Colorimetry and contrast performance of color picture tubes

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Although manufacturers use many technical terms to describe the quality of color television pictures, the ultimate appraisal is made on a purely subjective basis by the viewer. Therefore, it is more important to produce a picture that is "pleasing" to most viewers than to strive for an exact reproduction of an original scene which the home audience does not see. A viewer's subjective appraisal of a color picture depends upon the sensations he experiences as a result of various light stimuli. These sensations are produced by many properties of the light which can be measured and described in absolute values (e.g., total intensity, spectral energy distribution, hue, purity, brightness, contrast, and resolution). This paper discusses audience responses to chromatic stimuli of various hues, and relates the physical properties of these stimuli to the concept of picture "viewability."

VISIBLE LIGHT occupies the wavelength region between 4000 and 7000 angstroms. The spectral energy distribution of a light source is a detailed description of its color composition, i. e., the relative intensity of its light components distributed along this wavelength region. Each of the three phosphors used in color television is a primary emitter of light in a separate region of the visible spectrum, i.e., the three phosphors produce red, blue, and green light.

Color mixing

The triad of red, blue, and green phosphors is important in color television because the proper mixture of these primary emitters produces white light. Addition of any primary color to the white mixture produces the hue of that color; subtraction induces the complement of the primary color. The primary triad, therefore, can generate a countless number of colors (the totality of which is called its *color gamut*), as well as white. (Although this discussion treats the primary triad as pure, spectral, or "rainbow" colors, it also applies to the phosphors used in commercial color television, which have less sharply peaked spectral distributions.)

The standard color mixing diagram shown in Fig. 1, which was adopted by the International Commission on Illumination in 1931, illustrates the pairs of complementary colors generated by the primary triad. Because the proper mixture of complementary colors produces white, the straight line connecting each pair passes through the white, or neutral, point. The location of this point on the connecting line is an indication of the effectiveness of each primary color in neutralizing its complementary color. For example, blue light neutralizes its complement, yellow light, very effectively; red and green are less effective in neutralizing their respective complements, cyan (blue-green) and purple. (This property is described as relative luminance of each color, or as the luminance ratio between the complementary pairs.)

The neutralizing power of a primary color over its complement also affects a viewer's response to a field of that color placed in a luminous neutral (white) background. A neutral background of higher luminance (brightness) than the color area induces an apparent grayness into the chromatic field. The color at which the threshold of grayness is reached and "fluorence" (the appearance of fluorescence) begins to decrease is called a zero-gray color.[1]

Zero-gray colors for a given hue are described by their luminance and purity. The purity of a zero-gray color is the ratio of the luminance of the pure or chromatic hue-determining component to the total luminance of the color mixture (chromatic plus white additive) which complements

Final manuscript received October 16, 1968.

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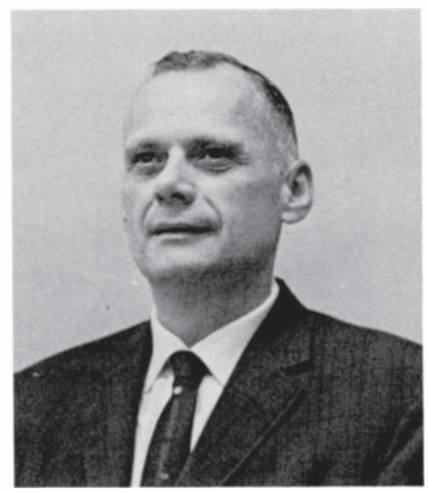

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it in a two-component mix and desaturates it. Both can be varied independently of the luminous background.

An experimental technique was used to determine zero-gray color curves for blue, yellow, green, red, and cyan hues produced by a P22 television phosphor screen when the grid voltages of the three electron guns were adjusted to generate the proper primary excitations for the standard television white. For a desired hue of red, blue, or green, the grid voltage exciting the corresponding phosphor primary is increased either slightly or noticeably to produce low and medium purities, respectively. Full purity occurs when the hue-producing primary alone is excited.

For example, yellow and cyan hues are produced when their respective phosphor primary complements (blue and red) receive less excitation than that required to produce white. When the blue or red phosphor is unexcited, full purity results in the yellow and cyan hues, respectively.

