Color Consistency: Definition, Quantification and Tolerances

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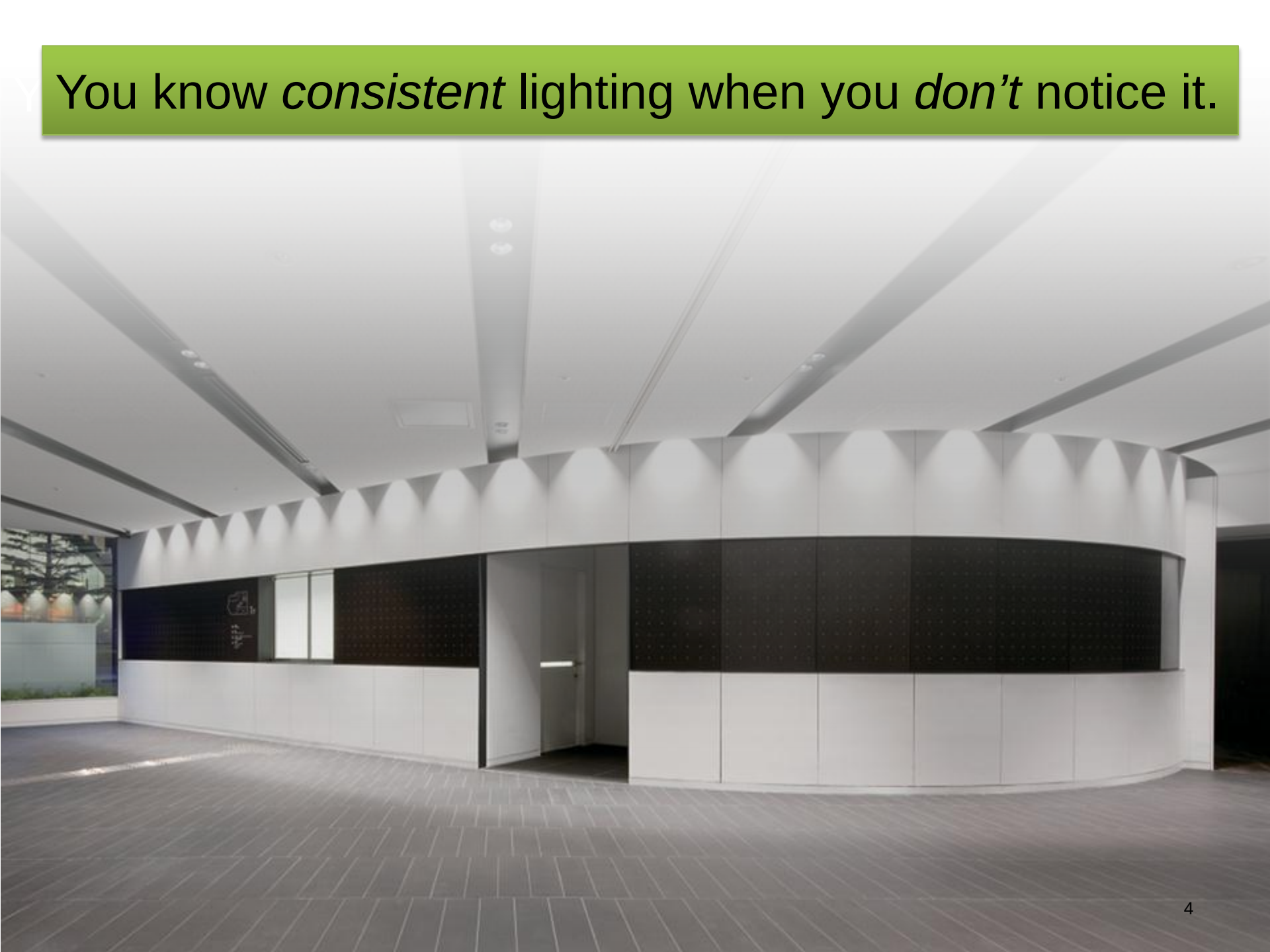
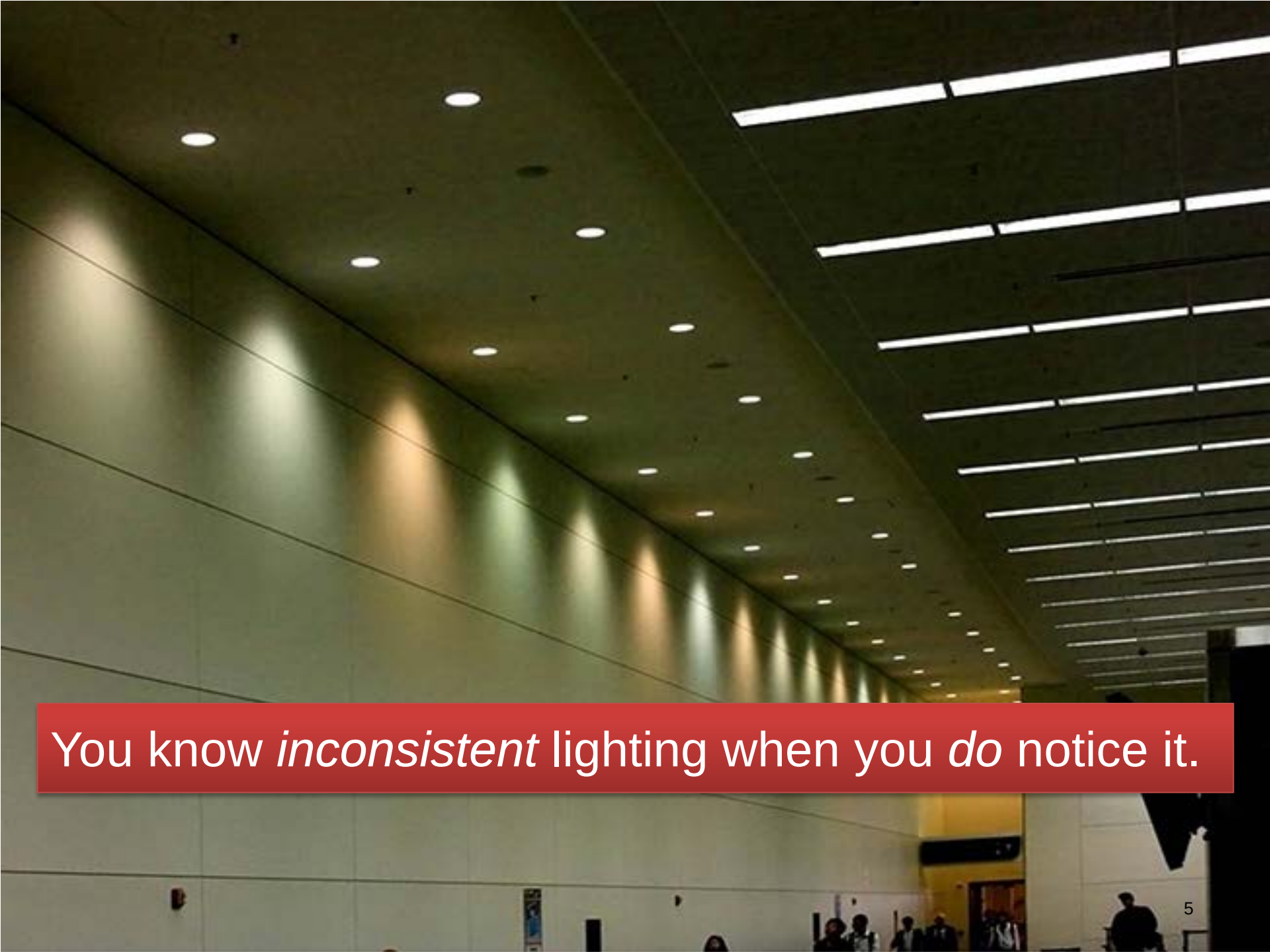
Outline

