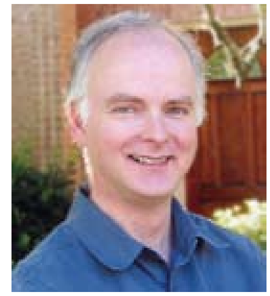
BY MIKE WOOD



To CIE or not to CIE, or how I learned to believe my eyes and ignore my light meter…

WE'VE TALKED IN THIS COLUMN BEFORE about how photometric measurements are not absolute. Readings of the output of a light in photometric units such as lux, foot candles or lumens are all based on the theoretical response of the standard human eye and, as such, are all really statistical units rather than physical. For example a light can emit as much energy as you want in the infra red or ultra violet regions of the spectrum but, if we can't see it with our eyes, then by definition it has zero light output. An infra red or ultra violet source has a power output measurable in watts but no light output measurable in lumens.

> "CIE 1924 is wrong, just plain wrong."

All this was brought home to me recently when I was measuring the light output of a new LED based luminaire in my workshop. This particular luminaire uses red, green and blue LEDs in an additive mixing configuration to allow the user to create the color they desire. All very normal and nothing unusual so far. As is my usual procedure I started the tests by measuring the total lumen output of the unit. I do this by measuring the light output at multiple points across the beam with a Minolta T-1 light meter. This is all straightforward stuff which I do all the time. However I noticed almost immediately that the readings I was getting were much lower than I expected. I first suspected the battery in my light meter and changed it. This made no difference. Next step was to try another light meter and here's where it got interesting. I have another couple of meters, one of medium quality and a cheap-and-cheerful unit I carry around for quick measurements—I find they all usually agree within a pretty close tolerance, irrespective of their purchase price, for normal use and so don't worry too much about which I use. However, when I measured this LED unit I got three different answers from the three meters. Not small differences either, the largest reading was twice that of the smallest! What's going on?

Blue light is invisible?

Next step was to try and narrow it down so I experimented with measuring each of the three colors of LEDs in turn and quickly narrowed it down to the blue. With red and green all three meters agreed within a close tolerance but, in blue, there was a huge difference, almost thirty times, between the smallest and the largest readings. At this point, if you'll excuse the metaphor, a light bulb went on. I knew there was some controversy about the accepted *standard* eye response at the blue end of the spectrum; could that be causing this problem? One meter was telling me there was no light there but you can't fool me that easily, I could see it and it was blinding me—clearly that meter was just plain wrong!

First a couple of definitions; the human eye, as I'm sure you know, has two main types of sensors, rods and cones. Cones provide our color vision but need quite high levels of light to trigger them. Rods on the other hand are much more sensitive but provide monochrome only. Clearly what we are interested in with a color changing luminaire is the response to color so it's the cones we need. The eye's response in brightly lit conditions when the cones are in full use is called the photopic response. (The eye's response in dim light when the rods are in use is called the scotopic response.)

CIE 1924 is wrong, just plain wrong.

The blue curve in **Figure 1** shows the internationally approved and agreed photopic response curve, CIE 1924. This curve, the photopic luminosity function or $V(\lambda)$, was derived from statistical surveys, mainly of college students and is published by the CIE (Commission Internationale de l'Éclairage) as an international standard. It represents the normalized level of response of the human eye in well lit conditions to different wavelengths of light. Also included in the figure and shown below the curve are approximations to the color each of those wavelengths represents—note this is very rough as the process used to print this journal cannot reproduce many of these colors. Just about all light meters are manufactured to follow

