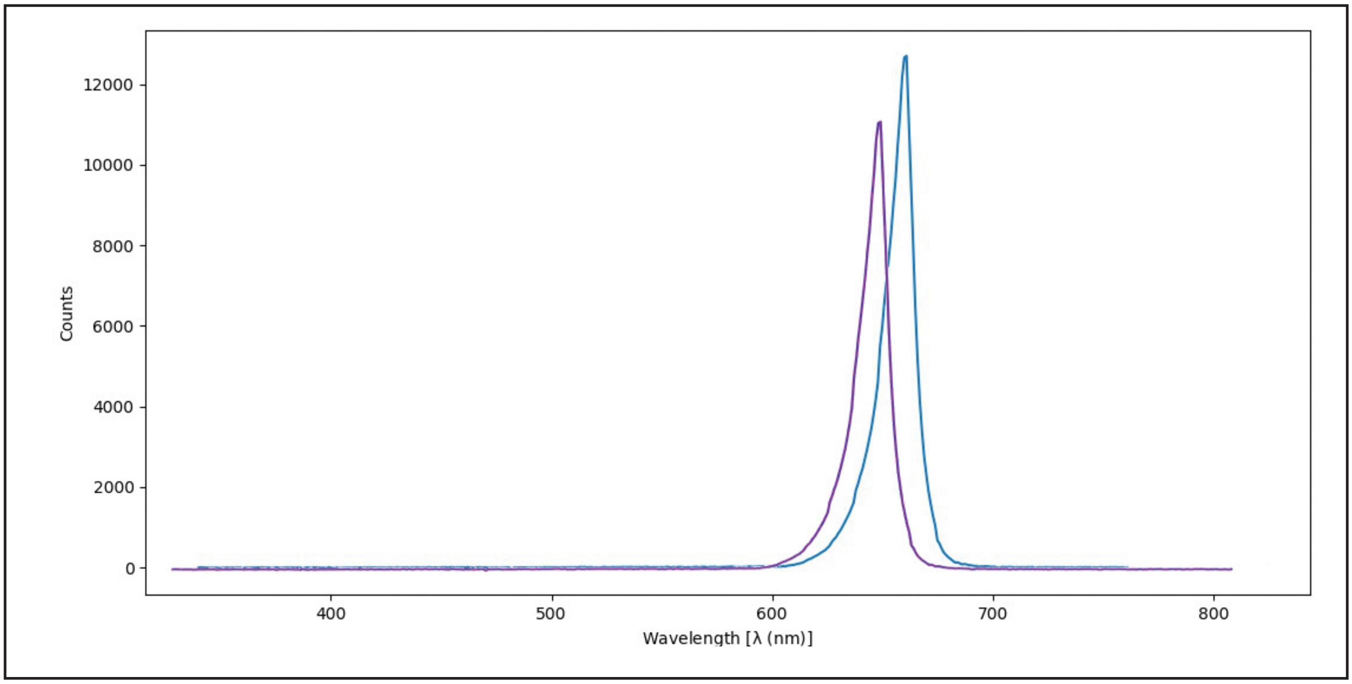
Chasing rainbows: Controlling color

BY **JAVID BUTLER**

MY LAST ARTICLE IN THE FALL 2020 *Protocol* discussed how the standards that ESTA has developed have enabled deployment of larger and more complex systems than ever before. There is always room for improvement of course, and this article will go into more detail on the challenges of controlling color in these complex systems. LED luminaires offer many advantages, but if they are not matched and controlled properly, they can create color shifts visible to the human eye and recordings. Simply setting different luminaires to the same RGB levels does not mean they will produce the same color. A performer moving across stage can show color shifts in their costume as they move from one light to another, and scenery can have an unwanted appearance if the lights don't have the spectrum to pull out the colors.

In discussing control of color, I'm only talking about using a control protocol such as DMX512-A to change the output color of a tunable luminaire and using that control to match colors between luminaires. Some shows need very close matching between luminaires, and color quality can be critical for film and television. Architectural projects often need high color quality over lighting conditions that vary throughout the day. And there are other times when the color on stage is, well, close enough for rock 'n' roll. Since anything that works in the more demanding applications will also work in other cases, this article will focus on the more difficult problems.

