POSITIVE COLOR MATCHING

In the process of living, we receive information and make decisions largely on the basis of what we see. Normally, we examine objects to determine their desirability or usefulness to us. Appearance involves all aspects of visual attributes by which things are recognized. Color is the most important optical attribute of product appearance although other attributes, like gloss, luster, turbidity, etc. are also obviously important. Buyers have strong preferences for products whose appearances appeal to them. The appearance should be uniform and constant from day to day. Nonuniform appearance is associated with a product of uneven, and even poor quality, with lack of quality control.

Accurate color matching is important in many industries, some of which are:

- Textile fibers, yarns and fabrics
- Plastic resins, moldings and films
- Paints and protective coatings
- Ceramic bodies, glazes, white wares, portland cement and plaster
- Foodstuffs and beverages
- Cosmetics
- Papers of all types
- Pigments and dyestuffs
- Inks, graphics, reprography, printed papers, and packaging materials

Color uniformity has such economic importance that a whole industry has built up around the color matching requirement to produce instruments that give an indication of the degree of match.

LIGHT

Light is a form of energy that occupies only a small portion of the whole ELECTROMAGNETIC RADIATION SPECTRUM (See Fig. 1) ranging from the highest energy γ (gamma) rays to the lowest energy (longest wavelength) radio waves. Light is the portion of the spectrum that stimulates the human eye and as such has ill-defined limits, depending upon the total amount of energy available and the particular observer. More will be said later about observer dependent effects.

The unique characteristic of electromagnetic radiation is its frequency of vibration and since the velocity in vacuum is
the same for all these radiations, inversely proportional to
the frequency is the wavelength. The radiations consist essentially
of electromagnetic disturbances transmitted as displacements
transverse to the direction of propagation. If the origin, or
the originating disturbances of the electromagnetic field is with-
in the nuclei of atoms, it gives rise to $\gamma$-rays with frequencies
of $10^{19}$ Hz, lower frequencies of $10^{17}$ Hz have their origin in the
inner atomic electron shells and lead to the emission of X-rays;
light of frequency about $10^{15}$ Hz originates in the outer electron
shells of the atom; infrared and radio waves of $10^{13}$ Hz and less
in vibrations of atoms within molecules, rotation of molecules
and so on.

For most practical purposes light can be considered to be a form
of energy, radiated as a transverse harmonic motion over a fre-
cquency range between $3.8 \times 10^{14}$ and $7.9 \times 10^{14}$ Hz. More usually,
light is characterized by its wavelength instead of frequency
ranging from 380 nm (3800 Angstrom Units) in the deep violet to
780 nm (7800 Angstrom Units) in the deep red.

With a dark-adapted eye and an especially intense source, the
limits may be extended down to 350 nm at the short wavelength end
and up to 900 nm at the longer end, the limits being set by ab-
sorption in the eyes optical media at the lower end and by the
retina's lack of photochemical reactivity at the higher end.

LIGHT SOURCES

The most common light sources are the sun, incandescent lamps,
and mercury vapor (flourescent) lamps. These light sources, like
practically all energy sources, do not emit equal quantities of
energy at all wavelengths. The sun emits maximum energy near
530 nm (green) and lesser energy towards the infrared and ultra-
violet regions. Fluorescent lamps provide very intense narrow
bands of energy at the mercury line wavelengths (405, 408, 436,
546, 577 and 579 nm) with lesser quantities between these lines.
Incandescent lamps have maximum emission near 900 nm (near infra-
red). If the filament temperature is increased by using higher
voltage, this peak will move toward lower wavelengths to provide
a greater proportion of blue light, while lower temperatures
produce relatively more red light. The term color temperature
is used to denote the relative proportion of different wavelengths
emanating from a source. In a strict sense, the term color
temperature should only be applied to "black body" emitters such
as incandescent lamps. As a point of reference, typical incandes-
cent bulbs have color temperatures of 2800$^\circ$K, mid-day sunlight
has a color temperature of 5400$^\circ$K, and candles produce a color
temperature around 1900$^\circ$K. Thus, there is a considerable differ-
ence in color temperature between different light sources, which
results in a considerably different color composition. The ratio
of the blue to red light is very dependent on the color tempera-
ture and differences in color temperatures are responsible for
greatly altering the appearance of an object when it is viewed
under these different illuminants.
TRANSMITTANCE AND REFLECTANCE

Both the intensity and wavelength characteristics are altered when light passes through or is reflected by another medium. If light passes through or is reflected by a gray or black surface, all wavelengths are absorbed equally and little change in color composition is experienced. If the light passes through or is reflected by a red surface, red wavelengths will be only slightly absorbed, whereas, other wavelengths are absorbed to a greater extent. Thus, we have both nonselective and selective wavelength absorption occurring whenever light interacts with another medium. Nonselective wavelength absorption determines how dark the substance appears, while selective wavelength absorption determines the color of the substance. It is important to understand these two phenomena, since this explains why a black object can have exactly the same color composition as a white object. Only the total nonselective absorption is different.