Bright light having the color of a 3500°K black-body radiator was used to illuminate a reflecting baffle placed between the observer and the television screen; the light passes through the viewing aperture in the baffle without striking the screen, as shown in Fig. 2. The observer views the screen through the baffle illuminated by a luminous background, adjusts screen luminance until the zero-grayness threshold is reached, and records two measurements: the total luminance of the phosphor screen and the luminance of the hue-producing primary (in the case of yellow hues, the blue-phosphor luminance is recorded). The first measurement is the zero-gray color luminance, the second measurement allows calculation of color purity. Fig. 3 shows the results of such measurements for blue and yellow hues.

Blue colors, which easily neutralize their yellow complements, remain fluorent until a high threshold value of background luminance is reached, while yellows lose fluorence and appear to contain gray at a much lower threshold. Television-gamut greens and reds behave as the yellow colors, while cyans exhibit intermediate behavior.

The uniqueness of the zero-gray colors for blue hues lies in the behavior of required blue chromatic luminance as a function of color purity in the presence of a bright background. The blue chromatic luminance curve in Fig. 3 is flat at all color purities above a low threshold value; therefore, reduction of the white component does not require an increase in chromatic illumination, and the zero-gray threshold is maintained all the way to full purity as the white component is gradually reduced to zero.

Although a decrease in the white component of luminance in a yellow hue produces a purer yellow on the color mixing diagram of Fig. 1, for fixed background luminance near threshold, the induction of grayness offsets this physical gain in purity. As a result, additional chromatic yellow illumination would be required to produce the same total luminance of the original color to a viewer. At zero-gray threshold, therefore, total luminance of yellow hues remains constant for purities ranging from zero (completely white) to unity (pure yellow). Whether the "pure yellow" is spectral or within the television gamut of a broadband green is unimportant in matters concerning fluorence of yellow hues. So far as fluorence is concerned, phosphor efficiency rather than purity of emitted color is essential in the green and red primaries.

Picture viewability

Viewability is best studied independently of a television picture so that the viewer can control some of the physical properties. When a television picture is simulated with projected color transparencies, the viewer can manipulate independently the color, the luminance (brightness), the resolution, and the ambient illumination to "create" the most desirable picture.

For each picture, the effects of the various factors influencing the viewer's judgment can be evaluated from a pattern produced by substitution of a RETMA resolution-chart transparency for the color transparency. The image provides a gray scale, broad black and white areas for high contrast, and resolution wedges. The gray scale, which has low contrast in both highlight and shadow areas, proves particularly useful.

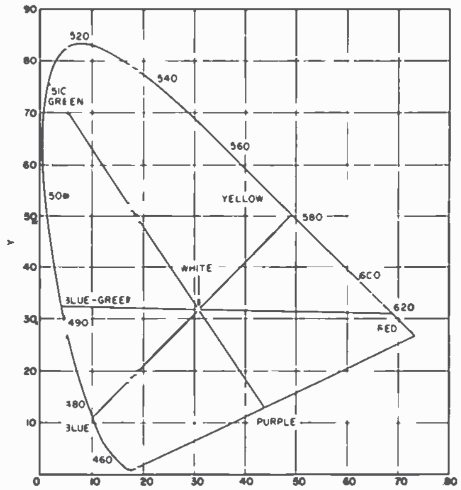

Fig. 1—Standard ICI diagram showing spectral colors and their complements (the color of neutral equals that of a 7000°K black-body radiator).

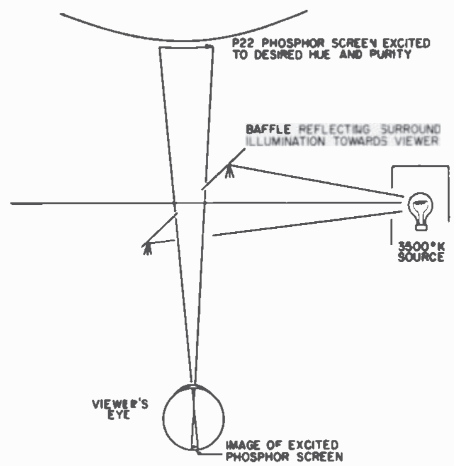

Fig. 2—Experimental determination of zero-gray colors.

One important factor is the picture brightness required for comfortable viewing at various ambient illumination levels. For example, the luminance required when pictures are viewed with 2.5 foot-lamberts reflected ambient illumination, comparable to that encountered in a moderately lighted room, is approximately 17 foot-lamberts. For prolonged viewing, the picture is judged uncomfortably bright at 40 foot-lamberts and too dim at 5 foot-lamberts. Fig. 4 shows the relation between the picture luminance for typical low and high brightness areas and reflected ambient illumination for satisfactory viewing.