One of the main challenges with matching color is that color science goes from "isn't that pretty" to mathematical transforms very quickly. If there is a place where the universes of art and science intersect, it is color. Our innate responses to color, and all the genetic, experiential, and cultural influences that determine our emotional reaction to colors are extremely



Two red LED curves, showing the narrow spectral power distribution. In two different luminaires, these reds would appear different with just the red control channel at full. To properly match colors between luminaires, it will be necessary for luminaires to store this data and send it to the controller to adjust levels for each. To match the colors, or create the same metamer, the controller would need to add a small amount of amber or green to the red LED shown with the blue line. That would also change the intensity, so if the intensity and the color both had to match, the controller would have to reduce the levels as well.

subtle, and the mathematics of color perception are complex. Individual perception of color varies from person to person, so just determining what we mean by color involves creating a model based on responses from multiple individuals. Unlike physical units, such as the second or the ampere, which have very precise definitions, color perception can have a range depending on who is observing and under what conditions.

This brings us to metamers. Our eyes have three primary bands of color perception. Human color perception is specific to our evolutionary history, and we have survived pretty well with just three. Other animals can see into ranges we can't, and some have more varied photoreceptors than we do. Mantis shrimp have more types of photoreceptors than humans and can see across a spectrum from UV-B to near infrared. But our ancestors lived in African savannas, not coastal reefs, and our survival was more dependent on dynamic range than color range. Human ancestors sitting in the shade of tree canopies that could see predators moving through grasses in full sun survived. Today that wide dynamic range allows us to sit in a building in an environment illuminated at 100 lux and look out a window to an environment lit at 100,000 lux and perceive fine detail in both places. Try that with a digital camera some time. Some part of the image will be washed out or too dark, while your vision can perceive both. The combination of sensing in the eye and processing in the brain has excellent survival characteristics on the African savannas, but makes us poor judges of color and intensity. Metamers scientifically measure the different ways our photoreceptors can be stimulated to give a perception of a particular color.

Having multiple ways to create the same color might seem to be beneficial, but it makes control of color more complicated. LED luminaires with different LED sources can in principle create the same color perception, but not at the same control levels. For example, a luminaire with a 440 nm blue should be able to mix many of the same colors as one with the same red and green LEDS but a 460 nm blue. Drive levels for all the LEDs in each luminaire need to be different to create the same apparent color, though.

Conceivably luminaires that are controlled by color using chromaticity coordinates in a color space rather than emitter power would provide these different drive levels internally, but that doesn't solve the larger problem of color matching. First is the selection of color space. There are many different color spaces in use, many developed for different applications, and the math to transform a specific color in one color space to the same apparent color in another color space gets complicated for the average user. The CIE 1931 color space is familiar to many people, but it is not as easy to use as other more recently developed color spaces. Luminaire manufacturers might reasonably choose other color spaces for a variety of very good reasons, but if controls do not support a particular color space the user is left without a good way to control the luminaire by color. There are enough different applications that use different color spaces that it would be difficult for luminaire and control manufacturers to support all of them effectively. A color space that is good for matching video may not match all paint, print, and fabric colors. Having a large number of color spaces would require users to have a knowledge of all those color spaces to select the best space for a particular application. Large shows would have to decide on a color space to use across the whole production, from lighting and video to sets and costumes.

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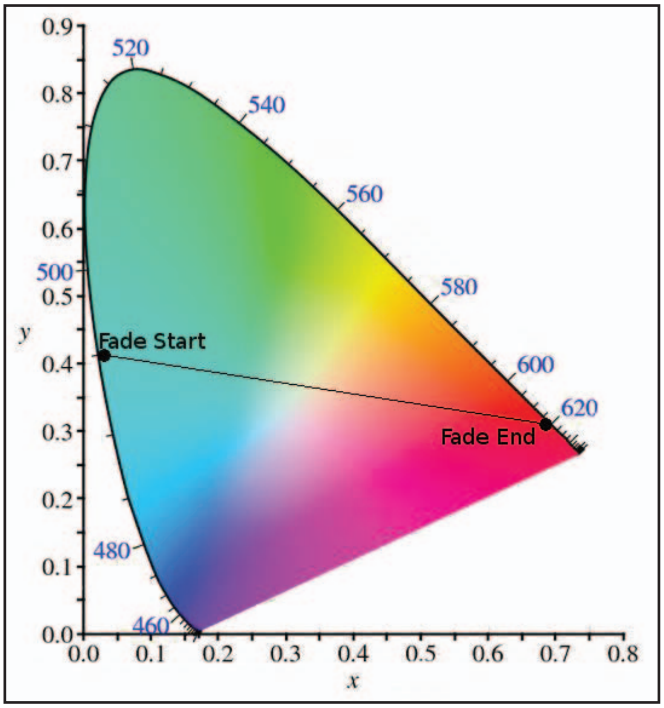
Assuming a reasonable approach to selecting a color space were found, luminaire calibration to the color space would still have to be consistent. Some manufacturers do calibrate each chromaticity controllable luminaire before shipping, which is necessary for good color matching between luminaires. While those luminaires will match well to each other, uncalibrated luminaires won't. LEDs drift over time, so luminaires with different runtime hours will have different calibration even if they were calibrated next to each other at the factory. LEDs also shift slightly in color when dimmed by a current drive. If the luminaire color calibration does not account for this, color shift will still occur at different levels.

