THE SECOND C: GOING TO THE LOO

Part 2: Oedipus Meets the Standard Observer

By Keith Hoover

**"Go, Prince. Go, noble heart!...
If I might touch them, I should seem to keep
And not to have lost them, now mine eyes are gone...."**

Oedipus Rex, Sophocles *(translated by Gilbert Murray, LL.D., D.Litt., F.B.A)*

In "The Second C: A Higher Class of Problem, Part 2," I pointed out that, although digital color management has had a big impact on commercial color replication in manufacturing, it has yet to achieve success in the selection or "invention" of the right colors at the beginning of the design process. Consequently, designers still rely on found objects and abbreviated color collections much as they did 75 years ago. The challenge for our industry is to come up with a new solution for accurate virtual color visualization.

ENTER THE DIGITAL TWIN

A Digital Twin is a simulation built using mathematical models having a high correlation in appearance and performance to its real-world (analog) counterpart. For several years now, this approach has been used to virtually develop products—especially products with critical performance requirements—and eliminate the need for physical prototypes. Software such as Siemens NX is used by General Dynamics Electric Boat-Groton to design and commission submarines for the US Department of Defense (no more wooden prototypes).

Certainly, if we can design submarines virtually, we ought to be able to leverage the success of CIELab color space and its accompanying equations and metrics to visualize color. And we must be able to validate the appearance of a virtual color against its real counterpart to make sure that it is an *Identical* Digital Twin, not a *Fraternal* Digital Twin. Here is an "acid test" to validate any "test system" that claims this capability:

- Select a non-textured color swatch (texture is eliminated in this test to differentiate between pure color and appearance due to surface quality)
- Measure it with a spectrophotometer and import its QTX master data into the test system
- Visually compare the physical non-textured color swatch to the virtual sample shown in the test system
- The visual match quality must be comparable to viewing two pieces of the same physical non-textured color swatch side-by-side – a perfect match

Bring it on.

THE SUFFICIENCY OF THE CURRENT MODEL

In the previous installment, we reviewed the CIE Standard Observer, a critical part of the Light/Object/Observer (LOO) tri-key concept used to model color perception. The Standard Observer models our visual system and how we see color. It was created based on the results of various experiments to capture "Color Matching Functions" (CMF's) of the participants in the experiments. These CMF's are expressed as a set of numbers that—when factored together with Standard Illuminant data and spectral data—can predict the color appearance of an object. So, the sufficiency of the Standard Observer is a dependency for a new Color Digital Twin solution.

Constant or Variable?

The Standard Observer is a constant, defining how a person perceives color. In terms of a model to understand color perception, this is accurate. The Observer is the constant and the Light and Object are variables. But real people are not mathematical models and how each person perceives color would seem to be a variable.

We have all heard that the lens in the eye yellows over time, thus impacting color perception. Those who have had cataract surgery can attest to the radical change in the colors they see before and after surgery. But other than lens yellowing, what physical factors impact normal color perception? Well, to be technical, color vision varies between people because of individual differences in macular and lens optical densities, photopigment optical densities, and spectral shifts in the underlying cone photopigment spectra [1]. Right. That defines *how* perception can vary, but what is interesting is *how much* it varies.

Recent work by Ronnier Luo sheds new light (light being a metaphor for truth, not a specific range of emitted electromagnetic energy) on color perception variation between different people. Two experiments were conducted using five 24-year-old male participants having normal color vision and a background in technical color science. The purpose of the first experiment was to calculate individual CMFs and the purpose of the second was to match the color of physical samples to digital representations of those colors (cross-media color matching).

One significant finding of the experiments demonstrated that "inter-observer variation" between the five participants was as high as 3.55 DE_{2000}. The color difference of each participant's results was compared to the MCDM (Mean-Color-Difference-from-the-Mean), that is, the average of the results of all participants. So, the results of any participant might have varied 3.55 DE_{2000} to the average of the group but could have varied by twice that much to another individual within the group. And if the CMF's of the individuals varied from each other, they also differed from the Standard Observer CMF's.

I participated in a similar cross-media color matching study with Luo and his students. In it, the participants used a novel viewing system that allowed them to match the color of individual physical swatches by adjusting the output of tunable LEDs projected onto a white cloth. The digital coordinates of each person's matches were recorded, allowing me to input the others' matches into the system and "see what they saw" compared to each physical color swatch. The scale of the difference was truly shocking, as high as 20.00 DE_{2000} in a few cases.

Yikes!