- Color consistency definition
- Quantification of color
  - Correlation with visual perception
- Aspects of color consistency
  - Initial
  - Maintained
  - Tolerances
- Impact on color rendering
- Other factors impacting color point(s)
- Conclusions

How do we define Color Consistency?

You know *consistent* lighting when you *don't* notice it.

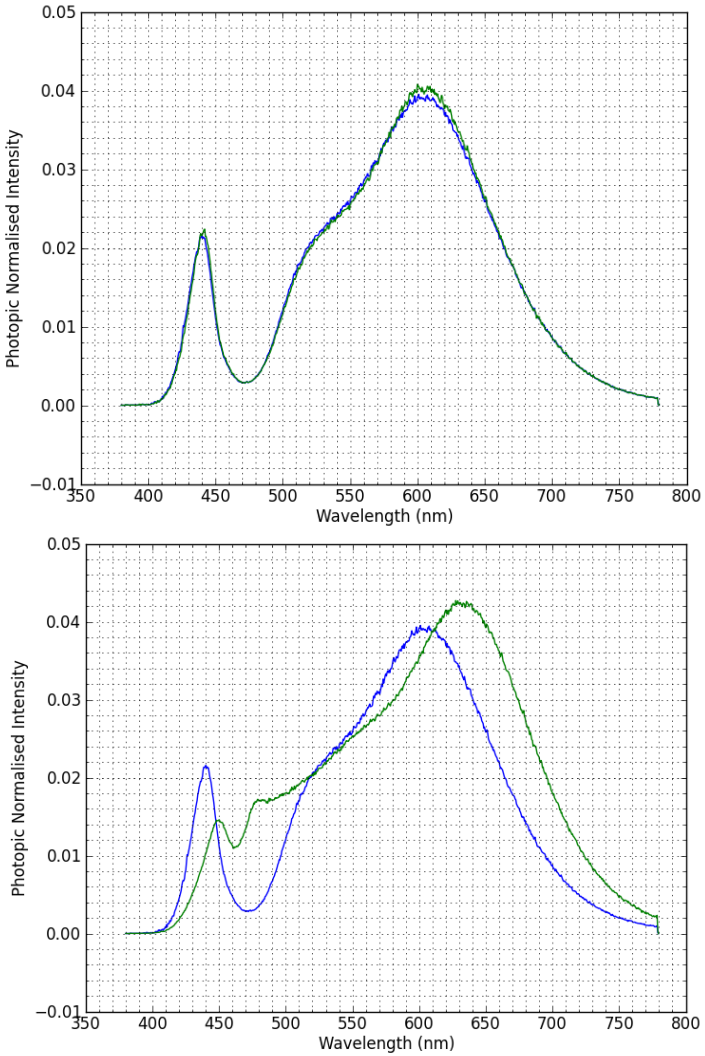



You know *inconsistent* lighting when you *do* notice it.

Color Consistency: Quantification

- Visually the differences should be minimum.
- Need to quantify this visual experience.
  - Hard to run production based on visual inspection.

