Metamerism and Multi-Primary Displays

The media in our eyes yellow with age, causing us to make different color matches as we get older. For multi-primary displays that push the gamut limits to colors that previously could not be rendered, metamerism can result: Screen colors that match in theory may not match to you, the viewer. To satisfy an aging customer population, manufacturers must minimize this problem. Here is how it can be done.

by Michael H. Brill and James Larimer

AS alternatives to traditional displays with three additive primary colors (R,G,B), new displays are emerging with more than three primaries. Multi-primary displays try to achieve two goals: to expand the color gamut available on the screen and to extend screen contrast and brightness to achieve the range of colors and highlights renderable in commercial (film-based) cinema. Meeting these objectives entails challenges, however. For example, as yet there is not even an agreed-upon number to quantify color gamut. In this article, we will look at one aspect of the color-rendering challenge – metamerism – whereby different light spectra have the same color appearance under the same circumstances.

For this article, we distinguish the number of primaries p_d in a display (a hardware function) from the number of variables p_c used to control that display (generally a software function).

Color Matching and Metamerism: A Personal View

When do two lights match? Clearly, a match is indicated if the lights have the same spectra. Such lights are called isomers and their match is called isomerism. When viewed in similar spatial and temporal contexts, isomers will appear identical in color to all observers. Of course, physically identical lights can appear different if presented in different spatio-temporal contexts, but that phenomenon need not concern us here.

The colors rendered on a three-primary display are controlled by three command signals that control the intensities of three color primaries ($p_c = p_d = 3$). Ideally, but not

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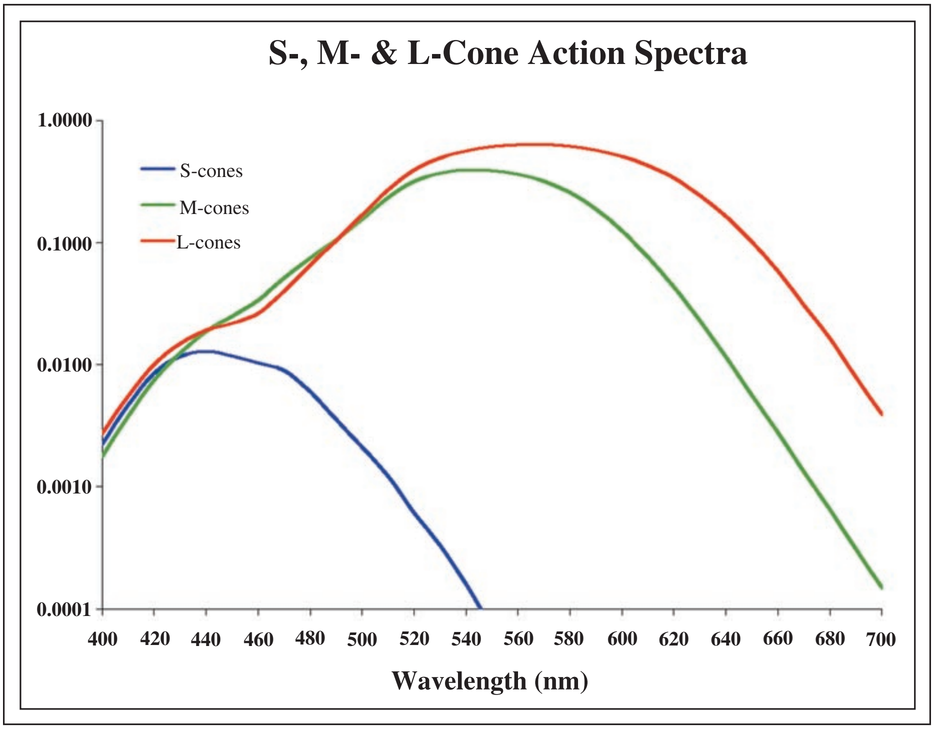

Fig. 1: The cone spectral tuning curves redrawn from a publication by Smith and Pokorny.[1]

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always in practice, all display pixels commanded by the same control values will be physically identical independent of screen location. On a three-primary display screen, all identically commanded pixels are isomers and will be perceived in similar spatio-temporal contexts as identical by everyone.