THE DIGITAL COLOR CONUNDRUM

Until recently, the variability of individual color perception has been merely an academic problem. Each person's vision system was "built in"—we couldn't see how another person saw colors because psychophysical perception isn't interchangeable between people. However, with these new advances in technology allowing the visualization of digital color described above, that has changed. (See Figure 1.)

With so much variation in individual color perception, does that mean digital color doesn't work? No, it means we're mixing apples and oranges.

On one hand, we know that people see color differently and on the other, commercial digital color management (using the Standard Observer) works. Color Matching Functions (CMF's) are responsible for both issues.

The CIE specifies that we must use one and only one set of CMF's when calculating colorimetric data. So, when we measure a color standard and color sample, the same

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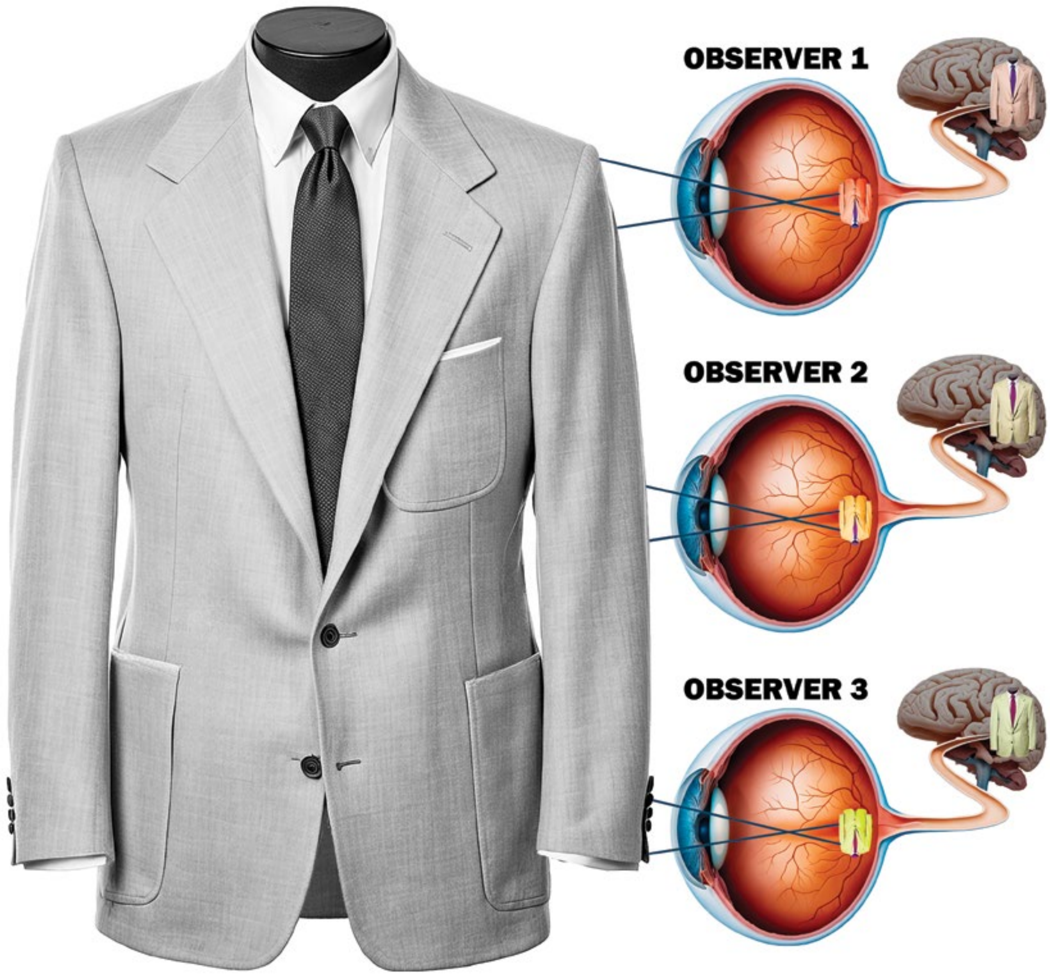


Figure 1 How three people see the same tan blazer: The color signals are received in the eye and processed in the brain. The blazer itself (on the left) is shown without color to emphasize that color is a psycho-physical phenomenon, not an object attribute.

CMF's have been used to digitize them both. We are applying a constant – the Standard Observer CMF's – to both sides of the equation.

By the same token, when each of us views color, we use what amounts to our individual CMF's as a part of how we see. When we look at a color standard and a dreaded lab dip in the lightbox, we, too, apply the same CMF's to both.