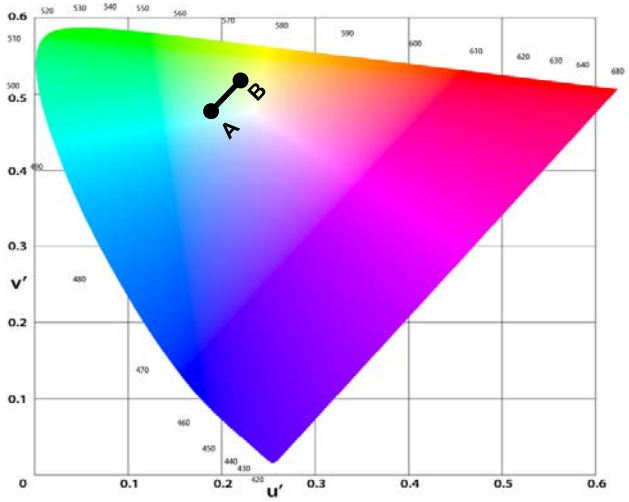
- Spectral Power Distribution (SPD)
  - Ideally, SPDs should be as close as possible (for the same product).
  - Limitations
    - No standard metric to compare SPDs
    - Little visual correlation
      - Slight spectral differences could look visually very different.
      - Or higher spectral differences could look visually the same.

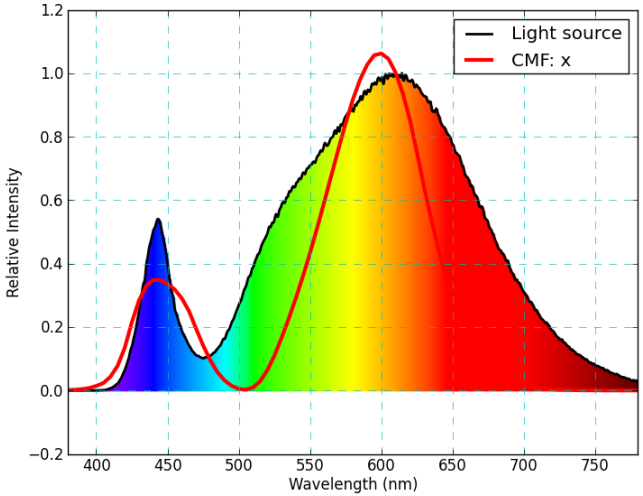


Visual Perception ↔ Colorimetry

- Colorimetric match should be the goal for consistent color.

- Important Consideration: Observer Differences
  - Colorimetry is based on the use of a single “average” observer (which includes field of view)
  - There are differences between observers from this average observer.
  - Much work still needs to be done!



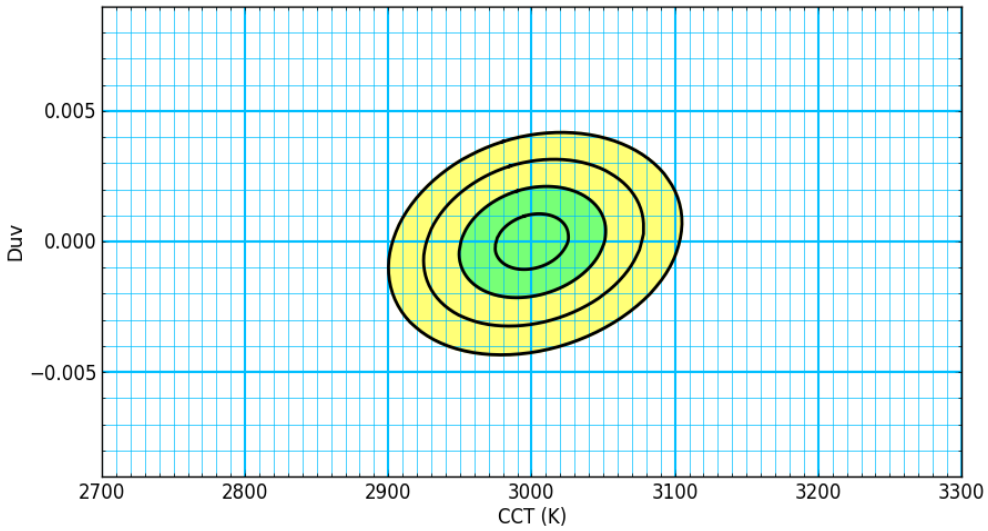


1931			CIE (2006)*		
u'	v'	Δu'v'	u'	v'	Δu'v'
0.2509	0.5192	0.005482	0.2534	0.5218	0.002596
0.2495	0.5245		0.2527	0.5243	

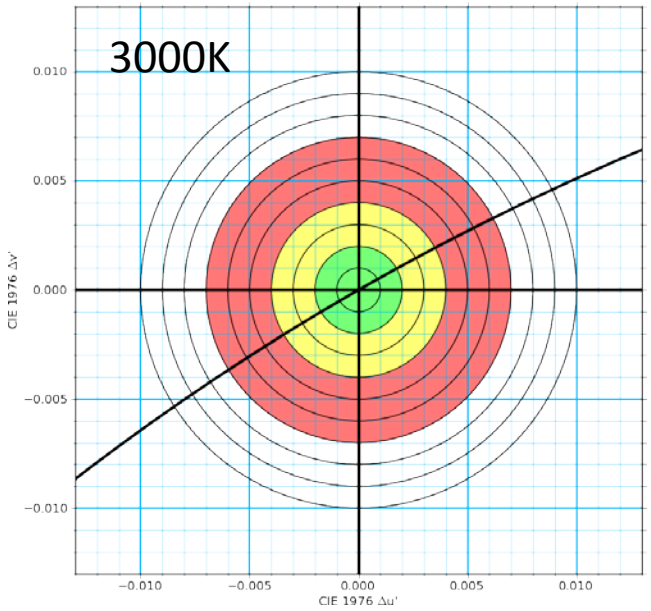
* CIE (2006), Fundamental chromaticity diagram with physiological axes, Parts 1 and 2. Technical Report 170-1. Vienna: Central Bureau of the Commission Internationale de l' Éclairage.

