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Fluorescent Lamps with High Color-Discrimination Capability

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Certain visual tasks require easy discrimination among colors differing only slightly. Much of human color experience involves this problem to a degree. Given an array of colored objects, discrimination among them depends on the illuminant; both its color and spectral power distribution are important. What appear to be optimum color and spectral power distribution have been found, and the capabilities of fluorescent lamps approaching this ideal are described and demonstrated.

ALTHOUGH a number of other sensations such as brightness, contrast, texture, are important, perhaps the essence of human visual experience is noting differences in color. The illumination is often sufficient to allow the observer to discriminate adequately well between the colors of objects, but there are exceptions. Distinguishing the red family car in a parking lot lit by vapor lamps can be difficult indeed. Color-discrimination is completely at the mercy of the illuminant. It is easy to imagine a game of billiards in light composed of a single, pure color, in which it is completely impossible to distinguish between the balls by means of color. Each ball assumes the pure color of the light source, and exhibits only differences in brightness.

Certain visual tasks require easy discrimination among colors with only small differences between them; an example is a wiring task with color-coded wires in numerous colors, some of which are not easily and rapidly distinguishable under common illuminants. Much of human color experience involves this problem to a degree. For such tasks, a light source affording the observer a maximum of color-discriminating capability is desirable. What is called "color-matching" often involves color-discrimination. The difference of interest to us here is that in color-matching, it is desired not to be able to perceive a color difference between two objects under a specified illuminant, while in color-discrimination, perception of a color difference is essential.

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From the billiard-game example we may infer that the chromaticity of the light source is important, that it should not be a pure or spectral color, and therefore should fall somewhere in the central region of the color diagram, and that there may be an optimum source color. From the parking lot experience, we may infer that the composition of the light is important, and that there may be an optimum spectral power distribution of the illuminant which is ideal for color-discrimination.

The purposes of this paper are to show that these inferences are correct, to specify approximately the ideal illuminant for color-discrimination, to show by what factor color-discrimination under the ideal illuminant excels that under conventional illuminants, and to demonstrate the coloration achieved under a fluorescent lamp which approaches the ideal illuminant.

Of the commonly held beliefs that for best color-discrimination the illuminant should be daylight-like, continuous, and white in color, none appears to be valid.

Method of Evaluating a Light Source for Color-Discrimination

Let us use the 1960 CIE u,v uniform color diagram (Fig. 1). A distance anywhere on this diagram corresponds approximately to the same perceived color difference. Let us use the eight CIE test-colors specified in the CRI procedure.[1] These test-colors are specified by their spectral reflectances, and were chosen to represent typical object colors of various hues (red, yellow, green, blue, purple, etc.)

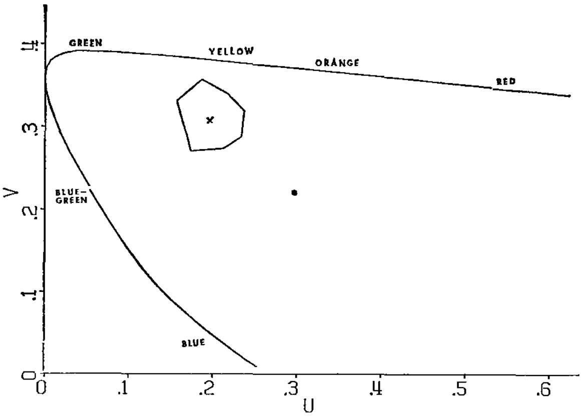

Figure 1. The 1960 CIE, u,v uniform color diagram. Heavy line: boundary of real colors, locus of chromaticities of the pure spectral colors. x: chromaticity of average daylight, illuminant C. Octagonal pattern: plotted chromaticities of the eight CIE test-colors illuminated by average daylight, illuminant C. Heavy dot: point equidistant, on the average, from the spectrum locus.