Unlike isomers, metamers are lights that have different spectral power distributions but look identical to an observer when viewed in similar spatio-temporal contexts. Metamers exist because the eye senses the light on the retina with three independent spectrally tuned photoreceptors called cones. Estimates of the cone-action spectra proposed by Smith and Pokorny[1] are shown in Fig. 1.

The cones down-sample the higher-dimensional space of all possible spectral power distributions to a three-space of cone quantum catches. Three independent neural signals result, creating metamer equivalence classes within the set of spectral power distributions. That any spectrum can be matched by three primary colors was discussed in Isaac Newton's *Opticks* and characterized quantitatively by Hermann Grassmann. Indeed, metamers in color vision provide all color-imaging technology with the capability of synthesizing a nearly full gamut of colors.

A visualization of a metamer pair is shown in Fig. 2. It shows two lights of radically different spectral power distributions that nonetheless look strikingly similar in color.

Metamers may be both created and destroyed by colored filters. Light reaching the photoreceptors must pass through the eye's cornea, lens, and the vitreous and aqueous humors of the inner and anterior chambers of the eye. These substances, as well as the retina and the choroid (a light-absorbing membrane directly behind the retina), all absorb and scatter light, filtering and changing the spectrum of light imaged on the retina. We each look at the world through a personal colored filter that yellows increasingly over a lifetime. An estimate of the lens's optical density for the average 32-year-old eye is shown in Fig. 3.

The eye's lens is essentially transparent at wavelengths longer than 650 nm but increasingly absorbs at shorter wavelengths. The absorption changes throughout life, adding at 400 nm about 0.12 density units per decade between the ages of 20 and 60 and 0.4 units per decade after the age of 60.

The personal filter endows each of us with a unique set of metamer-equivalence classes –

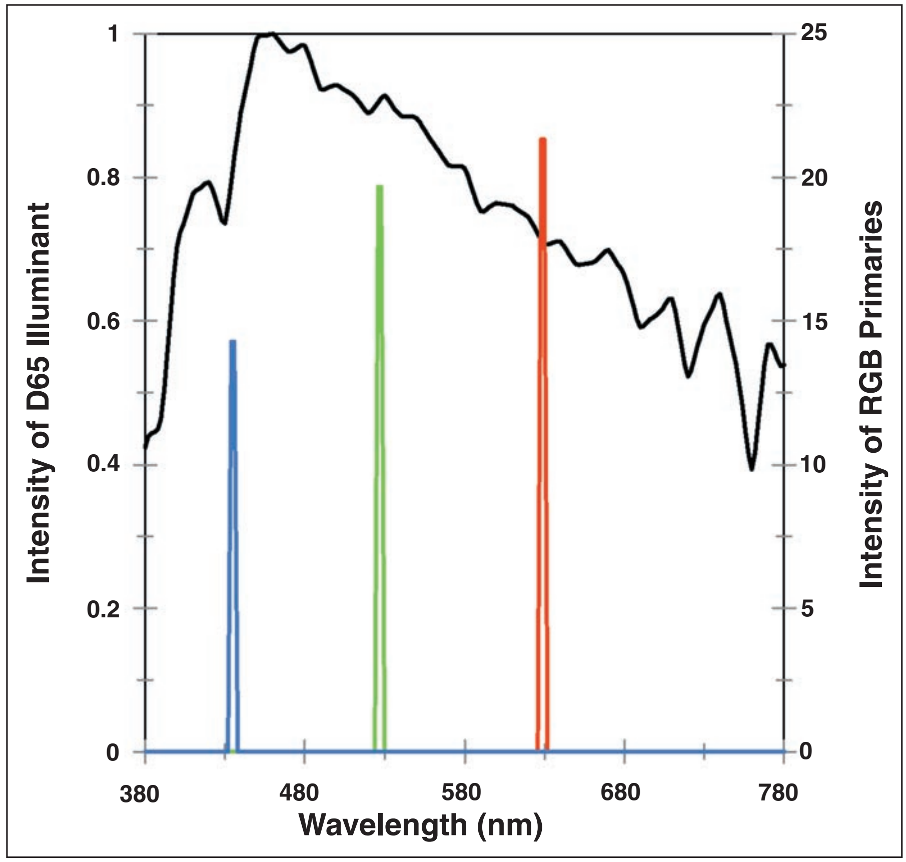

Fig. 2: *An example of metamers generated by CIE Standard Illuminant D65 (black curve) and three narrow-band primaries whose CIE tristimulus values match. (Figure courtesy of Louis D. Silverstein.)*