Although the contrast and the resolution of a color picture are decreased by increases in ambient illumination, viewability can be conserved by increased picture luminance. As an example, a picture was set up with a reflected ambient illumination of 0.5 foot-lambert. The white luminance of

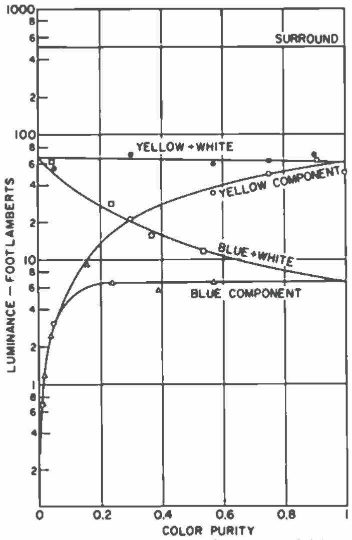

Fig. 3—The required luminance of blue and yellow hues and their respective chromatic components at zero-grayness threshold in a 500 fL surrounding.

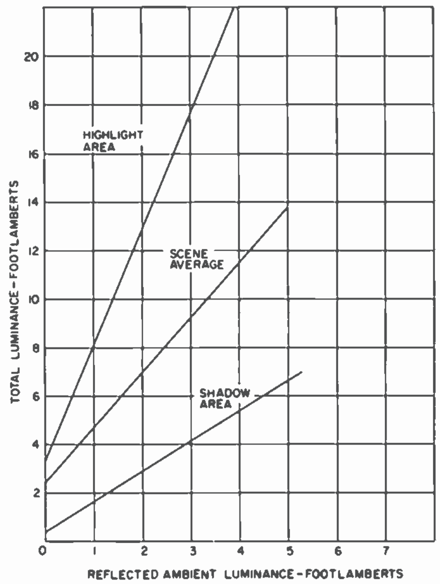

Fig. 4—Picture luminance for typical low and high brightness areas as a function of reflected ambient illumination.

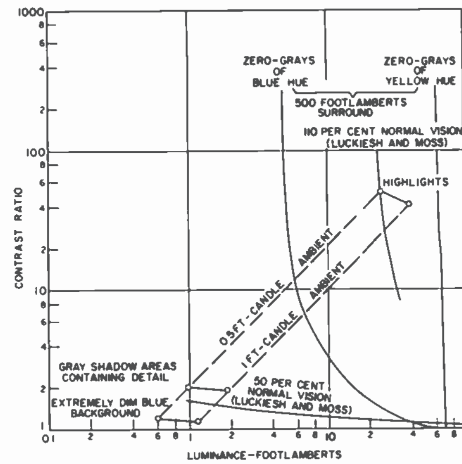

Fig. 5—Behavior of various areas in a scene judged equally viewable under different ambient conditions.

the RETMA slide measured 25 foot-lamberts and the highlight contrast ratio was 50. When the ambient illumination was increased to 1 foot-lambert, the contrast ratio was reduced to 26. The viewer then changed the picture brightness to "recover" the excellent picture. However, instead of increasing the highlight brightness to 50 foot-lamberts to produce the original contrast ratio of 50, the viewer settled for a highlight luminance of about 40 foot-lamberts, and a contrast ratio of only 40, as shown in Fig. 5.

The conservation of viewability was studied by Luckiesh and Moss[2] using the black-and-white Snellen eye chart at various room light levels; their results are shown in Fig. 6. The percent contrast has been recalculated in terms of contrast ratio, which is the luminance ratio of the highlights to adjacent areas on the eye chart. These curves should remain valid for comparison to color television, in which a self-luminous phosphor screen and a protective gray glass are placed in an ambient setting.

The experimental highlight data for constant viewability shown in Fig. 5 correspond to the 110% normal-vision curve of Luckiesh and Moss in Fig. 6. However, the slope of the latter curve indicates that a decrease in highlight contrast ratio should not affect the viewability, while the slope of the experimental data indicates picture degradation with decreased contrast ratios. This discrepancy was resolved when the experimental shadow-area behavior (i.e., contrast ratio and luminance) was plotted in Fig. 5 for the same ambient conditions as those placed on the highlights of the picture. This experimental curve nearly coincides with the 50% normal-vision curve of Luckiesh and Moss. This result indicates that the viewability conserved by the viewer is primarily in the picture shadow areas.