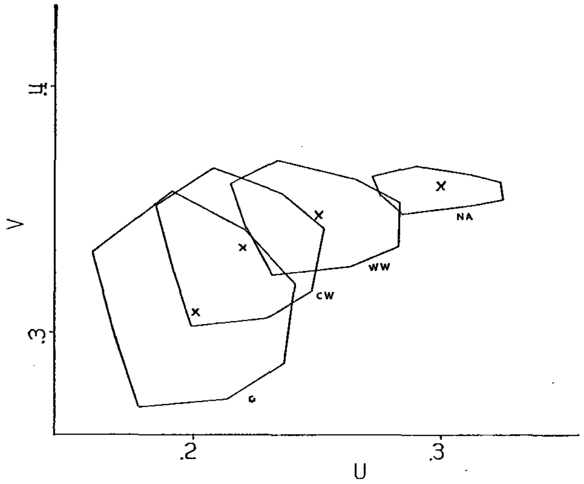

Figure 2. Enlarged area of 1960 CIE color diagram. x: chromaticity of illuminant. Octagonal pattern: plotted test-color chromaticities under that illuminant; the gamut area G, see text. Four illuminants: average daylight (illuminant C), commercial Cool White fluorescent, Warm White fluorescent, and high-pressure sodium lamps.

and medium saturation (chroma). We illuminate the group of eight test colors, measure their chromaticities under that illuminant, and plot the chromaticities on the color diagram. This is done in Fig. 1 using average daylight, illuminant C, as the illuminant. The locations of some of the pure spectral colors, whose chromaticities do not depend on the illuminant and form the boundary of the diagram, are indicated by name in Fig. 1.

Pracejus[2] has suggested the use of the gamut area of the pattern, a plot in the 1960 CIE u,v diagram of chromaticities of an agreed upon set of colored test objects under a given illuminant, as a measure of acceptability of color-rendering of a light source. Thornton[3] has defined a color-discrimination index (CDI) proportional to the gamut area; the larger the gamut area in a uniform color diagram, the greater the average distance (perceived color difference) between the rendered chromaticities of colored objects.

After a few minutes in average daylight, the normal observer is chromatically adapted to that chromaticity ("x" in Fig. 1) and calls it "white." After a few minutes under some other illuminant, with its source color in a very different part of the color diagram, he accepts that part of the color diagram as "white." It has often been pointed out that, for this reason, a certain part of the color diagram should not really be thought of as being associated with a certain perceived color except perhaps when the chromaticity of the light source is specified.

The plotted chromaticities of the eight test-colors always arrange themselves around a center point which represents the chromaticity of the light source itself. If the latter is not too near the boundary of the diagram, which is the locus of chromaticities of the pure spectral colors, the typical observer accepts the light source as white.

The gamut area *G* which we will use as a measure of color-discrimination capability is the area of the octagonal figure determined by the eight plotted chromaticities of the test-colors under the particular illuminant. The mean distance by which the pairs of chromaticities are separated is a measure of the mean perceived color difference and so of the ease of color-discrimination under that illuminant. An illuminant which increases the gamut area, increases the mean distance, and the ease of color-discrimination.

Fig. 2 shows the patterns of area *G* for a few commercial lamps, and again for illuminant C itself.

Chromaticity of the Light Source

Gamut area *G* depends strongly on the chromaticity of the illuminant. The nearer the boundary lies the chromaticity of the light source, the smaller *G* is generally found to be. The gamut of average daylight, illuminant C, is reasonably large (Fig. 2). As the source color of familiar commercial lamps is selected more yellow, their gamut areas are smaller, in order: Cool White fluorescent, Warm White fluorescent, high-pressure sodium, for example. The distance (perceived color difference) between the chromaticities of perceived white in the center of any gamut, and of perceived blue for example, near the bottom of the same gamut, lessens rapidly as source color becomes more yellow. The same is generally true of any perceived object hue and of any color of light source, as that color becomes more saturated. Decreasing distances between rendered chromaticities of objects and their associated white-point results in their becoming paler and less easily discriminated one from another.