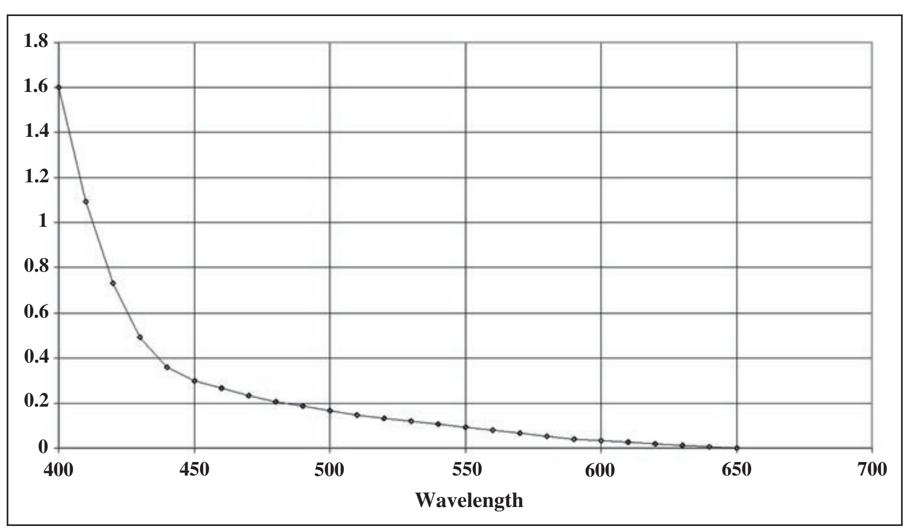

Fig. 3: Lens optical density in the average 32-year-old eye, redrawn from Pokorny, *et al.*[2]