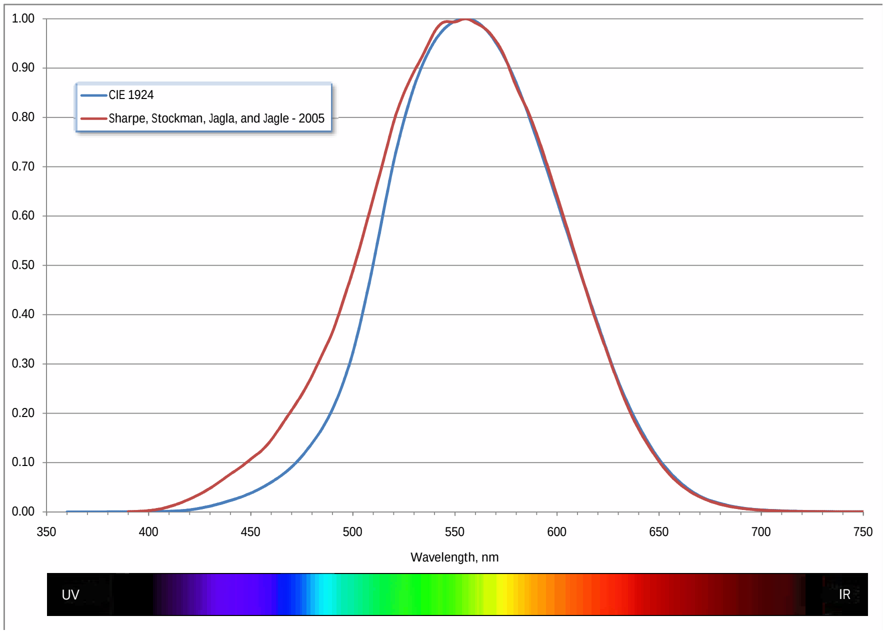


Figure 1

this agreed curve so all should be fine, right? However, here's what the seminal work on photometry, *Color Science* by G. Wyszecki and W.S. Stiles has to say about this curve:

> "The standard photopic luminosity function is based on a curious combination of luminosity data from several sources and obtained by several methods. The uncertainty surrounding it is illustrated by the fact that the values from the different studies that were averaged to define it diverged by as much as a factor of ten in the violet. The function seriously underestimates sensitivity at short wavelengths."

By the way—if you want to know anything about the human eye and color vision then get a copy of Wyszecki and Stiles. It's not easy reading but it's the standard work on the topic and covers absolutely everything. Amazon sells it!

This is the clue to fathom out what's going on here. Also shown in **Figure 1** as the red curve is a more recent photopic response study from 2005 by L.T. Sharpe, A. Stockman, W. Jagla & H. Jägle with data that, to me, is much closer to reality. You can see that it is much higher in the violet and blue areas indicating that light in those wavelengths appears much brighter to us than the older, 1924, data had suggested. Now compare that with **Figure 2** which shows the spectral output I measured of this particular luminaire. You can clearly see the peaks from the three colors of LEDs; red peaks at around 640nm, green at 525nm and, most interesting, the blue at just over 450nm. 450nm is a very deep blue of short wavelength often called Royal Blue; it's in the same area as Congo Blue gel and is almost into the violet. What's interesting here is that 450nm is slap bang in that problem area where there are huge differences between the CIE 1924 data and newer studies. My Minolta light meter is calibrated to that 1924 CIE data so it's no wonder it was reading low for the Royal Blue LED and probably also reads low for a Congo Blue gel. I mentioned this to Karl Ruling in the ESTA office and he postulated this could be why Congo Blue always looks brighter on stage than the very low transmission figure in the swatch book would suggest. That could well be the case; it would also look brighter to our eye than the light meter tells us. This was easily confirmed—I took a piece of Congo Blue gel, put it in a standard theatrical ellipsoidal unit and measured it. Sure enough, I got readings of 8 lux from the Extech meter, 13 lux from the Minolta T-1 and 120 lux from the rough-and-ready meter and, to my eye at least, the 120 lux reading was closest to my perception.

