PHOTO COURTESY CAROL ROSEGG

Color rendering: Narrow-band emitters give designers another tool

BY **KARL G. RULING AND MIKE WOOD**

TWENTY YEARS AGO people watching a tech rehearsal of the New York City Opera production of Arnold Schoenberg's *Moses und Aron* saw a surprising sight. The stage was washed with yellow light from low-pressure sodium lamps. As the chorus rushed on wearing street clothes, everything on stage was yellow, yellow-gray, or black—completely monochrome. And then colors emerged! The stage stayed the same intense yellow as gelled incandescent front light was faded up, but a chorus member who had been wearing a black skirt was now wearing a red one. Audience members at the performances did not see anything quite so startling, because of the tight color palette of the actual costumes and makeup, but they nevertheless saw scenes becoming less or more alive as lighting designer Hans Toelstede played light from fluorescent lamps and low-pressure sodium, high-pressure sodium, and mercury vapor discharge lamps against light from incandescent sources, using color rendering as a design tool in addition to the usual tools of hue, saturation, intensity, distribution, and movement.

Toelstede's use of low-CRI lamps on stage was unusual but not unique. Max Keller in *Light Fantastic: the Art and Design of Stage Lighting* has several pages describing the use of low-pressure and high-pressure sodium lamps on stage, complete with a picture of a shop-built, four-lamp, low-pressure sodium, open-face luminaire that needed a 20-inch mechanical douser to dim it. However, using these industrial gas-discharge sources on stage is not easy. They don't turn on instantly, they can't be dimmed electronically, and the luminaires that use them aren't spotlights by any stretch of the imagination. Furthermore, what they can do is limited. A low-pressure sodium lamp gives a virtually monochromatic yellow light, which is great for suppressing all color except yellow, but it's only yellow. High-pressure sodium is yellow-amber—not much different. Mercury vapor is white, but only one blue-green version of white. If a designer wants to play with color rendering in any color other than yellow, or any white other than the blue-green of mercury vapor, she is out of luck with these lamps. Working with color rendering as a design tool is just too difficult and too limited for the vast majority of productions, if the choices of narrow-band emitters are limited to gas-discharge lamps.

However, the choices of narrow-band emitters for a theatrical lighting designer are no longer limited to gas-discharge sources: LEDs also are narrow-band emitters. LED luminaires allow designers to use color rendering as a design tool if they are aware of their peculiar spectral properties, or to be unpleasantly surprised by strange colors if they are not.

Color perception

The human eye has two sets of receptors: rods and cones. The rods work at very low light levels and essentially give us no color information. The cones work at higher light levels and are the color receptors. They come in three types, often labeled L, M, and S—long, medium, and short—to describe the wavelengths of the parts of the spectrum to which they are sensitive. The actual photonic energy absorption curves for the cones do not align with what we normally call the primary colors of light and have significant overlap, but there is a lot of signal processing in the retina and brain that improves the color resolution—and obviously the system works.

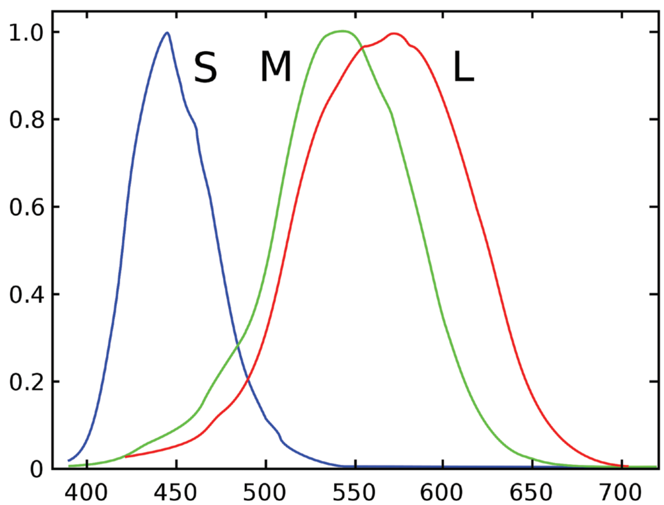

Figure 1 – Normalized responsivity spectra of human cone cells.
[The graphic is from the Wikipedia "Cone cell" article, and its use is licensed under the Creative Commons Attribution 3.0 License.]