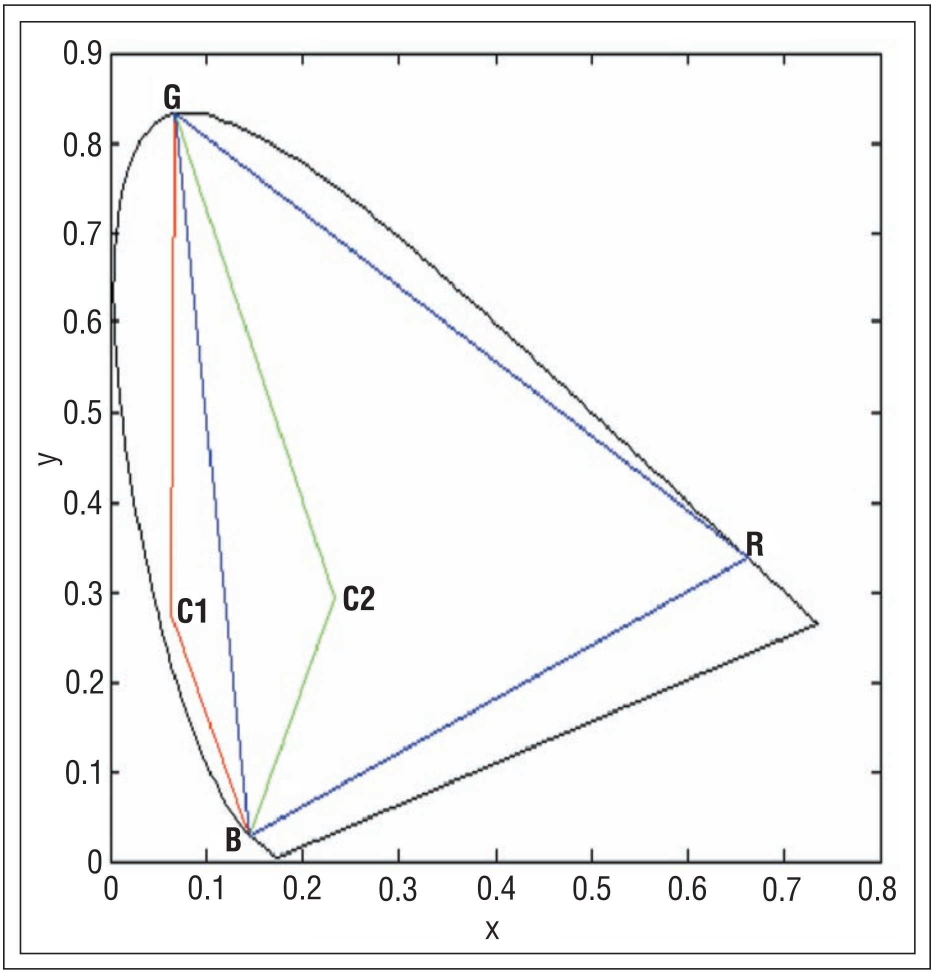

***Fig. 4:** Chromaticity space of a four-primary display, showing the migration of the C primary from C1 to C2 when a filter is introduced.*

what looks the same to you will look different to me. Color technology must produce colors that are seen by everyone, so it has ignored the personal filter in favor of a normative Standard Observer adopted by the CIE. The color of an object rendered on a display will exactly match a referent or off-screen object color only for the Standard Observer. In a well-designed display, the metameric differences between the referent colors and screen colors seen by each of us are generally no greater than the relative color shifts induced by changes in lighting, which viewers largely ignore.

The condition of contingent or metamer-based color matches is called "metamerism." Metameric matches are a fact of life and facilitate color technology because it is not necessary to make a spectral match to satisfy an observer. However, metameric matches are fragile in that they may be violated by vagaries such as a personal filter, external filters or lenses, and changes in illumination. Our objective is to avoid color matches – especially of two patches on the same screen – that succumb to the frailties of metamerism and break down because of such things as a personal color filter.

How Metamerism Affects Displays

When a three-primary display commands two pixels with the same control triad ($p_c = p_d = 3$), the pixels emit the same spectrum of light (*i.e.*, the pixels are isomers). However, when more primaries are added ($3 = p_c < p_d$), the situation changes. A $p_d > 3$ primary system and a $p_c = 3$ control can work only if the control signal is up-sampled to command all p_d of the display's primaries. The up-sampling rule is not unique. Less appreciated is that different control 3-tuples can yield non-isomeric screen colors. These will be metamers for some observers but not for others. We call this effect "on-screen metamerism," and it can result in a face that appears smoothly changing in flesh tones to one observer but changing from healthy pink to sickly bluish for another. A $p_d > 3$ system can cause colors of familiar objects to invert their relative hues for some observers and not for others. On-screen metamerism is best avoided.

On-screen metamerism is very different from what we call "off-screen metamerism," the color match of a screen color with the "original" color of what is presented on the screen. Unlike on-screen metamerism, off-screen metamerism is actually alleviated by using many primaries – or at least enough primaries to approximate a spectrum in the outside world. Increasing the number of primaries of a display allows the spectrum of a reproduced color to be closer and closer to its original and, hence, the two should filter identically to preserve an individual's color matches.

If the primaries are narrow band, more of them are needed to approximate a smooth and broadband spectrum typical of natural objects. The down side of broadband primaries is a smaller gamut of renderable colors. Genoa Color Systems presented a color-proofing system with six primaries as described at CIC14[3] and in the article by Eliav and Ben-Chorin in this issue. Genoa's system requires all six primaries to be commanded by a six-dimensional control vector; there is no on-screen metamerism and the off-screen match for the design goal lighting is also broadly maintained across observers. Off-screen metamerism is reduced by the broadband primaries – which together approximate the off-screen spectrum – but the color space available is constrained to low-chroma colors typical of printers.

Expanding the Contrast Range of the Display's Gamut

Extra primaries may be used to intensify colors and to increase the brightness and contrast of a display. Projection systems commonly increase white-to-black contrast ratios and improve tone transfer by adding a bright green, yellow, or white primary. Here, the primary and secondary colors must give up some luminance to allow rendering of more faithful highlights. This is rarely a problem with natural imagery but can impair a graphics display.

The example of an RGBW system is informative.[4] A single spatial-light-modulator projector that reconstructs using a time-division tone scale can achieve a 50% luminance increase by including a white segment in the color wheel. However, the white spectrum produced by adding the red, green, and blue primaries need not be the same (up to a scale factor) as the spectrum of the white. In this familiar situation, the personal filter of each observer will alter the relative hues of these two whites. When these two whites are matched in luminance, only rarely will anyone other than the CIE Standard Observer see them as identical colors. So, for such displays, on-screen metamerism can cause an observer to see undesirable color shifts with intensity in the neutral colors – *e g.*, a bluish or greenish tint or an overly red flesh tone that connotes illness.