If we take a closer look and zoom in on the blue/violet area of the response curves we can get a clearer view of what the problem is. **Figure 4** shows five curves; the blue curve is the original CIE 1924 photopic data, the red curve is the 2005

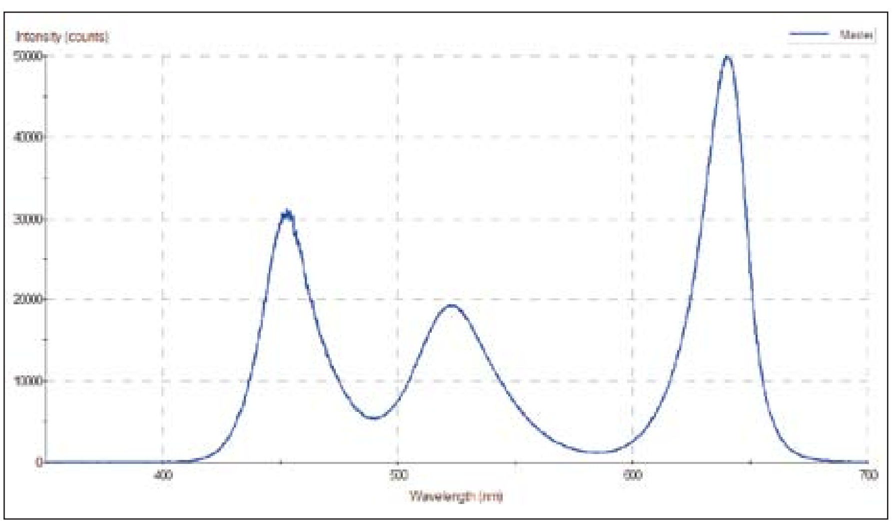


Figure 2

Figure 3

version while the green and violet curves show you the published response curves of two of my light meters. Looking closely around the 450nm wavelength of the Royal Blue LEDs you can see that, just to make things worse, the Minolta T-1 (*point D*) actually reads slightly lower at 450nm than the CIE curve (*point C*) and would therefore give a reading about one fifth of what the more modern study predicts (*point A*). The cheaper, Extech, meter actually does a slightly better job (*point B*) at 450nm but does a poor job at slightly longer wavelengths around 480nm. This matches very closely with what I saw in the workshop and explains the differences in the measurements—it's pleasing when theory matches practice like this; it doesn't always work out that way! The CIE actually partially recognized this problem and, in 1988, published the curve shown in Figure 4 by the dotted blue line. This is commonly known as *Judd's modification* and slightly improves the response curve below 460nm. This modification (known as $V_M(\lambda)$) is a supplement to, not a replacement of the 1924 $V(\lambda)$ as the standard photopic curve.

Redemption

Let me hasten to say that CIE 1924 and most light meters that use it are perfectly good with normal, continuous spectrum, light sources and give you answers within a very few percent of each other. The problem comes when they are used to measure sources with very narrow spectral outputs, particularly when you are using them in 2007 to measure LEDs that emit colors of light that couldn't be reliably produced 80 years ago in 1924. The problem we have now is that every light meter on the planet is calibrated to that CIE 1924