Metrics to measure color differences

MacAdam Ellipses

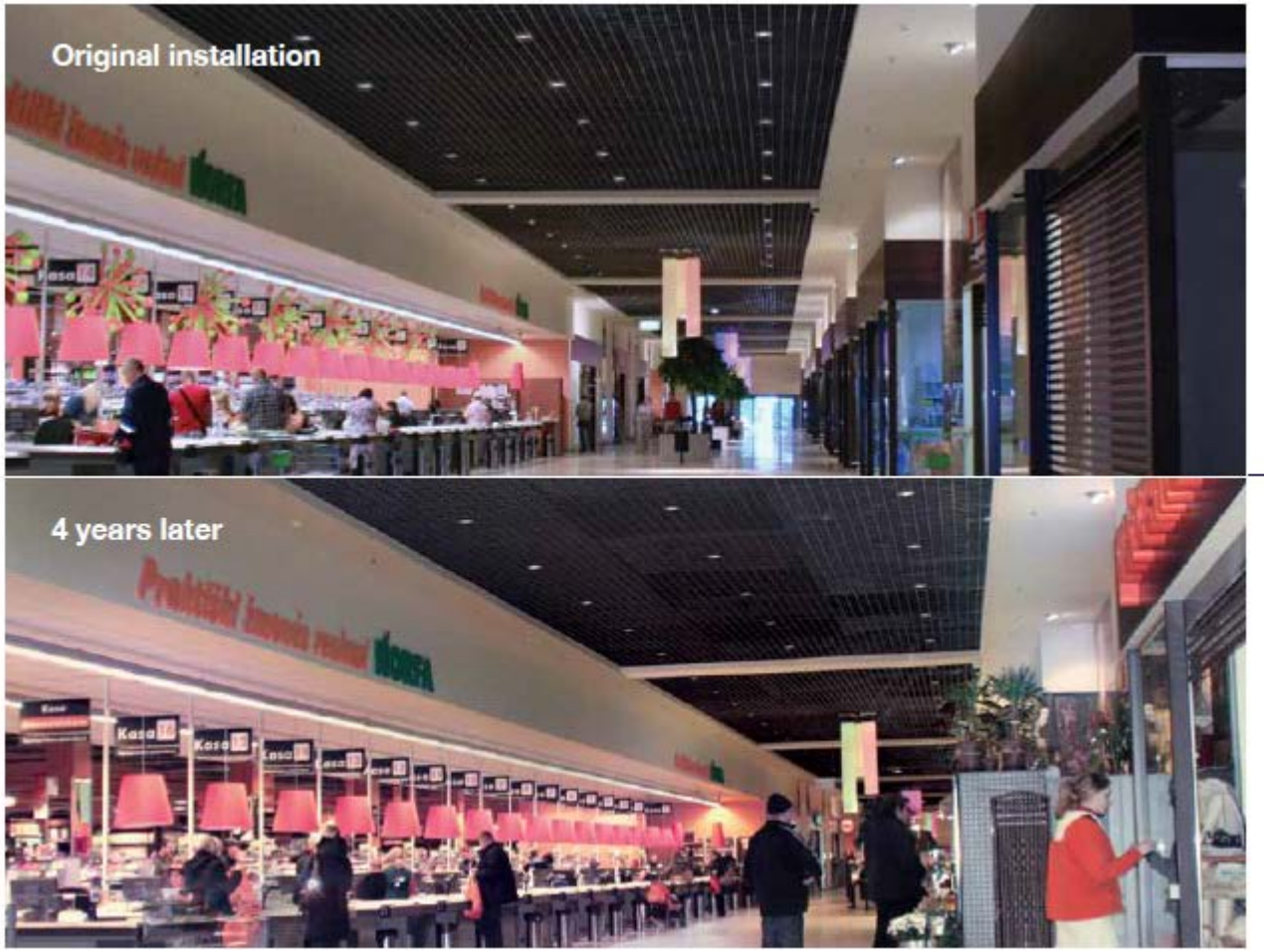


Δu’v’