A look at the sensitivity curves shown in **Figure 1** can make it clear how we see color. A pure red light at 680 nm, for example, will stimulate the L cones, but stimulation of the M and S cones is virtually nil. The signal from the L cones and the lack of signals from the others is interpreted by the brain as "red."

The mechanism for perceiving a color at an extreme end of the spectrum is fairly easy to understand, but the perception of colors in the middle is more complicated and interesting. For example, the yellow of low-pressure sodium is produced by light of two very closely spaced wavelengths: 589.0 and 589.6 nm. That stimulates the L and M cones, and the signals from the cones are processed in the retina and the brain to yield the perception "yellow." However, the same sensation could be produced by light of two more widely separated wavelengths, for example, 550 nm and 630 nm. The perception of the same yellow also could be created by a band of wavelengths centered around 589 nm—the situation with the gelled incandescent front light on *Moses und Aron*. As long as the relative levels of stimulation of the L and M cones are the same, the perceived yellow will be the same. A cone has no mechanism for signaling that its stimulus is any particular wavelength; it can only signal stimulation or the lack of it.

The system of three cones also allows us to see colors for which there is no single corresponding wavelength of light, magenta for instance. That is the color we see when the L and S cones are stimulated by wavelengths of light at the long and short wavelength ends of the spectrum, but there is little or no light in the middle of the spectrum to stimulate the M cones. Magenta gels are sometimes called "minus green" because they are.

Metamerism and metameric failure

Any particular color can be described by how much it stimulates the three types of cones—its tri-stimulus values—but for colors in the middle of the spectrum, several combinations of wavelengths of light, several spectral power distributions, can create a particular set of tri-stimulus values, a particular color. Colors that look the same but that actually have different spectral power distributions are called "metamers." The yellow of the low-pressure sodium lamps and the yellow of the gelled front lights on *Moses und Aron* are one example, but metamers abound in everyday life. It is a safe bet that anytime you see something painted to match a dyed fabric you are seeing metamers; it is unlikely that the paint pigment is reflecting exactly the same spectrum of light as the dye. It only looks the same when observed under what we call "normal" light, be that daylight, incandescent light, or some other general-purpose white light source.

Metameric failure happens when objects that look the same under one lighting condition do not look the same under another. The skirt on the chorus member in *Moses und Aron*, which matched the jeans worn by another chorus member under the low-pressure sodium but that didn't match under the gelled incandescent light, is one example of metameric failure, although probably most people wouldn't call it a "failure," just what you can expect with low-pressure sodium. However, metameric failure really is a failure when automobile upholstery matches the paint under daylight but doesn't under streetlight.

Metameric failure happens when a wavelength that a paint or dye is using to create its color under one set of lighting conditions isn't there under another. For example, we could have a teal paint that reflects a band of light peaking at 505 nm and a different teal paint made with pigments that reflect a spectrum of light with peaks at 470 nm and 525 nm. They can both look the same if illuminated by full-spectrum white light or incandescent light filtered through a cyan or princess blue gel, which lets through a broad range of wavelengths and will surely cover 470 nm through 525 nm and more. However, the results are much less predictable if we illuminate the two paints with LED color-changing luminaires that use colored

LEDs to make a range of colors including white. Five-hundred five nanometers is the dominant wavelength of a cyan LED, and 470 nm and 525 nm are the dominant wavelengths of blue and green LEDs respectively. The two paints are likely to look different if the LED luminaire illuminating them includes cyan LEDs or not, and certainly will change differently, if not in hue then in intensity, if the LED luminaire does a color fade to deep blue.