There is also agreement between the Luckiesh and Moss normal-vision data and the experimental data on induced grayness in a chromatic field. The Luckiesh and Moss curves for 50, 80, 100, and 120% normal vision are not associated with independently adjusted background luminance. In their work, the background is identical to the highlights. However, when zero-gray curves for blue and yellow hues in a background luminance of 500 foot-lamberts are replotted from Fig. 3 onto the Luckiesh and Moss plot, they show significant correspondence. (Color purity in Fig. 3 is converted to contrast ratio in Fig. 5. The contrast ratio for color mixtures of chromatic light and white light composing the hues of Fig. 3 is the ratio of the total luminance of the hue to that of the white component.)

For dim colored areas such as blue on a projected picture, the zero-gray curve for blue shifts to the left in Fig. 5 (and produces smaller threshold luminance for the same contrast ratio) as a result of the much lower background luminance values (0.5 and 1 foot-lambert) used in the experiment. The experimental curve of constant viewability in the blue background then agrees fairly well with the shifted zero-gray curve for blue color areas. These experimental results of constant viewability may be altered if the dim background area is yellow, red, or green in hue because of the radical difference between the zero-gray curves for blues and for greens, yellows, and reds in the low-contrast-ratio region, where the fluorence of the latter hues is less sensitive to contrast ratio. Vertical lines in Fig. 5 would then represent constant viewability as determined by the zero-gray condition of the green, yellow, or red hue. It is also possible, however, that detail in the shadows must be conserved for any hue, or even for true grays; this condition would lead to horizontal lines of constant contrast ratio at the highlight regions as well as in the shadow regions for constant viewability of a picture.

Detail resolution and picture fluorence are not necessarily incompatible, therefore, since both are enhanced by gain in picture luminance. For a scene with dim, unstructured chromatic background mixed with ambient illumination, however, a compromise may be necessary between increased background fluorence and a slight loss in detail resolution in other shadow areas of the scene as the ambient luminance is increased. If picture fluorence were much more critical than detail resolution, constant viewability of pictures with green, yellow, and red shadows would require constant luminance, and the viewability curves would be vertical or nearly so in the highlight-area behavior of Fig. 5. Pictures containing detail in green, yellow, and red shadow areas would not suffer in this respect. Because the increase in picture luminance recovers both fluorence and

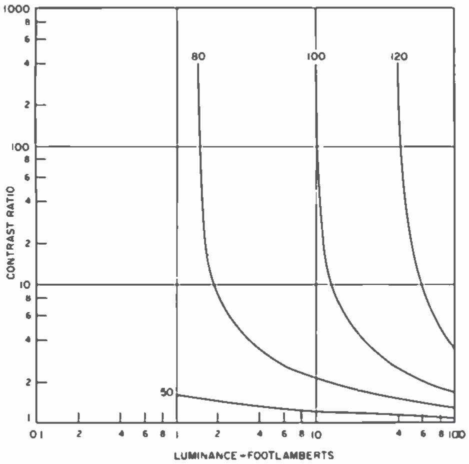

Fig. 6—Constant viewability curves of Luckiesh and Moss.

shadow-area detail (except for dazzling background luminances), and because both are desirable in a given area of a scene, the viewability is limited by shadow detail provided no dimmer unstructured chromatic background exists.

Fig. 7 shows the effects of reflected ambient illumination on shadow detail contrast for a specific case of two adjacent picture elements in a shadow area with luminances L_1 and L_2, where L_1 is twice the value of L_2. (At zero ambient, the contrast would equal 2.) The average scene luminance is defined as the sum of the average luminance of the two picture shadow areas and the reflected ambient.

As an example of the use of Fig. 7, the following conditions are assumed:

Average scene luminance 7 foot-lamberts (i.e., $L_1 = 4$ foot-lamberts);
Reflected ambient luminance 4 foot-lamberts;
Screen reflectivity 1.0;
Glass reflectivity 0.04;
Faceplate transmission 0.5.

When no faceplate is used, the contrast is 1.33. With the faceplate, the reflected ambient luminance is reduced by 75% (doubly attenuated) and the area luminances L_1 and L_2 by 50% (singly attenuated). The result is a 64% decrease in average scene luminance but a 12% increase in contrast. (Although this latter figure seems insignificant, the eye is capable of discerning a 2% shift at this brightness level.) In a television receiver, the loss of brightness can be compensated by an increase of video drive. If the video drive is quadrupled to produce the original average scene luminance of 7 foot-lamberts, the contrast increases by 35% to 1.8.

Table I shows the effect of the faceplate transmission on contrast for the above example, without video-drive compensation. Decreasing faceplate transmission decreases luminance, but increases contrast.