1 SDCM ≈ 0.001 Δu’v’

Two aspects of Color Consistency

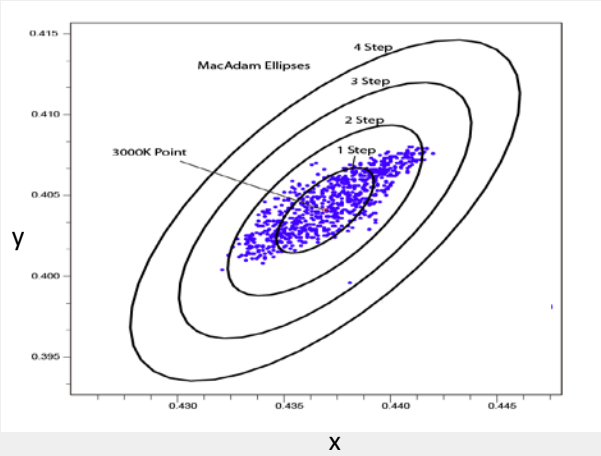


INITIAL

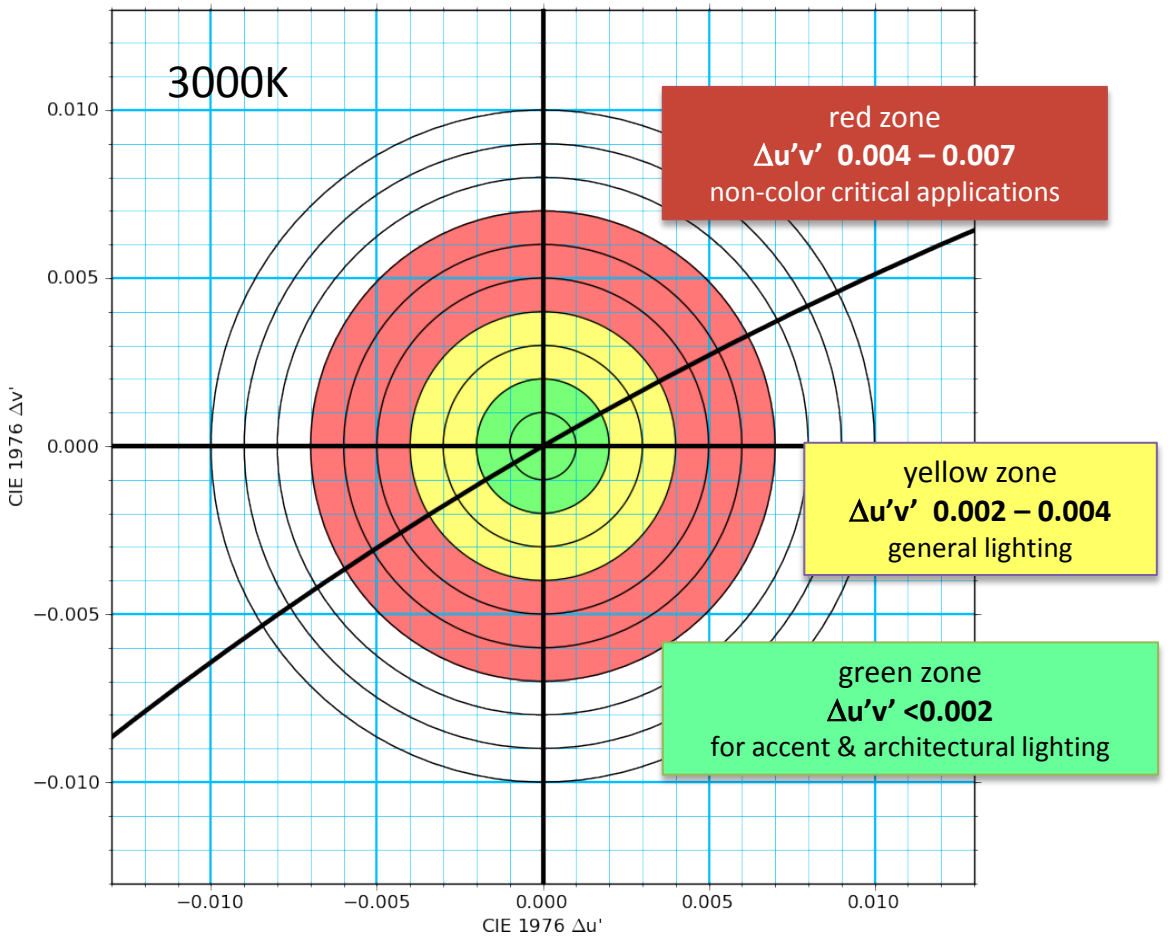
MAINTAINED

Initial Color Consistency

- Part to Part
  (e.g. same product)
- Product to Product
  (e.g. different product, same lumen package)



Tolerances: Initial Color Consistency

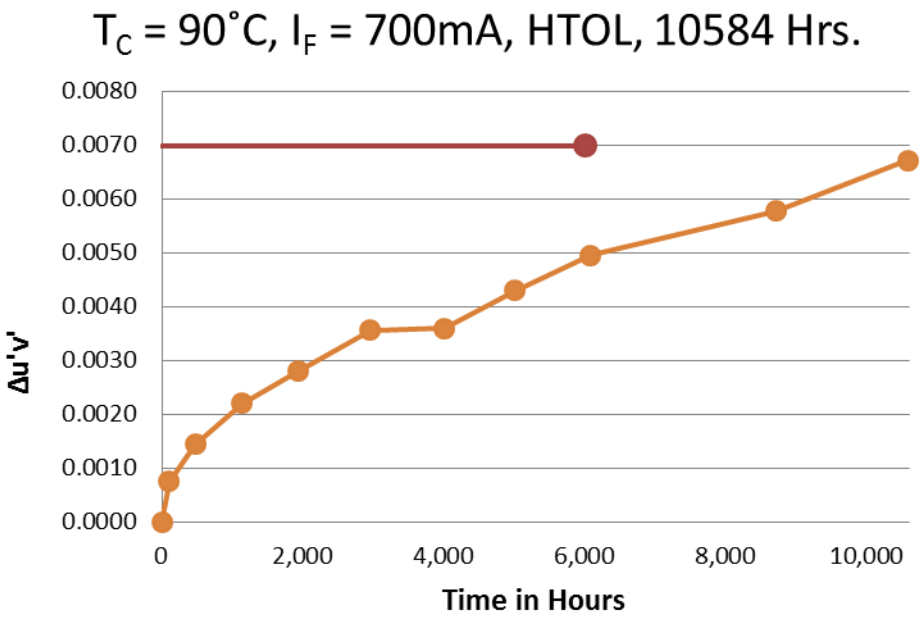


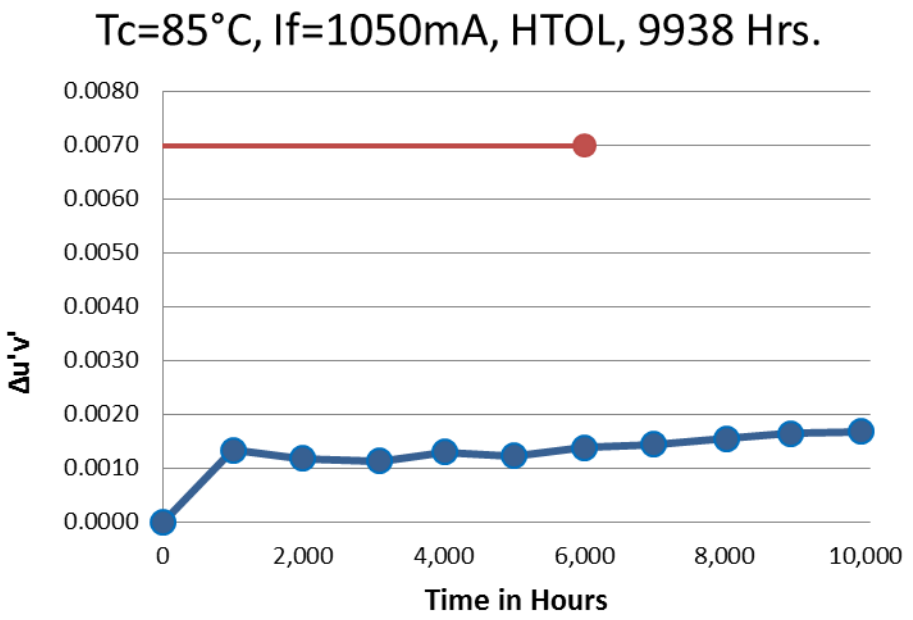
** Harbers et al, Visual Color Matching of LED and Tungsten-halogen Light Sources*