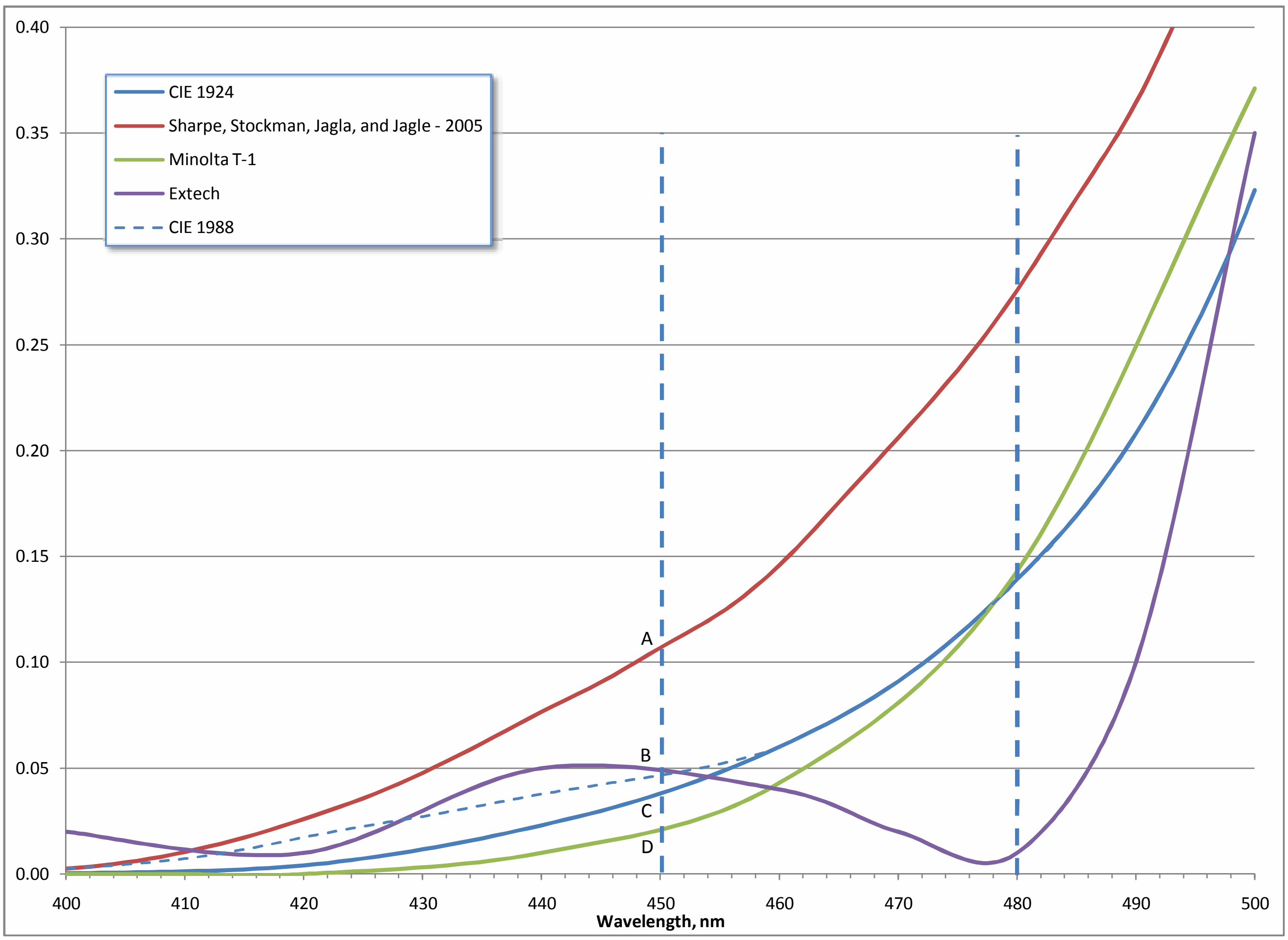


Figure 4

> ". . . if a light looks bright to your eye but the meter disagrees then trust your eye . . ."

photopic curve so switching to a new corrected curve isn't trivial. Every light meter would have to be recalibrated or replaced and, realistically, that isn't going to happen any time soon. As Wyszecki and Stiles comment,

> ". . . any minor improvement at this stage would be outweighed by the very considerable practical inconvenience of a change in the basic function on which all photopic photometry has been based for more than 50 years."

Those 50 years are now 80 and we have to live with CIE 1924, but we should do so with care and with an educated eye. Whenever we use a CIE corrected light meter for a very narrow bandwidth light emitter like a saturated color LED, particularly one in the deep blue, we need to think. Do we know that the wavelength is long enough (more than 480nm is usually safe) to get out of the danger band? Remember that photometric measurements are supposed to mimic the response of the human eye—if a light looks bright to your eye but the meter disagrees then trust your eye. No matter how much you paid for that meter your eye is correct, by definition. Use three different light meters to measure the output of deep blue LEDs and you will likely get three very different readings. In my case the expensive calibrated light meter couldn't see the blue but my cheap rough-and-ready one could.

So, what did I do to get true readings for the LED luminaire in my workshop? I went back to first principles, measured the spectrum (**Figure 2**) loaded the data into Excel and applied the photopic response curve nanometer by nanometer. Funnily enough I got an answer which was closer to the cheap light meter than the expensive one which must prove something; I'm just not sure what . . .. ■

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