In color television, the white light that mixes with and desaturates a color is related to the background luminance by a factor that involves the television faceplate transmission. Zero-gray colors of the various hues are produced in the picture shadow areas, and the purity of these threshold colors is controlled by the faceplate transmission.

In the case of zero-gray colors of yellow, red, and green hues, varying faceplate transmissions also cause zero-gray areas of the scene to be redistributed, even when the product of the picture signal luminance (video drive) and glass transmission remains fixed. If glass transmission is decreased to enhance the contrast ratio, the blue threshold colors return to the original distribution in the picture after video-drive adjustment. In the case of the other hues, video drive must be further increased until the total picture luminance is the same as that for the original high glass transmission.

For constant ambient luminance and video drive, highlight-area behavior is directly related to shadow-area behavior as the glass transmission varies. For different faceplate transmissions, contrast and luminance in the highlights have been compared with the experimentally determined conditions for constant viewability. If a particular scene has dim achromatic detail upon a still dimmer and unstructured blue background, Fig. 8 shows that 40% transmission is a reasonable value for practical use. Values lower than 40%, including the 24% value for optimum contrast, reduce picture viewability primarily because of decreased luminance. Transmission higher than 40% produces a substantial increase in the reflected ambient illumination and a consequent loss in detail contrast. The contrast loss can be recovered by an increase in the picture brightness with video drive; however, resolution will

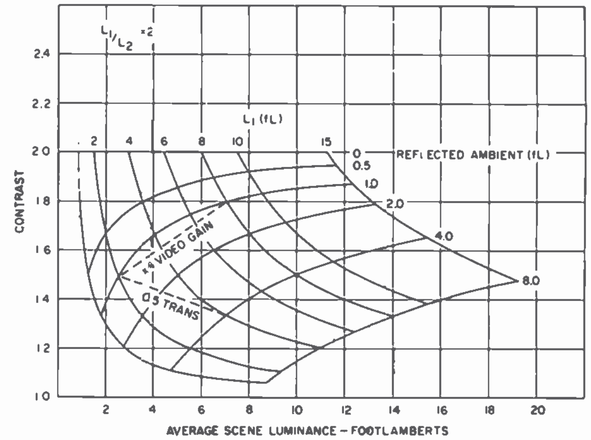

Fig. 7—Effect of reflected ambient illumination on shadow-area detail contrast for two picture elements with luminances L_1 and L_2.

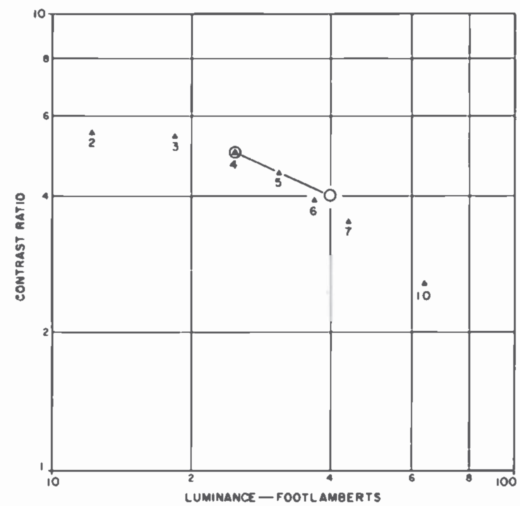

Fig. 8—Effect of glass transmission choice for fixed operating conditions as compared to experimental segment of constant picture viewability drawn for highlight region.

decrease as a result of beam blooming and beam power requirements will increase.

References

1. Evans, R. M., and Swenholt, B. K., "Chromatic Strength of Colors: Dominant Wavelength and Purity," *J. of Optical Soc. of Amer.* (Nov 1967).
2. Luckiesh, N., and Moss, F. K., *The Science of Seeing* (D. Van Nostrand Co., New York, N.Y., 1943) p. 133.

Table I—Contrast and average scene luminance change as a function of faceplate transmission for a scene of low brightness and low contrast ($L_1/L_2 = 2$)

Faceplate Transmission	*Reflected ambient Luminance (fL)*	*L_1 (fL)*	*Ave. scene luminance (fL)*	*Contrast*
1.0	4.0	4.0	7.0	1.33
0.8	2.56	3.06	4.85	1.37
0.7	1.96	2.68	3.97	1.40
0.6	1.48	2.30	3.20	1.44
0.5	1.08	1.92	2.52	1.47
0.4	0.75	1.53	1.90	1.50
0.3	0.49	1.15	1.35	1.54
0.24	0.32	0.92	1.00	1.60