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Optimizing White Light Spectral Power Distributions to Any Action Spectrum

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Konica Minolta, Inc.

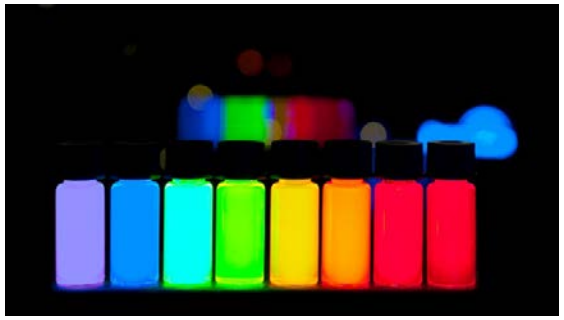
Outline

- Background / objective
- Ideas for optimized SPDs / advantage
- Examples
- Possible disadvantage
- Summary & future

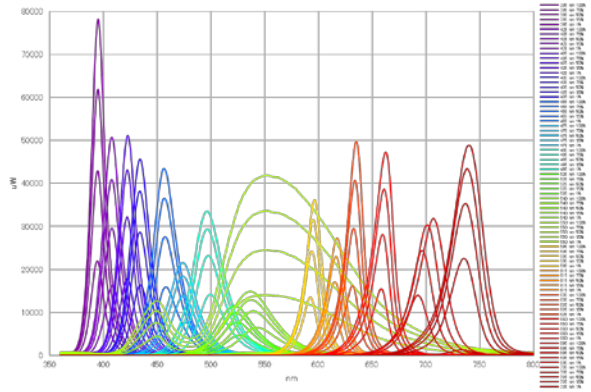
Background / Objective

- **Background**
  - **Any Spectral Power Distribution (SPD) for white light might be realized in the future**

How to use the freedom?



https://en.wikipedia.org/wiki/Quantum_dot

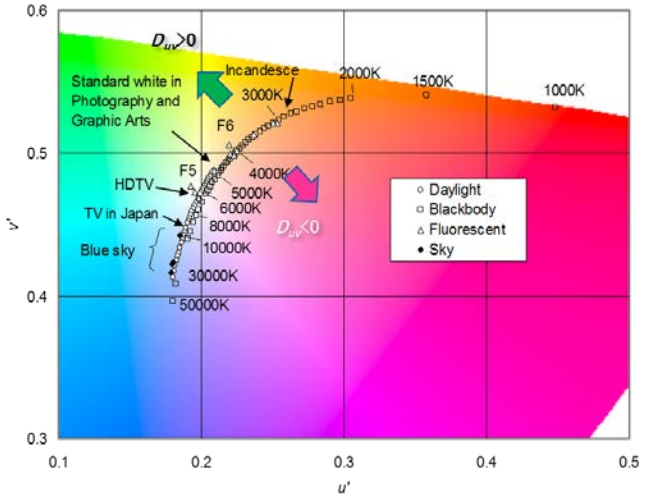


Telelumen Light Replicator (LEDs)

- **Objective**
  - **Optimize SPDs for any applications**
  - **Identify possible disadvantages**

Freedom in Spectrum

- **Evaluation of light**
  - Correlated Color Temperature
  - D_{uv}



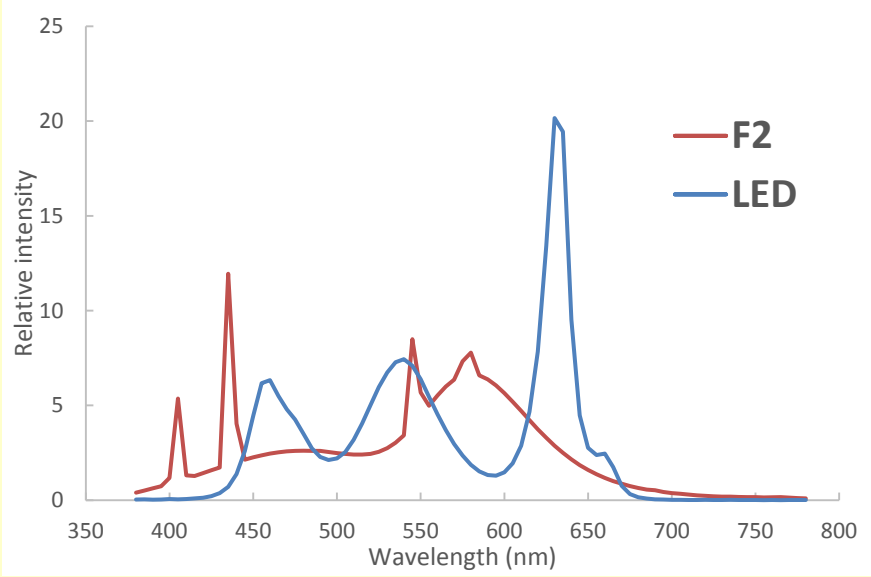
  - CRI (R_a)