It appears that for best color-discrimination, source color should be near the center of the color diagram. One method of defining the "center" of an irregular figure like the color diagram is that point farthest, on the average, from the periphery of the diagram, the locus of spectral colors (the heavy border of Fig. 1). This point of the u,v diagram lies approximately at $u = 0.30$, $v = 0.22$.[4] We may expect the light source chromaticity associated with best color-discrimination to lie in this region.

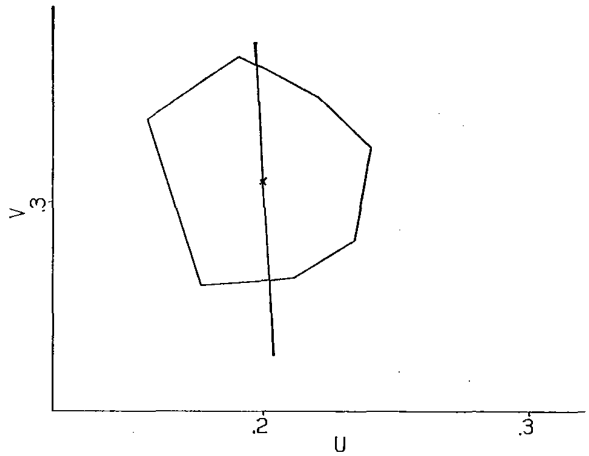

Figure 3. Enlarged area of 1960 CIE color diagram. x: chromaticity of illuminant. Patterns: plotted test-color chromaticities under illuminants of the color of average daylight, illuminant C. Two illuminants: average daylight (illuminant C), light of the same color but composed of two spectral colors (blue and yellow).

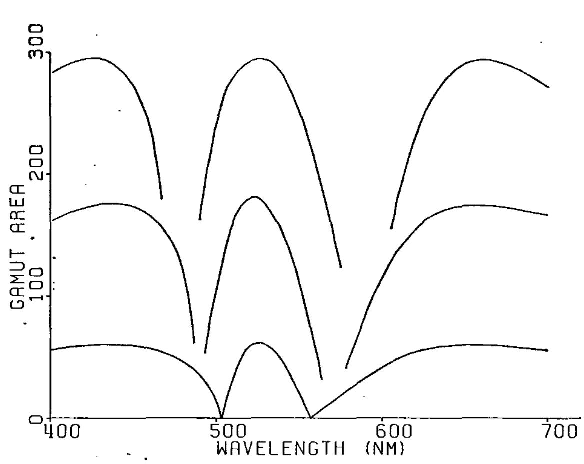

Figure 4. Plot of gamut area G vs wavelength of one variable spectral color. Top set: chosen chromaticity x = 0.32, y = 0.16; light of this chromaticity is composed of three spectral colors, two remaining fixed at 430 nm or 530 nm or 660 nm and the third spectral color varying in wavelength. Middle set: chosen chromaticity x = 0.31, y = 0.32, that of illuminant C. Bottom set: chosen chromaticity x = 0.30, y = 0.50. Gamut area of real daylight (illuminant C) = 100 units.

Spectral Power Distribution of the Light Source

Gamut area G also depends strongly on the spectral power distribution of the illuminant. If daylight-colored light is composed of only two spectral colors, the chromaticities of colored objects illuminated by this light will fall on the straight line connecting the chromaticities of the two spectral colors; the gamut area G will be zero, as shown in Fig. 3, and the light will be of little use for color-discrimination.* In the example shown, of white light matching the color of illuminant C but composed only of blue and yellow spectral lights, a blue-green object may be indistinguishable from a purple one (both appear blue), or a green object from a red (both appear yellow). Real average daylight, as typified by illuminant C, affords far better color-discrimination (Fig. 3) in that there is plenty of room for many hues and saturations to be distinguishable one from another and from white. It is one of the fascinating characteristics of human color vision that, although color-discrimination is very poor under white light composed of only two spectral colors, and far better under white light of the same color composed of a mixture of numerous spectral colors, *e.g.* illuminant C, it is better still under white light of the same color composed of a mixture of exactly three spectral colors, providing those three are chosen with care.