Given these preliminaries, we will now explain how to test for and prevent on-screen metamerism when $p_d > 3$ and $p_c = 3$.

How to Avoid On-Screen Metamerism

A three-primary display automatically avoids on-screen metamerism because each in-gamut color is produced by exactly one RGB triplet, a simple matrix-inverse giving the rule of correspondence. For a display with p_d primaries, one can avoid on-screen metamerism for the CIE Standard Observer by activating only three primaries at a time: Choose a triangular tiling of the chromaticity gamut of all p_d primaries, locate the target color in one of these triangles, and then produce the color using only the primaries defined by the vertices of that triangle. (Of course, using only three primaries at a time will not generate all the luminance possible, especially for white. We'll discuss how to mitigate this problem below.)

Using this strategy, no match made by the CIE Standard Observer will mismatch under filtering. However, unless the primaries are well behaved, one primary triangle may flip onto another when filters (such as sunglasses) are applied or the observer is non-CIE. In that case, colors that are distinct to the CIE Standard Observer will coalesce and produce new matches. To avoid such new matches, the spectra of the primaries in any chromaticity triangle must in some sense be well behaved.

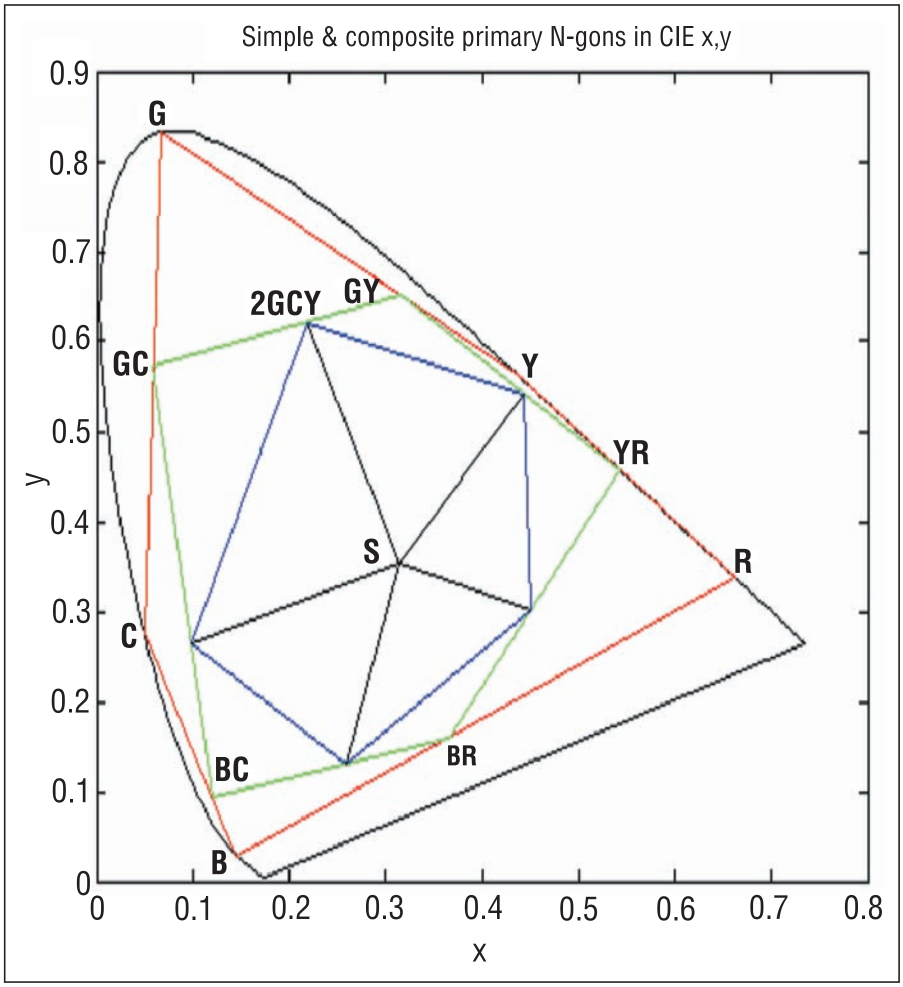

Fig. 5: Color space for a display with five simple monochromatic primaries.