HUMAN COLOR PERCEPTION

Color is an extremely complex psychological response to a physiological stimulus. The human brain utilizes at least nine separate parameters to evaluate the color of an object. Only three of these parameters can be evaluated by present day technology, brightness, hue, and saturation. Brightness is a measure of the gray quantity. As increasing quantities of gray or black are added to a color, the brightness (reflectivity) will decrease. Hue refers to the relative proportion of each primary color, i.e., one object is bluer, yellower, or redder than another. Saturation refers to the purity or whiteness, i.e. pink versus red, pale blue vs. deep blue.

The sensitivity of human color discrimination for two side-by-side samples cannot be equalled by any instrument if all secondary parameters are kept constant. However, the apparent brightness, hue, and saturation is not only affected by the object itself, but also by the light source, the color characteristics of nearby objects, and the viewing angle. Furthermore, no two individuals have the same degree of perception, and no individual can remember the precise color shade for more than a second.

METAMERISM AND COLOR MATCHING

Metamerism may be defined as the phenomenon of identity of color appearance between optical stimuli of different spectral composition. In some color matches the difference in spectral composition may be small and in others considerably different. Evidently there are varying degrees of metamerism.

In commercial color matching of dyes and pigments, it is important that the metamerism be kept to a minimum because items that are dyed or pigmented and matched under one illuminant are unlikely to match under another illuminant. The higher the degree of metamerism the greater the mismatch. Similarly, the greater the spectral differences of the illuminants, the more sensitive will be the detection of metamerism.
The special lamp in the CM-100 Cabinet is particularly rich in light in the 420 and 660nm region of the spectrum and lacking at the prime colors near 450, 540 and 610 nm, which tend, when present in an illuminant, to make a natural daylight match persist.

The manufacturer can examine his products for the initial match under the daylight source in the CM-100 and then under the special lamp rich in 420 and 660nm. He can note any mismatch remaining and be assured that no customer will view his products under less favorable conditions for a match. At this stage, steps can be initiated to reduce the mismatch in his product.

WHY DOES METAMERISM OCCUR?

Metamerism is a unique sensory phenomenon and has its origin in the perception of color through three retinal processes with broad overlapping spectral sensitivity curves such as those illustrated in Fig. 2. Once the light incident on the retina has been absorbed in the three groups of receptors, all record of the spectral composition of the incident light is lost. We are left instead with three levels of activity in the red, green and blue processes. Two stimuli can therefore give rise to the same color sensation, even though they are of quite different spectral compositions, provided they arouse the same levels of activity in the three retinal processes.

The actual absorption of the light quanta in the chromophores of the photochemical substances in the receptors will no doubt produce different patterns of molecular disruption depending on the spectral composition of the incident light, but the signal that is emitted by the receptors into the bipolars and ganglions is presumably determined by the total energy absorption. If the curves of Fig. 2 are accepted as the sensitivity curves of the actual physiological processes, two light stimuli will therefore be metameric if they react equally with these sensitivity curves. Expressed algebraically, this means that if two stimuli which are metameric have spectral distributions \( P(\lambda) \) and \( P'(\lambda) \) and if the sensitivity curves of the three processes are \( s_1(\lambda), s_2(\lambda), s_3(\lambda) \), then

\[
\sum (P_\lambda \cdot s_{1\lambda}) = \sum (P'_{\lambda} \cdot s_{1\lambda}) \\
\sum (P_\lambda \cdot s_{2\lambda}) = \sum (P'_{\lambda} \cdot s_{2\lambda}) \\
\sum (P_\lambda \cdot s_{3\lambda}) = \sum (P'_{\lambda} \cdot s_{3\lambda})
\]

While these equations lay down the stimulus relations that must be satisfied for metamerism, they give no indication at all of its degree. To assess this we have to know the spectral distribution of the components in each of these summations.

The problem can best be understood by studying the curves in Fig. 4 for the metameric pair A and B of Fig. 3(a), and the curves in Fig. 5, for the metameric pair E and F of Fig. 3(c), as seen under illuminant C* of the National Bureau of Standards.