By trial and error it is found that 430, 530, 660 nm is the set of three spectral colors which, mixed in proportions to form light of chromaticity in the central region of the color diagram, yields approximately the largest possible gamut area. Three of the final sets of curves in this iterative method appear in Fig. 4. The wavelengths of two of the three spectral colors are fixed at 430 nm or 530 nm or 660 nm, and the wavelength of the third is varied, always adjusting proportions so as to maintain the chosen color of light. The central set (top to bottom) of Fig. 4 represents a mixture with the daylight color of illuminant C. Largest gamut is achieved with the three approximate wavelengths 430, 530, 660 nm, and its area is about 80 per cent larger than that of illuminant C itself (100 units).

If the best triad of spectral colors is chosen *and* the color of the mixture is chosen to be that of the "center" of the diagram (u = 0.30, v = 0.22), the gamut area G becomes almost three times that of daylight (top curves in Fig. 4).

The contours of gamut area G in Fig. 5 show that the chromaticity of largest gamut is essentially that of the

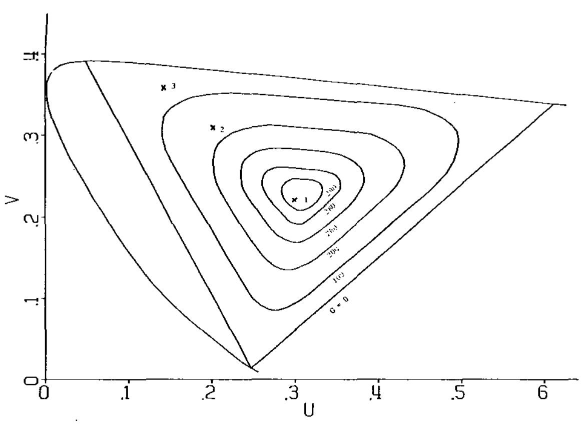

Figure 5. The 1960 CIE u,v diagram. Contours of equal gamut area G, where G = 100 for average daylight, illuminant C. Light of all chromaticities is composed of the three spectral colors 430,530,660 nm. 1: chromaticity of the point equidistant from the spectrum locus. 2: chromaticity of average daylight, illuminant C. 3: the third (greenish) chromaticity of Fig. 4.

* A linear gamut is a case where gamut area is zero, yet some color discrimination is possible. However, such an illuminant will not reliably allow color discrimination, as is pointed out in the text, so the implication of zero gamut area is still fairly reasonable.

center of the diagram; *i.e.* the point equidistant on the average from the spectrum locus. Mixtures of other spectral colors lead to about the same chromaticity of largest gamut.

Similarly, Fig. 4 indicates that light composed of a mixture of spectral colors near 430, 530, 660 nm is close to ideal for color-discrimination whatever the color of the mixture.

We conclude that, for the practical purpose of easy color-discrimination of colored objects, a light source of chromaticity near $u = 0.30$, $v = 0.22$ ($x = 0.32$, $y = 0.16$) and composed predominantly of colored lights centered near 430, 530, 660 nm (Fig. 6) should perform well. Its huge gamut is shown in Fig. 7 compared with those of other illuminants.

Practical Lamps

Three commercial phosphors roughly approximate the required spectral colors: strontium chloroapatite:Eu^{2+} (blue-violet), zinc silicate:Mn^{2+} (green), and magnesium fluorogermanate:Mn^{4+} (deep red). Fluorescent lamps made from a blend of these three phosphors, with chromaticity $x = 0.31$, $y = 0.20$, have been tested visually for their color-discrimination characteristics. The gamut area G of these real lamps is 220 *vs* 290 for the ideal illuminant and 100 for daylight, illuminant C. The gamut of these real lamps is indicated by the dash-dot pattern of Fig. 7.