The triangle flip is illustrated in Fig. 4, which shows the chromaticities of notional primaries in a four-primary display. The R,G,B primaries for this illustration are monochromatic at respective wavelengths 609, 519, and 459 nm. The cyan (C) primary has 99% of its power at 489 nm and the rest at 609 nm. To the CIE Observer, the chromaticity of the C primary is C1, and the primary triangles C1-G-B and B-G-R represent each color uniquely. Let a filter be interposed that reduces the 489-nm power 20-fold but transmits completely the 609-nm primary. Then the C primary migrates from C1 to C2, which flips the C1-G-B triangle so it overlaps triangle B-G-R and hence produces new color matches.

What constitutes good behavior of a primary triangle so as to avoid flipping as in Fig. 4? If the primaries are monochromatic, their chromaticities are fixed and immune to filtering. But the chromaticities need not be fixed. It is enough[5,6] that the spectral power densities of all subsets of three primaries $P_i(\lambda)$, $P_j(\lambda)$, and $P_k(\lambda)$ be such that the locus $[P_i(\lambda), P_j(\lambda)]/[P_i(\lambda) + P_j(\lambda) + P_k(\lambda)]$ is convex in wavelength.

Avoiding on-screen metamerism requires use of only three additive primaries at a time. At first, this seems to limit luminance for chromaticities that could otherwise be made from more than three primaries. However, we can get more luminance by expanding the definition of "additive primary" to include composite primaries – fixed linear combinations of the p_d simple primaries.

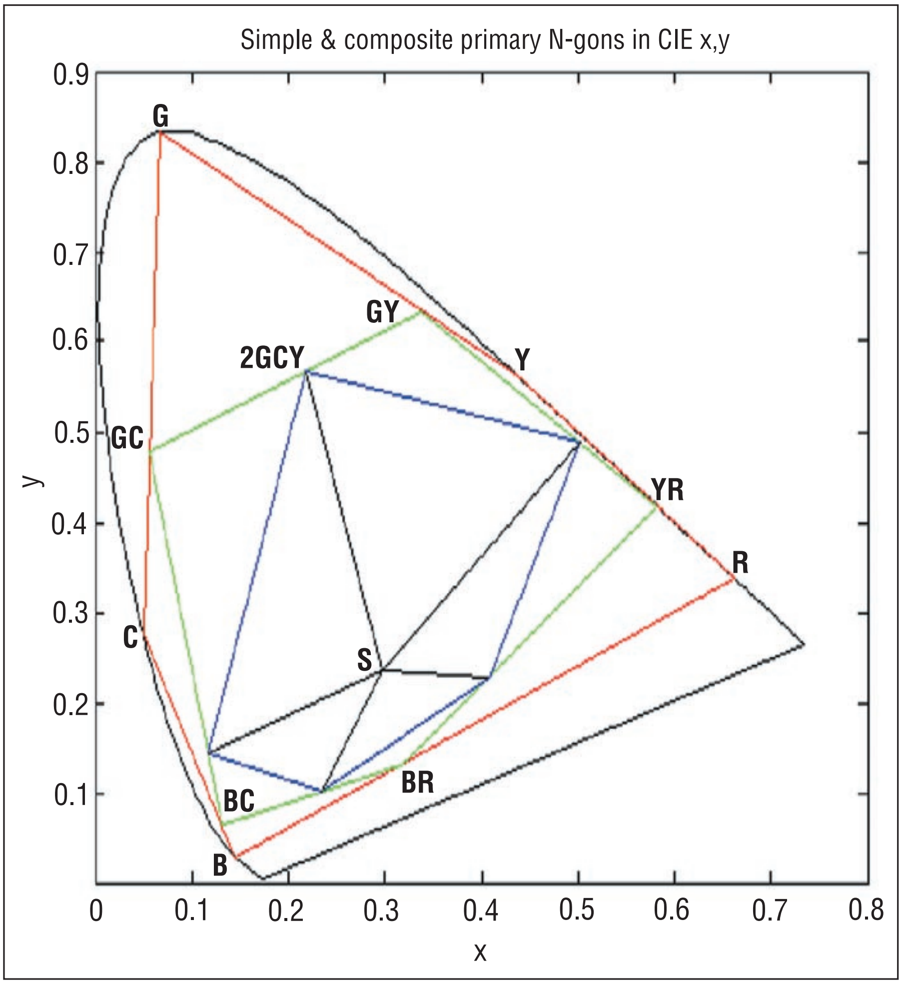

Fig. 6: Color space for the display of Fig. 2, but with filtered monochromatic primaries.