*This illuminant is intended to be representative of daylight and obtained by using a particular gas-filled tungsten lamp in combination with filters.
The two diagrams in Fig. 4(a) give the products (P, β₂, S₁) and (P, β, S₁) plotted against λ. In Figs. 4(b) and (c) the corresponding products for S₂ and S₃ are given; similar pairs of diagrams are shown in (a), (b) and (c) of Fig. 5. The curves in Figs. 4 and 5 are in effect the tristimulus distribution curves for the metameric stimuli and the condition for metamerism is that the areas under each pair of curves should be equal.

The degree of metamerism, on the other hand, is given by the difference in shape of these distribution curves. Clearly in Fig. 4 there is a major difference in shape for each pair of diagrams, and these patterns are therefore highly metamerism. On the other hand, the difference in shape between each pair of curves in Fig. 5 is relatively slight and the degree of metamerism is correspondingly small.

In passing it should be noted that although metamerism is related to the physical composition of the matching stimuli, a straight comparison between their spectral distributions would take no account of the varying sensitivity of the eye to different wavelengths. Thus, if a metamerism pair possessed a major difference in spectral composition at the far end or far violet ends of the spectrum, this might suggest a high degree of metamerism, yet because the eye has only a limited sensitivity to these wavelengths, this conclusion might be quite misleading. It is only after the energy distributions have been weighted by the sensitivity curve of the retinal receptors that a true assessment of the metamerism is possible. We should also note that the degree of metamerism could well be different for each of the three processes S₁, S₂ and S₃.

The spectral reflectance curves of metameric surface colors are characterized by the common feature that the pairs of curves cross each other at least three times within the visible spectrum.

Moreover, each crossing point tends to be located near to the three maxima of the sensitivity curves of Fig. 2. Only if this occurs will it be possible for the higher reflection which one of the fabrics possesses at wavelengths on one side of a cross-over point to be balanced against the lower reflections at wavelengths on the other side of a cross-over point for each of the three processes. The precise points of intersection will, of course, depend on the particular dyes and on the illuminant for which they are metamerism, but the existence of at least three crossing points is mandatory by virtue of the existence of the three retinal color processes. There can, of course, be more than three.

THE ILLUMINANT MANIFESTATION OF METAMERISM

One of the curious features of metamerism is that when we are looking at a pair of metameric samples which are a match to us under a given illuminant, we are unaware of the metamerism. It is only when some change is made in the conditions of viewing, usually when the quality of the lighting is changed, that we realize the
match under the first illuminant was metameric. This is revealed because under the new illuminant the match breaks down. Oddly enough, because the match no longer holds, the samples cannot then be described as a metameric pair. We might perhaps call them BROKEN METAMERS.

The cause of the color-match breakdown is easy to understand, since the metamerism under the first illuminant depends on a critical balance in tristimulus values as expressed algebraically by the previous equations. Once this balance is upset by a change in the \( P \) \( A \) values, a breakdown in the match must be expected. The magnitude of the mismatch will be a function both of the spectral reflection characteristics of the two samples and of the spectral distributions of the two illuminants.

At least one of the samples, and possibly both, will change in color appearance with the change in illuminant, although in many cases the alteration in appearance may be so slight that it would pass undetected if the second sample were not available for comparison.

However, with certain types of light sources, such as gas discharge lamps, there may be gross color distortion. Also, with certain types of dye, notably those which give a main reflection band in the green and a secondary one in the far red, the color may change from green to brown in passing from daylight to tungsten light. A fabric dyed in this way would therefore be highly metameric relative to a more normal green dye.

DOES THE PARTICULAR OBSERVER AFFECT THE COLOR MATCH OBTAINED?

Variations in density of the yellow macular pigment in the eye of observers of all ages, and the inevitable yellowing of the crystalline lens with age has a significant effect on metameric matches.

The main difference between a lightly pigmented observer and one with heavy pigmentation is the reduction in amount of the blue and violet wavelengths in the light reaching the retinal receptors. This is by no means the same as the illuminant manifestation of metamerism, since this owes much of its effect to the excess red energy of tungsten light compared with daylight and fluorescent tubes.

In addition to differences of color vision and discrimination among normal observers, there is about 8% of the male population and a much smaller percentage of the female population that possess more or less grossly defective color vision. The border line between excessive variation from the normal and the initial stages of defective vision is ill-defined, but the outstanding characteristic of "COLOR BLINDNESS" is an inability to detect color differences which may be readily distinguished by the normal observer. A defective observer cannot be employed for making general visual matching measurements because he is unable to repeat his matches with sufficient accuracy or recognize errors in color quality so readily. He is also likely to be handicapped since his description
of a sample may not correspond with that given by a normal person.

**HOW DOES THE SURFACE TEXTURE AFFECT COLOR MATCHING?**

It is sometimes required that materials which are very different in surface texture should be similar in color or at least have the same hue. Examples of this are when the color of a dress has to be matched by the buttons, belt, hat, gloves, handbag or shoes.