For years, we have used CIELab-derived data to define color in software. Is color appearance consistent cross-media? What happens when we compare a physical swatch (medium 1) to an onscreen color derived from a spectrophotometric measurement of that swatch using the CIELab model (medium 2)?

There are a few problems here. [2] First is the difference in luminance of the media, that is, the amount of light either emitted from a source or reflected from an object. The physical swatch absorbs light and the monitor emits it. That's a discussion for another day.

The relevant problem for this discussion is the mixing of CMF's. When we look at a physical swatch, our individual CMF's are used to perceive it. When we look at the "matching" digital version of that color on a monitor, it has been "pre-processed" with the Standard Observer CMF's – which are different from ours. The CMF's are no longer constant – a different one has been applied to each side of the equation. So, unless you are a walking version of the Standard Observer, the physical color swatch won't match the virtual onscreen color.

Calibration

"Hold on, doesn't monitor calibration solve the onscreen color accuracy problem? I mean, I'm not comparing swatches to the monitor—I just want to see the right colors." No. Calibration addresses color *precision*, not color *accuracy*. If you look at the same color on 20 monitors and all appear the same, that's precision. If they happen to display each color in the way that the Standard Observer models it, that's accuracy. As long as color accuracy on a display is pegged to the Standard Observer, then it won't necessarily generate colors as you see them.

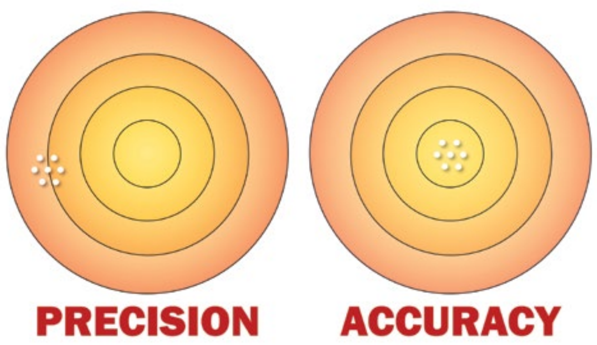


Figure 2 Precision vs Accuracy.

Individual CMF's

There are a few ways to generate and apply Individual CMF's as a substitute for the Standard Observer when generating colorimetric data. Thouslite provides two products, LEDMax and LEDSimulator. [3] Adopting this technology will allow virtual colors to agree with your perception of their analog counterparts. But, since they generate your own personal CMF's, others looking at the wonderful color palette you created won't necessarily see what you see.

Figure 2 shows an example of this. Two people, Colorist A and Colorist B, import a QTX file for the color "Wink" into a color visualization software specifying D65 as the illuminant and the CIE 10˚ Observer. The color along the top labeled "Std Obs" appears, showing what the color looks like using the Standard Observer CMF's.

"Are you kidding me???" they exclaim in unison. "A" represents how Colorist A perceives the color of the Wink physical standard and "B" represents how Colorist "B" sees the same physical standard. Colorist A does not perceive Wink the way Colorist B does.

Each then substitutes their individual CMF's for the CIE 10˚ Observer in the software, which instantly produces the virtual colors "A1" and "B1" respectively. "A1" matches what Colorist A sees and "B1" represents what Colorist B sees. They then invite each other to see their virtual matches, leading each to believe that the other is seriously "chromatically challenged."

