant, for example Standard Illuminant A ($S_A$) or a particular type of fluorescent lamp, a chromatic adaptation transform can predict the values of $X$, $Y$, and $Z$ for a color that looks the same under a reference illuminant, for example $D_{65}$. If the values for $X$, $Y$, and $Z$, computed in the usual way, for the sample under the reference illuminant are different from the values computed by the transform, then the magnitude of the color difference, $\Delta E$, can be used as a measure of the color inconstancy of the sample when the illuminant is changed from the test to the reference. ($\Delta E$ can be evaluated using a conventional color difference formula because the reference illuminant is of daylight color), Although the CIE has not yet recommended a Color Inconstancy Index, the adoption of a chromatic adaptation transform in the color appearance model CIECAM97s, makes it possible to derive such an index that is compatible with it by virtue of using the same transform. It is convenient to refer to such an index as *CON97*, and the chromatic adaptation transform as *CAT97*. Details of CON97 and CAT97 are given elsewhere[10,11], but the main steps in computiong CON97 are as follows.

The degree of color inconstancy for a sample is computed as follows[11].

1. The tristimulus values, $X$, $Y$, $Z$, of a sample in a test illuminant are measured or computed, and the values $X_r$, $Y_r$, $Z_r$, of the sample in a reference illuminant are measured or computed similarly. (The difference between $X_r$, $Y_r$, $Z_r$ and $X$, $Y$, $Z$ is the *illuminant colorimetric shift*.)

2. Using the 1997 chromatic adaptation transform[10] (the one used in the CIECAM97s Color Appearance Model) with the $D$ factor set to 1.0, the tristimulus values, $X$, $Y$, $Z$, are used to compute the tristimulus values, $X_c$, $Y_c$, $Z_c$, for the corresponding color in the reference illuminant. The $D$ factor is set equal to 1.0, because otherwise the Inconstancy Index for the perfect diffuser would not be zero, and this white is usually regarded as being color constant. (The difference between $X$, $Y$, Z and $X_c$, $Y_c$, $Z_c$ is the *adaptive color shift.*)

3. Using a suitable color difference formula, the color difference, $\Delta E$, defined by the difference between $X_c$, $Y_c$, $Z_c$, and $X_r$, $Y_r$, $Z_r$ is computed. This difference, $\Delta E$, provides the 1997 Color Inconstancy Index.

Notes

1. The $X$, $Y$, $Z$ tristimulus values used may be either for the CIE 1931 Standard Colorimetric Observer or for the CIE 1964 Supplementary Standard Colorimetric Observer, but it must be made clear which Observer has been used (and, if the latter, all the symbols for colorimetric measures must have a subscript 10).

2. Both the illuminants must be specified, and the reference illuminant should normally be $D_{65}$; if a different reference illuminant is used its details must be clearly stated.

3. It must be clearly stated which color difference formula has been used.

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