The surface finish of these different articles is likely to range from the almost completely matt to the highly glossy. Now a match between a matt and a glossy surface will often, but not always, be possible, but where it is possible it will only hold for some given condition of illumination and viewing. Thus, when the illumination is highly directional, the top surface reflection from a glossy surface is only seen in the highlights and does not contribute to the main body color of the sample.

With diffuse illumination, on the other hand, there are no highlights and the top surface reflection mixes with and desaturates the "true" color of the material. Allowance for changing the illuminating and viewing angles is made in the CM-100 Color Matching Cabinet by having a variable angle sample holder. The phenomenon is often referred to as GEOMETRY METAMERISM, but is quite different in origin from the metamerism that was discussed earlier.

**HOW CLOSE CAN AN OBSERVER MATCH TWO DIFFERENT COLORS?**

In practice, there is a limit to the precision within which a real observer can make a visual match because there are several possible reasons why two stimuli have to differ by a finite amount before a difference in sensation can be detected. It is by no means easy to decide which factors are the most significant in any particular case.

Thus the stimulus itself may not be constant with time, or uniform over its area; the sensitivity of the receptors may vary over the retina or fluctuate from moment to moment; there may be spontaneous discharge in the retina and other sources of physiological 'noise', and the perceptual processes themselves must almost certainly have some discrimination limit, which is likely to be affected not only by the degree of attention that the observer is prepared and able to devote to the task, but also by the inherent interest and significance of the stimulus changes.

Its size will also be governed by the psychophysical relationship between stimulus and sensation as established through the physiological mechanism of the eye and brain.

We can hardly hope to know the exact form of this relationship, but the ability to distinguish between two wavelengths appears to originate in the existence of three types of retinal receptor with different spectral sensitivities. Yet unless there are also different qualities of sensation associated with these different types of receptor, there can be no color discrimination. Hence, for example, defective color vision could have its origin either in the retina or in the brain.
Our powers of discrimination are at their best when we are looking at two adjacent areas of color with a sharp and almost invisible boundary line between them, when the areas are large, when the illumination is good and when we are using unrestricted binocular vision free from any optical encumbrances such as eyepieces or exit-pupils. Moreover, when a trained colourist is matching two pieces of cloth he will transpose them and view them at various angles to the light and to himself, and generally introduce a dynamic element into the viewing situation. This is made possible in the CM-100.

We can understand the reasons for these conditions, since we know from electro-physiological studies of the retina that the receptors are most sensitive to sudden changes of stimulation, and that they react more rapidly when the retinal illumination is high. When comparing or matching two areas of color, the observer will naturally look from one area to the other, and this scanning across a sharp boundary provides just the conditions likely to produce the maximum change in physiological activity for any given difference of stimulus between the two halves of the field.

It is perhaps less easy to explain the need for a large area of color, except that the larger the area the more information available for analysis by the retina and brain. It would seem also as if stimulation of a large number of receptors, accompanied presumably by a correspondingly extensive activity in the brain, is an essential element in the evocation of a full color sensation.

We have also to remember the specific loss of blue sensitivity, leading to small-field tritanopia, which occurs when very small areas are being viewed, (i.e. subtending less than 20 minutes of arc). Evidence suggests that the foveal center is devoid of blue receptors and therefore differs from other retinal areas.

COLOR DISCRIMINATION THROUGHOUT THE SPECTRUM

The spectrum is so fundamental to our understanding of color perception that observations on the ability to discriminate one wavelength from another have always been regarded as of special interest. The basic experiment is as follows: The two halves of a photometric field are illuminated by light of the same wavelength and their luminances are adjusted to be equal. The wavelength of one half of the field is then gradually changed to \( \lambda \pm \Delta \lambda \) until a difference in color between the two halves of the field can just be detected, the luminances meanwhile being maintained equal. The difference that is detected is then solely due to the change in wavelength. If the experiment is repeated for other values of \( \lambda \) through the spectrum, \( \Delta \lambda \) can be plotted against \( \lambda \) to give the wavelength discrimination curve, a typical curve as recorded in one investigation being shown in Fig. 6.

With the 2° field of view a wavelength difference of about 1nm in the yellow-orange and blue-green parts of the spectrum gave rise to a just detectable color difference. Under larger-field conditions, a smaller wavelength difference would be noticeable in these regions of the spectrum and color matches could be repeated to an even higher precision.
Figure 1. Electromagnetic Radiation Spectrum

Figure 2
Set of Color Sensitivity Curves of the Receptor Processes
Spectral reflection curves of pairs of dyed fabrics which are metameric under daylight illumination
Figure 5

Figure 6