Let's take a look at a few examples to illustrate the different color rendering with different monochromatic LED mixes. Please note that in order to get as clean a comparison as possible, the camera was left locked to incandescent color balance and only exposure times were adjusted between photographs. The brightness and contrast were slightly tweaked in Photoshop to make the light levels comparable, but no colors were touched. The sample is a piece of colored fabric with stripes in many different colors in front of a pure white projection screen as our reference. We've confine our examples to luminaires that use colored LEDs for simplicity of argument. Some color-changing LED luminaires also include white LEDs in the mix. These are usually made by putting a fairly broad-band yellow fluorescent phosphor over a blue LED. The white that emerges is a mixture of the output from the blue LED and the phosphor. It is a more continuous spectrum than you get from mixing the output of monochromatic LEDs to create white, but the spectral power distribution isn't flat, and the color rendering is still dependent on the choice of LEDs and mix of phosphors. Hence, the technical issues are pretty much the same, but photographs of variable color rendering with white LEDs in the mix are not as dramatic.

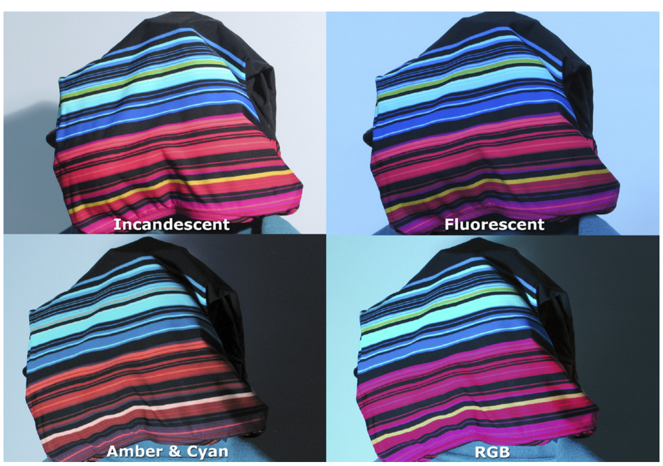

Figure 2

Figure 2 shows the result when the subject is lit by four different sources: incandescent; cool white fluorescent; amber and cyan LEDs balanced to a white; and finally red, green, and blue LEDs also balanced to white. The final three all show a blue tint because the camera is white balanced to the incandescent, but, allowing for this,

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we hope you'll agree, in all cases the background whites are similar. Which one is correct? You might initially be tempted to say the incandescent, but, because of its lack of blue wavelengths, it does a poor job of rendering the different pink and magenta stripes near the bottom of the photo, which the fluorescent picks out well. On the other hand, the fluorescent does a poor job of the yellow and overemphasizes the blue. The amber and cyan mix is visually very pleasing, until you realize that everything that was yellow, red, or pink now shows as different shades of amber, and the green has gone completely! The RGB does a good job on the whole, but we lose the warmth in the reds and everything is a little hyper-real and cartoony.

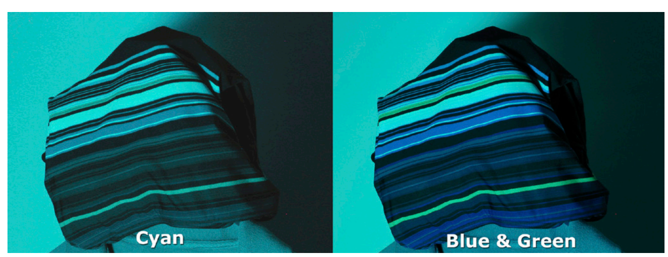

Figure 3

Figure 3 shows an example of two metamers of a color, in this case cyan. The left image shows the sample illuminated with a cyan LED alone while the right shows blue and green LEDs mixed and adjusted to match the same hue. You can see that the color on the background white screen is very similar on the two images. The color rendition though is very different: the cyan LED on its own gives a very flat colored image with only shades of cyan, as you would expect, while the other shows much more variation, with greens and blues appearing out of the teal mire.