*** Rensselaer Polytechnic Institute, Lighting Research Center, Developing Color Tolerance Criteria for White LEDs, Assist Program*

Maintained Color Consistency

Absolute Shift



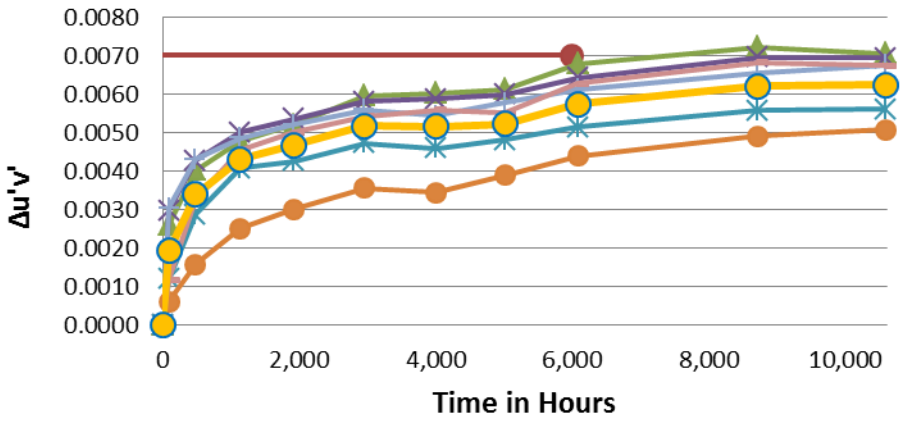


ENERGY Star

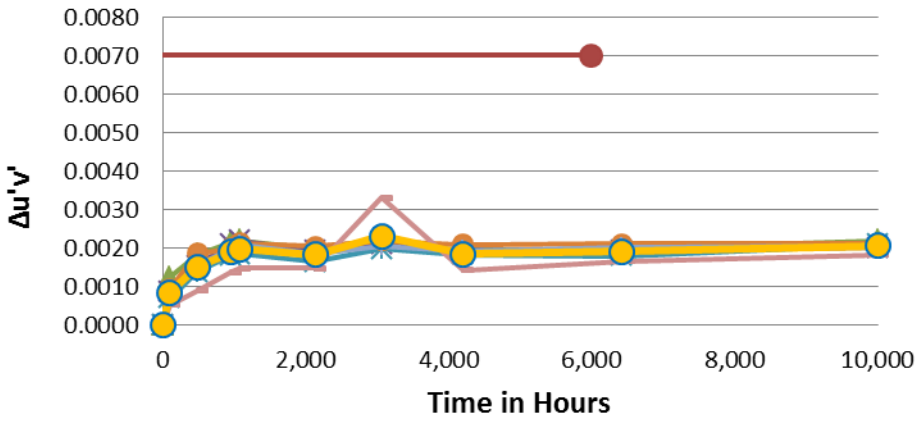
Maintained Color Consistency

Relative Shift

T_C = 90˚C, I_F = 700mA, HTOL, 10584 Hrs.



T_C = 90˚C, I_F = 700mA, HTOL, 10003 Hrs.