Controlling luminaires by chromaticity also requires that the same fades be used for all luminaires. Fading from cyan to red goes through white, if you look at the CIE 1931 color space and plot a straight line between the two colors you will see why. A color fade would follow a curve bending either toward green or blue to avoid this, or could reduce overall intensity as it faded through white to reduce distraction. There are many ways to approach this fade, and if color changes are sent to luminaires as endpoints and fade times it is likely that different luminaires will use different fade algorithms. That means a consistent color fade has to be done by the controller as individual small changes in chromaticity sent to all luminaires. Fading an incandescent lamp using DMX512-A is effectively one dimension of change, even with a dimmer profile, as the output can only move along the dimming curve. With color it is a two or even three-dimensional change depending on the color space being used, and there are many paths to get from one color to another. Just sending starting and ending colors and a fade time will likely result in a muddy color fade unless all the luminaires use a standardized color fading algorithm.

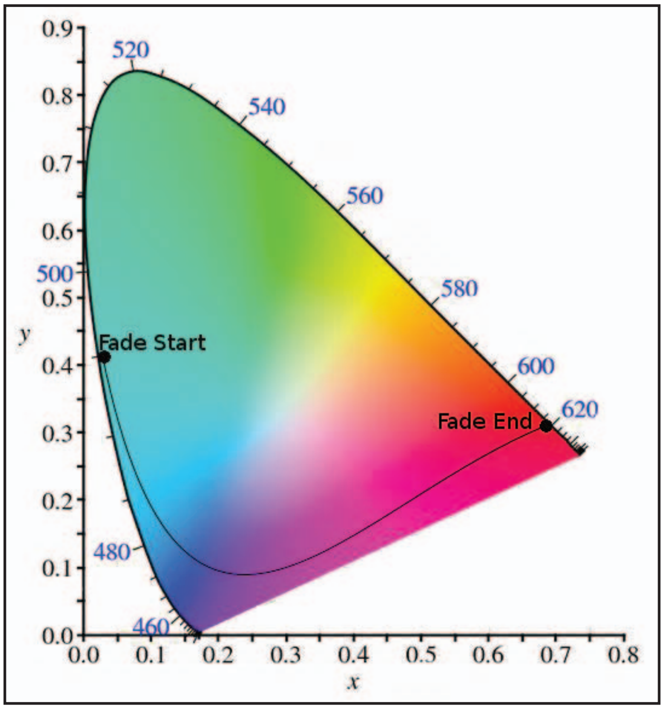
There are times when controlling luminaires by chromaticity is useful, but it is not a panacea. Between selecting a color space and ensuring all the luminaires in a show are calibrated to that color space it is unlikely that large and sophisticated shows will be able to achieve good color matching using a chromaticity control protocol. It can also be troublesome to diagnose a color matching issue using a chromaticity control protocol, depending on the color space used. One of the problems with CIE 1931 for chromaticity control is that the x and y coordinate axis do not directly align with any of the primary colors, so trying to match colors through adjusting the color coordinates sent to the luminaire can be tricky. There is another approach, though, if you know the spectral power distribution (SPD) of the LEDs in the luminaire.