Algorithm for Encoding a Target Color

The above idea – to derive trichromatic production primaries (simple or composite) for each target color – is captured in the algorithm below:

Step 1. Check that any three of the p_d primary spectra obey the above convexity criterion. Also make sure the chromaticity polygon of the primaries is convex.

Step 2. Starting with the polygon of the simple primaries, add the primaries from adjacent vertices to make second-level composite primaries. Divide the gamut region between parent and second-level primaries into triangles.

Step 3. Similarly, from the second-level polygon, generate a third-level polygon. Define primary triangles between the second- and third-level polygons.

Step 4. Continue making triangles out of adjacent polygons as long as desired. Then connect the vertices of the innermost polygon with the sum S of the parent primaries.

Step 5. Given a target chromaticity (x,y), find its triangle among those generated in Steps 2-4, and then use (only) the primaries of that triangle to render (x,y) on the display.

Example and General Discussion

The above algorithm is illustrated by the chromaticity diagram in Fig. 5. The chromaticities of five simple monochromatic primaries are connected by the pentagon R-Y-G-C-B. Second-level primaries are connected by the pentagon YR-GY-GC-BC-CR. Third-level primaries are connected by the pentagon 2YRG-2GCY-2CGB-2BCR-2RBY (only one of whose vertices is labeled in Fig. 5). The sum of all the primaries at any level has the chromaticity of the white S at the center of the diagram.

Figure 6 illustrates the distortion of the five-primary system in Fig. 5 due to filter factors 1, 1/2, 1/4, 1/3, and 2/3 (from shortest to longest wavelength). Filtering leaves the first-level pentagon fixed, slides the second-level vertices along the first-level-pentagon sides, slides the third-level vertices along the second-level-pentagon sides, and moves the white point within the third-level pentagon. These actions do not reverse any of the depicted triangles.

Special attention is needed if the polygon of the simple primaries is not convex – *e.g.*, in an RGBW display. This case is discussed in Ref. 5. Here, we mention only what to do to increase the luminance of W by adding in R,G,B. To stay out of trouble in that case (so all the neutrals have the same chromaticity for each observer), it is important not to change the proportion of light from the primaries as you increase the luminance of the neutral color. If you treat the W+R+G+B as a composite primary, then the neutrals will be relative isomers – otherwise, they will not. (Of course, in digital systems, low luminance will pose a practical challenge to achieving such proportional representation of the primaries, but this problem is also encountered with three-primary displays.)

Shape of the Three-Dimensional Gamut

Any color gamut actually inhabits three dimensions, not just the two we have been discussing. The shape in tristimulus space of a multi-primary display's color gamut potentially seems to be quite complicated, composed as it is of three-primary sub-gamuts each of which seems to comprise a tristimulus parallelepiped, an ensemble of which would look like complicated gables on a roof. The reality is a bit simpler. The rooftops are not always accessible colors in the gamut. For example, having commanded full excitation of G, one cannot additionally obtain full excitation of GY and GC, for that would drive G beyond its limitations. Hence, the "gabled roof" defined by the triangles of the main gamut is planed off to tetrahedra by the constraints of maximum excitation on each sub-gamut. The "gabled roof" never happens, and that simplicity is an advantage in addressing colors that come from other media.

Outlook

Besides the problem of rendering colors within the irregular gamut we have described here, other practical details must be resolved in using multi-primary displays without on-screen metamerism. Some remaining challenges are the imperfect additivity of most "additive" displays, and also the tendency of existing liquid-crystal-display (LCD) primaries to violate a strict convexity criterion on their spectra. Still, the challenges that remain in display design so as to mitigate on-screen metamerism seem manageable. Meeting those challenges will free the display engineer to use as many primaries as necessary to reproduce natural off-screen colors faithfully and without on-screen metamerism.

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