Average Rendering Index *Ra*

Special Rendering Index *Ri*

- **Requirement from application side**
  - Lower energy consumption
  - Better color
  - Better biological response
  - Lower damage to objects…

An example: Two spectra having the same CCT (=4225K), D_{uv} (=0.0018) and R_a (=64)



How to optimize -> Use of action spectrum

Ideas for Optimizing White SPDs for Specific Applications

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Name	Applications	Function	Advantage	Action spectrum
Maximum LER	General lighting	Minimize energy consumption	Save energy	Luminosity function
Maximum Color Gamut	Retail, theater	Boost color saturation	Better sales at retailers	(color gamut)
Maximum Impact on ipRGC	Office, assisted living, airplane	Stimulate, wake-up	Prevent sleepiness, increase productivity	Melanopic function, or ipRGC (intrinsically photosensitive retinal ganglion cells) sensitivity
Minimum Impact on ipRGC	Assisted living, Sleep light, cockpits	Keep pupil open, Not to suppress Melatonin, not-to-awake	Safe in dark environment, Not-to-awake	
Museum Light	Museum, galleries	Minimize damage to fine arts	Preservation of art objects from fading	Damage function
No-Blue Light	Clean room (semiconductor manufacturing)	Reasonable CRI without 500nm or under	Comfortable work environment	Photoresist sensitivity

Optimization: Wanted & Unwanted Action Spectra

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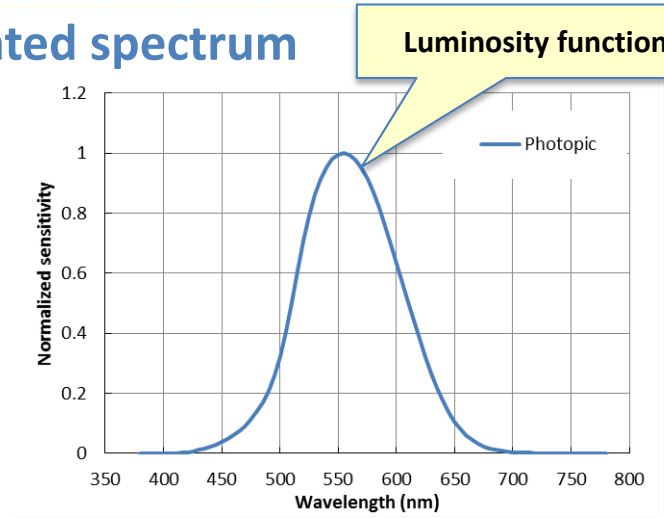
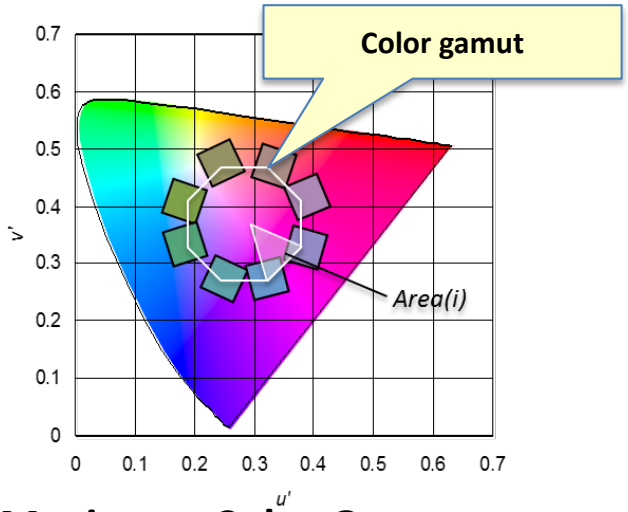
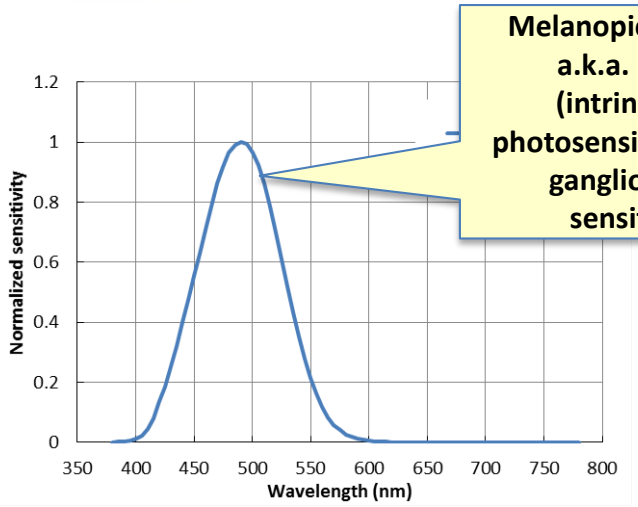
- **Wanted spectrum**