Compared to most other light sources, color LEDs have a very narrow spectrum. The spectral width of a color LED emitter, measured at half the peak output point, might be 30 nm, or just ten percent of the human visual spectrum. Knowing the SPD of each LED in a luminaire, it is possible to calculate the range of colors the luminaire can produce. From the SPDs of the LEDs in two different luminaires it is possible to calculate the colors that both luminaires can match well. Right now, this is largely a manual process, but it can be automated in controllers.

Direct emitter control is already familiar to most people, as RGB control channels for luminaires, often with additional amber, white, or other channels. Luminaires have one control channel for each LED color, whether that is one LED or multiple LEDs of the same color. Adding SPDs to direct emitter control gives a precise control of color and color mixing. Color matching problems that we see today often come from sending the same control levels to different luminaires, resulting in different colors on stage. This can be tuned manually by operators, but is easier when you know the spectral power distribution of the LEDs. A board op that knows they have a 440 nm blue in one set of luminaires and a 460 nm blue in another set can adjust the cues to match the luminaires as well as possible.



Starting from levels of 100% green and blue and linearly fading to a level of 100% red goes through white. This can often be seen in a linear crossfade of cyc lights but applies to any linear fade that crosses multiple primary colors and is true of both LED emitters and incandescent lights filtered with color media. It does not matter whether the linear fade uses chromaticity coordinates or direct emitter control, the result will be the same.



Starting from levels of 100% green and blue and color fading to a level of 100% red by first reducing green while slowly increasing red. Once in the magenta range, blue is reduced and red is increased. This fade does not go through white, and will appear to be a smoother color transition. This fade can be better matched across different luminaires by using direct emitter control when the emitter SPDs are known.

Another advantage to using direct emitter control with SPDs is working with colors on stage. Due to the relatively narrow emission bands of color LEDs some colors on stage may not render well. If you know the SPDs of the luminaires during design, it is possible to either select scenery and costume colors that fall near the peaks, or add luminaires with LEDs that bring out the colors on stage. Knowing color information up front avoids problems later. Color samples can be tested under the lights by changing each emitter and watching how the apparent color of the sample changes.

If you have a spectrometer available, it is possible to light a color sample under white light and see where the reflected peaks are. When doing this, always take a dark measurement first, to get a base reading, then measure the white light source, so you know the SPD it is generating, then measure the sample under that light with no stray illumination. Make sure the spectrometer is only measuring light reflected from the color sample and not colors around it by testing it on a black background. The color sample may not look good to your eye against a black background, but remember your eye did not evolve to do this kind of measurement. A spectrometer will measure the actual energy in each frequency of light, while your eye can fool you. Field measurements can take time to get right, but there is a lot to learn by doing them. Over time, measuring color samples under different lights will help you develop an almost intuitive feel for how colors will render. Sometimes small changes in the control levels will have a large impact on how something looks and having a good understanding of how the spectral power distribution of sources and the reflected power distribution of objects interact will help bring out colors to their maximum effect.

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Manual color matching is the best we can do now, but technology can easily automate color calculations to make it easier for users to achieve good color matching. Next generation controllers will need to collect SPD data from luminaires using RDM or other protocols. Once SPD information from the luminaires is in a controller, it can do the math to match the colors and send the correct levels to the LEDs. Many luminaires have detailed SPD measurement done as part of their development. It is necessary for standards such as *IES LM-79*, and for color space calibration, so many luminaires have good quality SPD data already. As we start to see next generation controllers that can fully use SPD data from luminaires many of the current color matching issues will fade away.

When using SPDs today or in the future it is important to consider the quality of the SPD measurement. There are always some small differences between SPDs of individual luminaires due to variations in LEDs, drivers, and optics, and SPD data measured on individual luminaires will provide better color matching than data measured on a sample luminaire. While it is possible to estimate an SPD based on LED data sheets it will not be as accurate as data measured on a complete luminaire. As an industry we are just starting to recognize the problems of color control. SPD's quality will get better over time, as more people not only recognize the problem but realize it can be corrected.

There is a bright future for LED lighting, and we are just starting the journey. There are technical issues to overcome, but we have a good handle on the science, and it is just a matter of educating people on color and developing the tools to make color control easy. Using direct emitter control with LED SPDs puts control into the hands of the user and gives them the ability to fine tune color. Other control techniques have their place, and luminaires that support both direct emitter control and chromaticity coordinate control are useful. It will be exciting to see what the next generation of color control brings to light. ■

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