Illumination by the new lamps has a number of interesting characteristics. The writer has performed normal visual tasks for eight-hour intervals for several hundred hours under the new fluorescent lamps, at a level of about 50 fcd, and twenty other observers have experienced the illuminant for much shorter times. The visual system accepts the source color as white in a few minutes. Coloration of normal office surroundings is very bright. Colored felts of the type commonly used for rough assessments of coloration under a new light source become so bright as to appear fluorescent. White loses its place, as the brightest of colors, to objects with saturated colors. After an hour under the new lamps, the enhanced coloration tends to be accepted as the norm. Daylight-lit scenes appear very green and of drab coloration, and illumination by conventional fluorescent lamps becomes almost monotonous. Because of the enhanced coloration, perceived overall brightness of a scene appears to be higher than that indicated by a footcandle meter, compared to normal fluorescent illumination.

It is quite obvious to the typical observer under the new illuminant that color-discrimination is enhanced by a very large factor. The evidence so far is that the new illuminant is tolerable to work under for long periods. Although the strong coloration is not unpleasant, it is not natural in the sense mediated by the CRI,[1] nor preferred in the sense mediated by the color-preference index (CPI).[5] Hence this work confirms the necessity for a number of indices of quality of light.[6]

The chromaticity of maximum G is near the centroid (center of mass) of the u,v color diagram. It is also near the point equidistant, on the average, from its spectrum locus; as the chromaticity of the light source approaches the spectrum locus, the gamut area G approaches zero, so it is not unexpected that the source chromaticity farthest from the spectrum locus should be the chromaticity leading to largest gamut G. This suggests that this neutral chromaticity is the "natural white" of the human visual system, and that much-greener daylight is our normal white reference

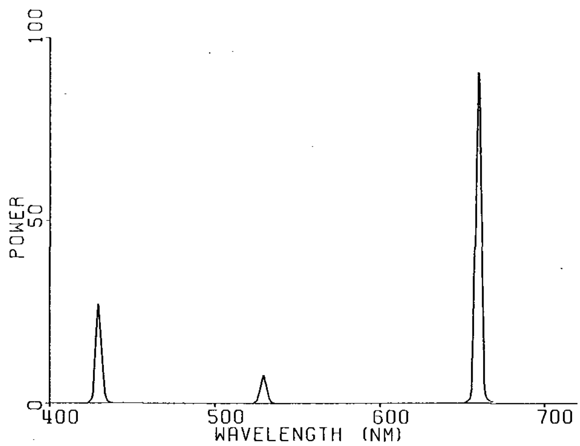

Figure 6. Approximate spectral power distribution of the illuminant ideal in chromaticity and composition for the purpose of color-discrimination.

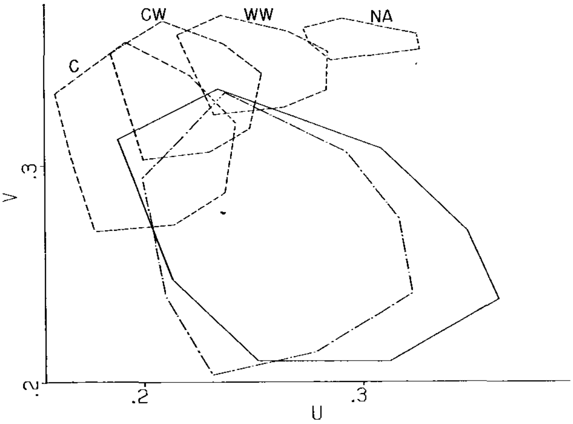

Figure 7. Enlarged area of 1960 CIE u,v color diagram. Heavy line: gamut of ideal color-discrimination illuminant of Fig. 6. Dash-dot line: gamut of real fluorescent lamp approximating the ideal illuminant. Dashed lines: gamuts of average daylight (illuminant C), commercial Cool White, Warm White, and high-pressure sodium lamps.

only by reason of long familiarity.

The coloration produced by real fluorescent lamps of very large gamut area G was demonstrated.

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