Figure 4

The final example, **Figure 4**, shows just how little light of a wavelength is needed to give your eyes the clues they need. In this case both halves of the image have the same primary illumination—blue and green LEDs—but the right image has the addition of a very small amount of light from a red LED, less than 10% of the other. Amazingly, that tiny amount of red is enough to make the reds pop out. Look at the white background; the red isn't enough to make any real difference to the overall hue, nor is it enough to turn the two apparently green stripes to the yellow they should be, however your eye latches onto that red and uses it where it can.

LEDs and color rendering

The above discussion does not mean that LED luminaires are bad for color rendering, but it does mean that they can make color rendering a design tool, with the advantage of being easier to use than gas-discharge lamps. A designer can use them for accurate color rendering, or a designer can use them to create forced, fantasy colors, or to suppress color, as Toelstede did in *Moses und Aron*. Designers should keep in mind, however, that even when they are not trying to consciously manipulate color rendering, the color rendering on stage will be affected by the LEDs used in the luminaires; luminaires using different sets of LED colors may be able to make the same range of whites and virtually the same colors on a white surface, but will render colored objects differently.

Obviously, an LED luminaire that uses red, blue, and green LEDs is not going to give a designer many choices of how to make any particular color. Yellow is going to be made by turning on some mixture of red and green LEDs. That's it, there are no other options. However, not all RGB LED luminaires use the same red and green LEDs. Some, to get a bit better yellow and color rendering with pastels, use red-orange LEDs (615 nm) rather than red (625 nm). Others, to get more intense blues, will use royal blue (460 nm) rather than blue (467 nm). The choices all work, but a designer using luminaires with different LED color sets will find that the rendering of colored objects is not quite the same, even if the color of the light produced, when projected on a white surface, looks the same.

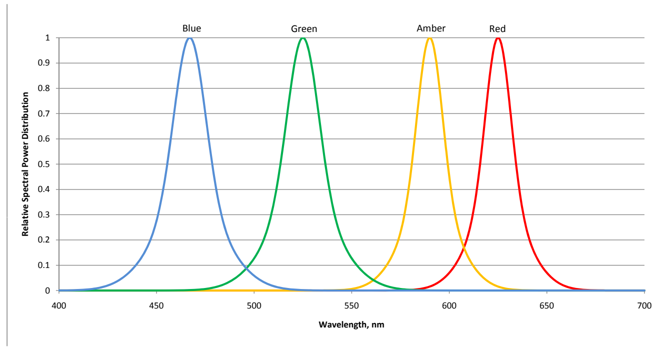

Figure 5: Common LED wavelengths

Using four or more LED colors in a luminaire makes it possible for a designer to begin to play with color rendering as a design tool. As seen in **Figure 2,** most often the first color added when going beyond an RGB system is an amber at about 590 nm to fill the otherwise large gap between red and green at 625 and 525 nm respectively. Now a designer can make yellow hues by turning on the amber LEDs, turning on the red and green, or by turning on all of them and playing with the relative intensities. There are now many different ways to make any particular yellow hue, but the color rendering will be different with them. Add in red-orange LEDs (615 nm) and the choices expand, and so does the amount of time spent fiddling with control channel settings.

The control challenge

As the number of different colors of LEDs in a luminaire expands, so does the complexity of picking a particular mix of control channel settings to get the desired hue, saturation, intensity, and now color rendering quality. Individual color channel control gives a designer great control, but it can be as maddening as setting moving light parameters by moving sliders on a preset desk. Many advanced lighting control consoles have some type of color picker feature to help simplify the selection of colors on color-changing luminaires, but these so far let a designer select hue and saturation, with intensity on another controller. None seen so far at trade shows has a color quality picker.

And what is color quality anyway? How do we describe it in terms that are quantifiable and easily understood by others? As Mike Wood has written elsewhere, we have long used CRI (color rendering index), which works fairly well for describing the output of essentially white sources such as general purpose fluorescent, incandescent, and HID lamps. However, CRI is inadequate for describing color rendering with colored light.

More work is being done to develop a good color quality metric. (See this issue's "Out of the Wood" column on page 14.) In the meantime, designers simply will have to play with mixing colors from narrow-band emitters and be delighted or dismayed with the effects they achieve. ■

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