Maximum LER

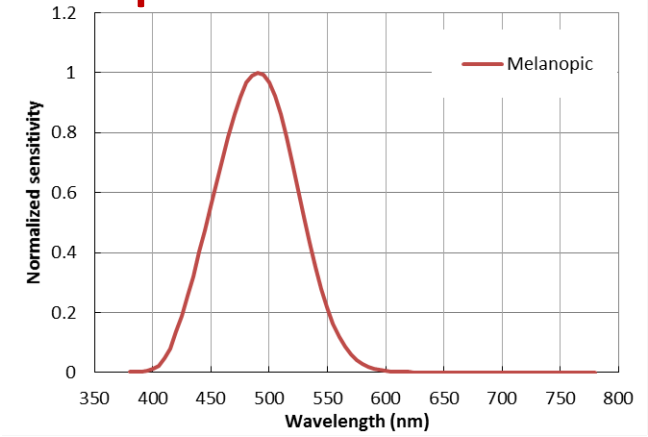


Maximum Color Gamut

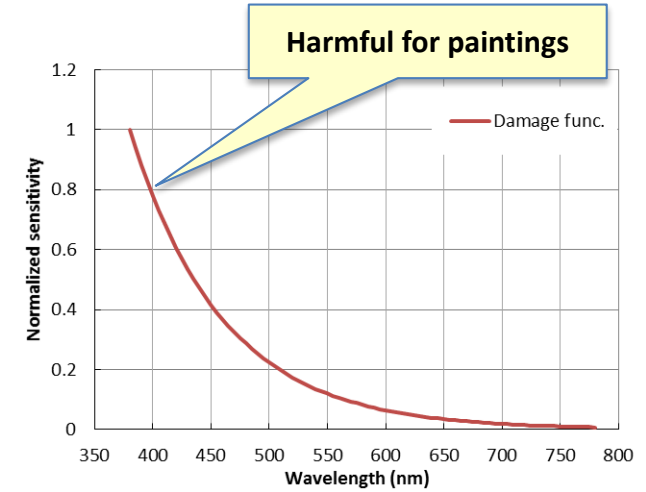


Maximum Impact on ipRGC