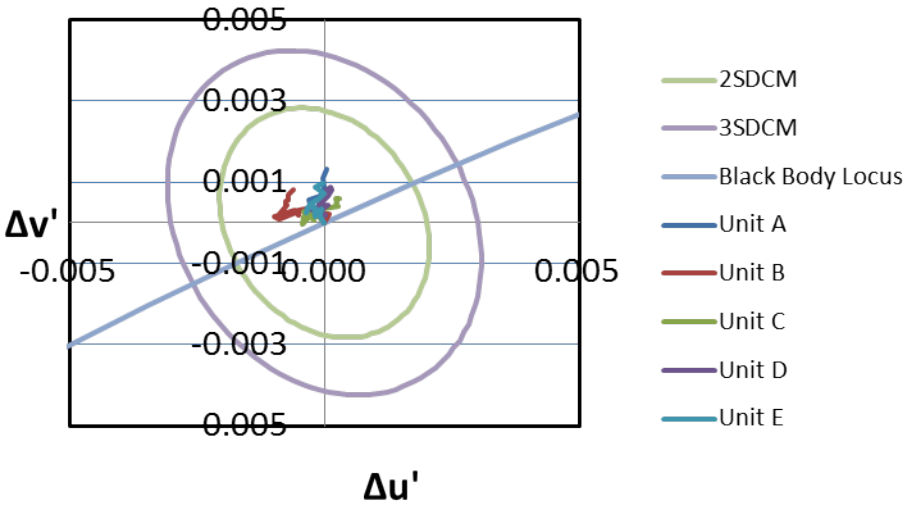


ENERGY Star

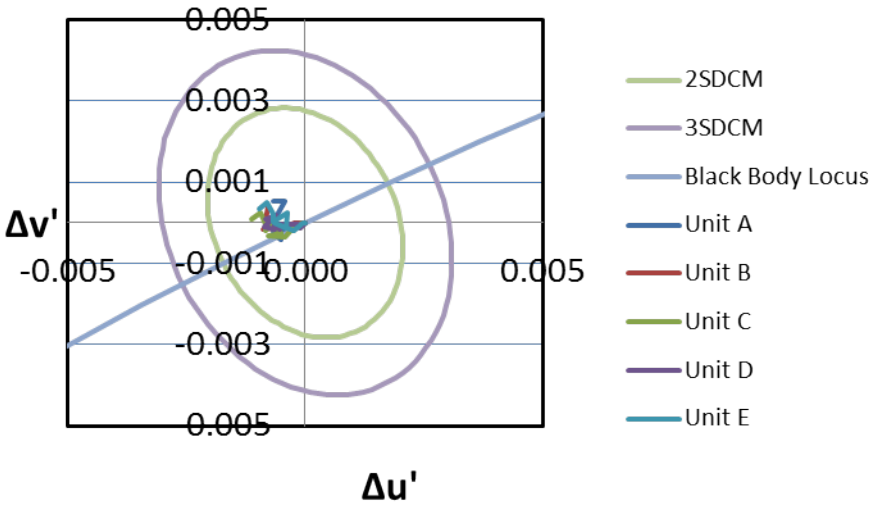
Maintained Color Consistency

Relative direction of shift is important!

T_C = 90˚C, I_F = 1050mA, HTOL, 8000 Hrs.



T_C = 90˚C, I_F = 1050mA, HTOL, 6106 Hrs.



Tighter tolerance on absolute shift does not guarantee visual coherence in a space

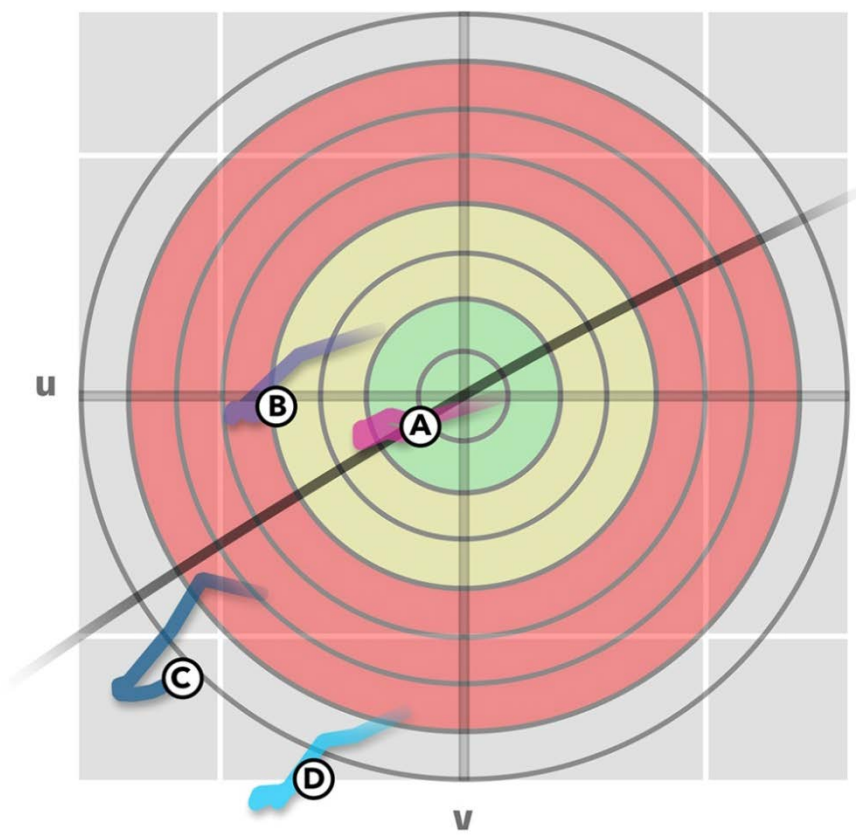
Tolerances: Maintained Color Consistency

Energy Star	Example Metric
• $\Delta u'v' < 0.007$ at 6000 hrs • IES LM-79-08 & IES LM-80-08 test methods • … too relaxed, need for less shift over longer time!	• $\Delta u'v' < 0.003$ at 50,000 hrs • C3/50,000 hrs

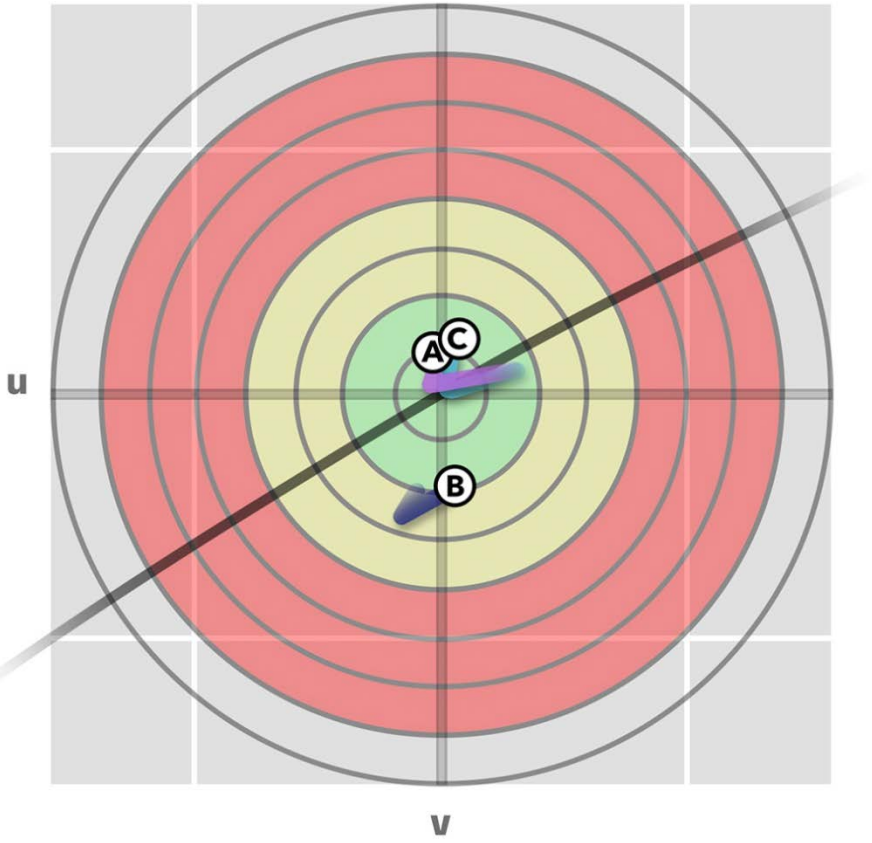
- Need for a standard projected color maintenance metric/methodologies (a la TM-21)
- Lack of which, only way to asses color maintenance is to look at manufacturer's datasheet and color warranty, if any.