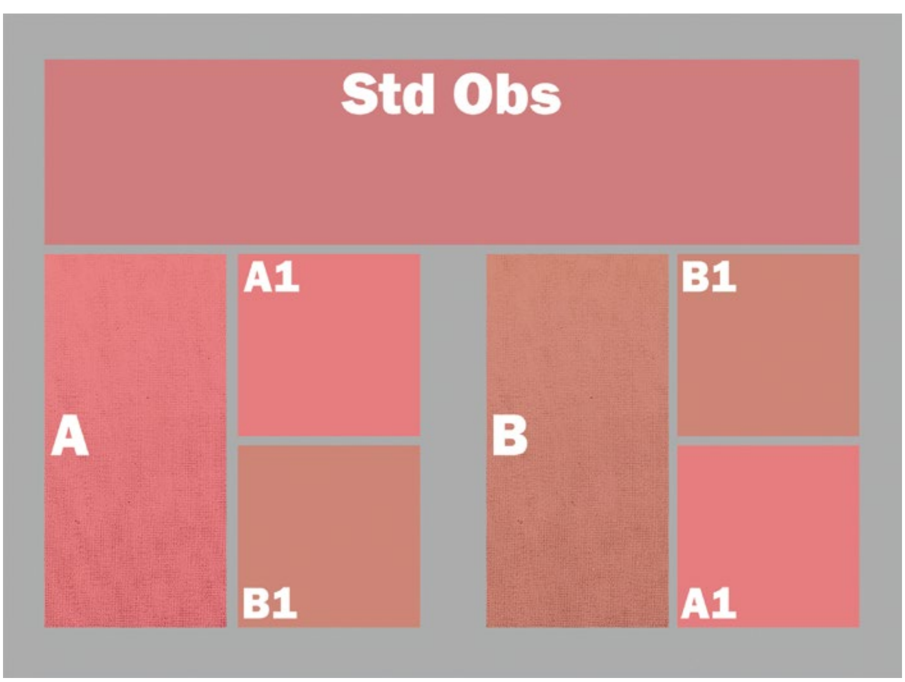


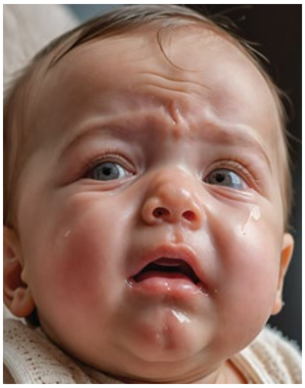
Figure 3 The problem with mixing CMF's: The color on top shows the standard "Wink" digitally visualized using the Standard Observer CMF's. "A" shows how Colorist A sees Wink and "A1" shows Wink digitally visualized using Colorist A's individual CMF's. "B" shows how Colorist B sees Wink and "B1" shows Wink digitally visualized using Colorist B's individual CMF's.

There are other things to consider. For instance, if you used a color program that created and integrated your individual CMF'S in place of the Standard Observer to visualize a QTX file, the onscreen color would be accurate. It would even match the physical swatch (if you could solve the luminance problem). However, any colorimetric data generated using your individual CMF'S would be non-standard and incompatible with programs using conventional CIELab data.

In a way, individual CMF'S in and of themselves, are like the final verse in Judges: "In those days there was no king in Israel: every man did that which was right in his own eyes." [4]

THE RISE OF THE GOLDEN EYE

Well, the "acid test" results were a little complicated. So, we need a specific set of rules to manage the complexity introduced by multiple CMF's.



"Waah. Digital color is too hard. Let's just keep cutting garment samples and sending them all over Kingdom come." No, that's a dopey idea.

Just as the Messiah was the answer to the problems encountered in Judges, the Golden Eye may well be the model for Colorists in the digital age of apparel design. A King determines the law; a Brand's Golden Eye determines the color for the company. Most brands already have a Golden Eye—or at least the archetype of a Golden Eye. They're called Colorists (as in the Second C).

Colorists are responsible for choosing color palettes—determining the aesthetic point of view of the brand. Today, they are left with a "lonely, uncharted wilderness" [5] of color reference resources. In the next installment, we will look at new CIELab-compatible color visualization technology capable of systematically navigating and defining nearly 2,000,000 colors.

Notes

[1] Andrew Stockman and Lindsay T Sharpe. Cone spectral sensitivities and color matching. Color vision: From genes to perception, pages 53–88, 1999.

[2] According to Ronnier Luo, recent technological advances in display technologies that use spectrally narrow primaries to produce wide color gamut displays (e.g. LEDs, OLEDs, lasers, and Quantum Dots) have likely increased the incidence and severity of observer metamerism.

[3] https://www.thouslite.com/product_detail/744.html, https://www.thouslite.com/product_detail/169.html

[4] God, The Bible (KJV), Judges 21:25

[5] Chen, Yun & Yu, Luwen & Westland, Stephen & Cheung, Vien. (2021). Investigation of designers' colour selection process. Colour Research & Application. 46. 10.1002/col.22631

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- Hoover, K. The Second C: Color with a Purpose. *AATCC Review*. **2022**, *22* (1), 36-39.
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- Hoover, K. The Second C: Going To the LOO Part 1: Dips, Diapers, and the Standard Observer, *AATCC Review*, **2024**, *24* (5), 40-43.

Keith Hoover, President of Black Swan Textiles, implements manufacturing-centric digital processes for color and fabric development. He has implemented digital color management programs for Ralph Lauren, Target, Lands' End, JCPenney, and Under Armour, ultimately leading to a process that eliminated lab dips altogether. At Under Armour, Hoover championed the UA Lighthouse, driving digitalization and advanced manufacturing processes to explore local-for-local sourcing. He has worked hands-on in mills worldwide and is a frequent AATCC presenter.