Initial and Maintained Color Point Consistency: The Whole Picture

Supplier A



Supplier B



What about Color Rendering?

- Color Rendering examples:
  - *Consistent, but different color rendering (A).*
  - *Inconsistent color rendering (B)*
- Ensuring that (B) <u>does not</u> occur is most important.

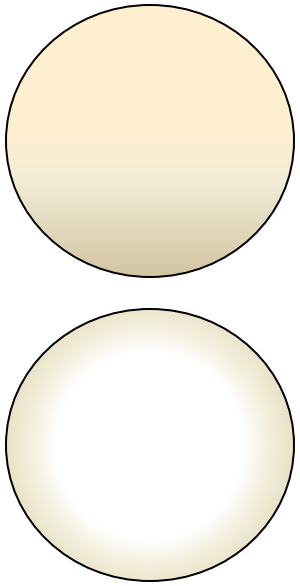
Desired color rendering consistency.

A

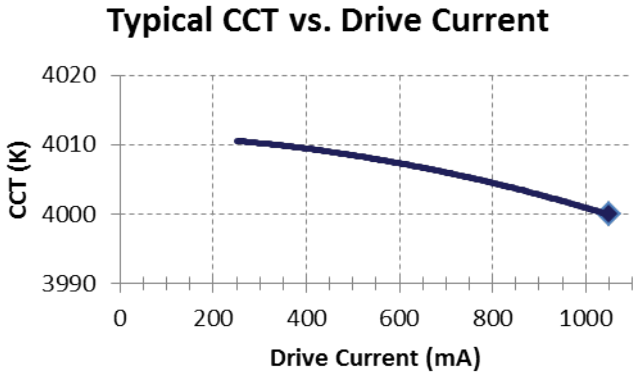
B

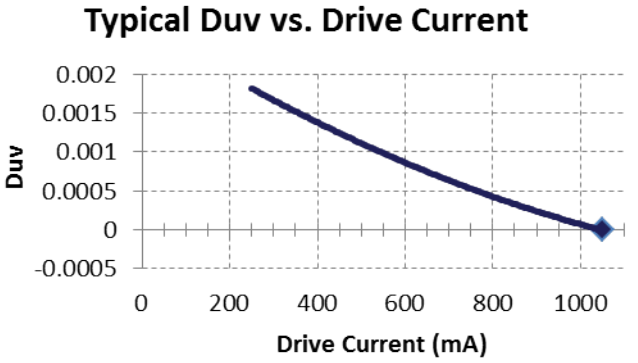
Other factors

Optics

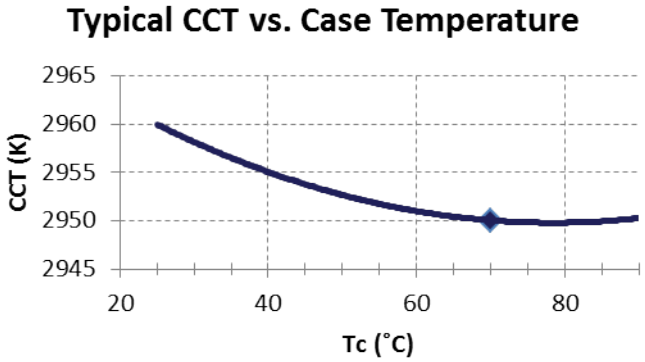


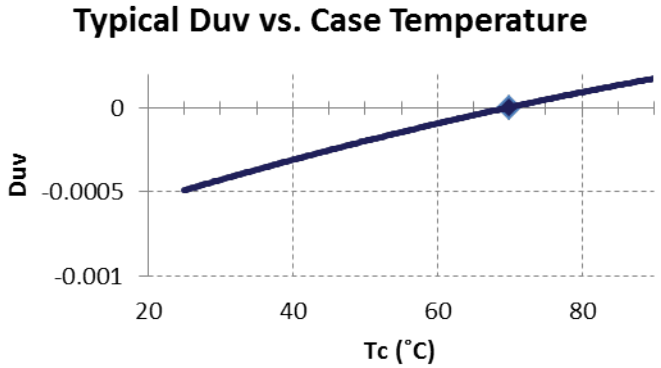
Drive Current





Temperature





Need to look at performance curves, if available from manufacturer, and optics to check if luminaire will result in color point shift (initial and maintained).

Conclusions

- There are limitations to quantification of visual perception.
- Both initial and maintained color consistency should be considered.
- Need for standard, tighter tolerances.
  - Or application dependent tolerances.
- Luminaire and installation conditions can negate the color consistency of LED packages/modules.