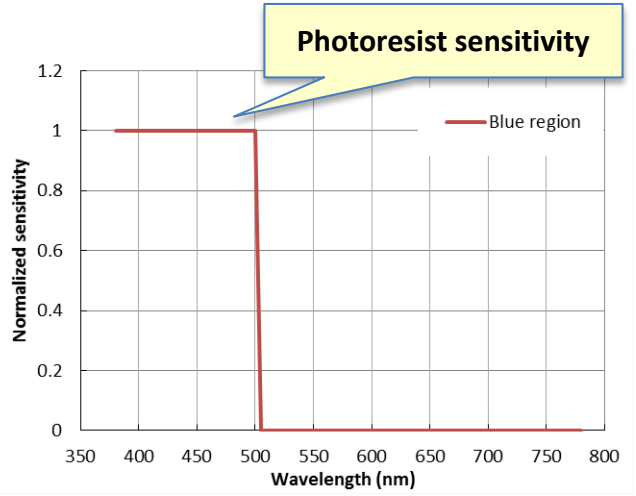
- **Unwanted spectrum**



Minimum Impact on ipRGC

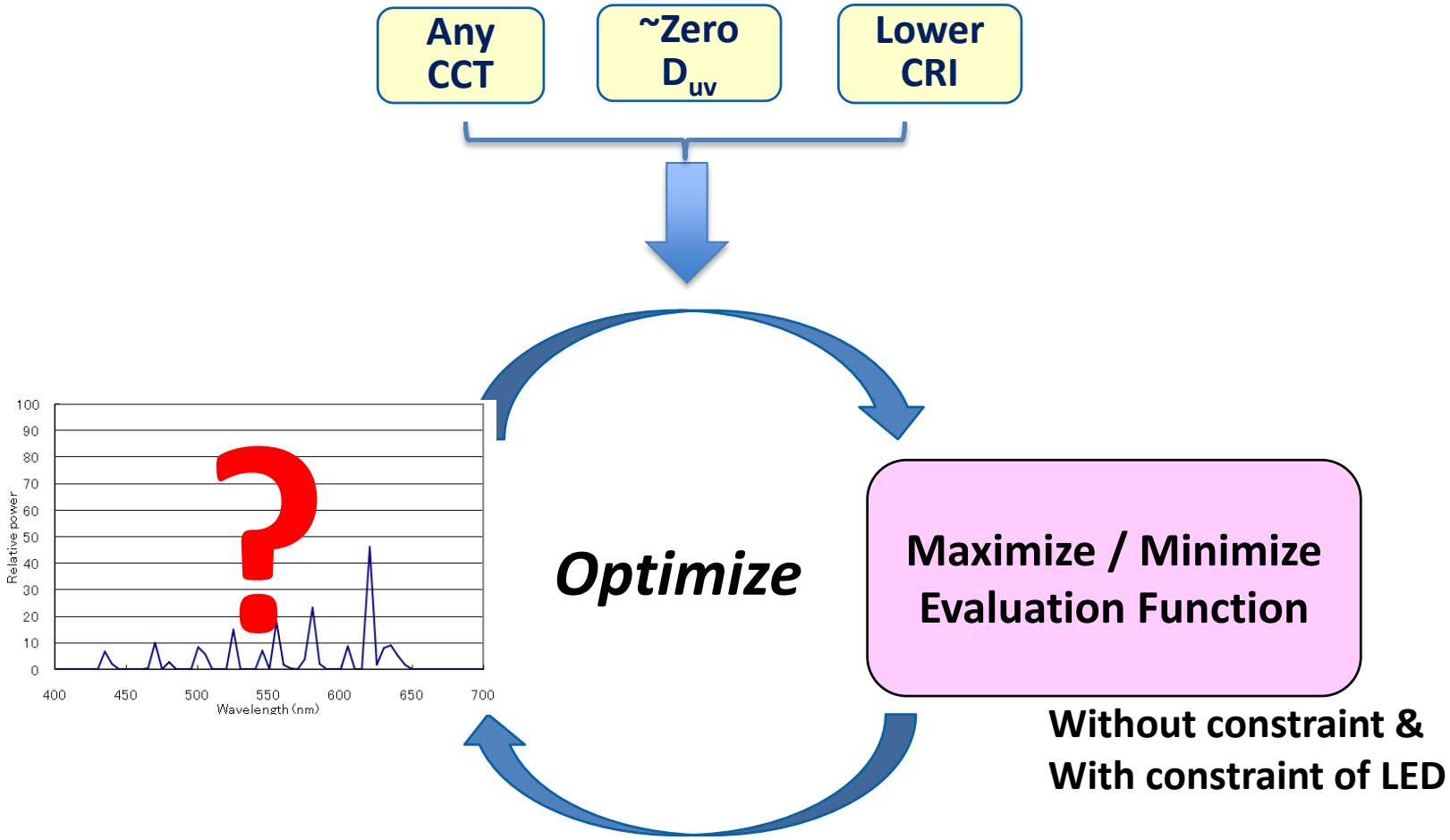


Museum Light



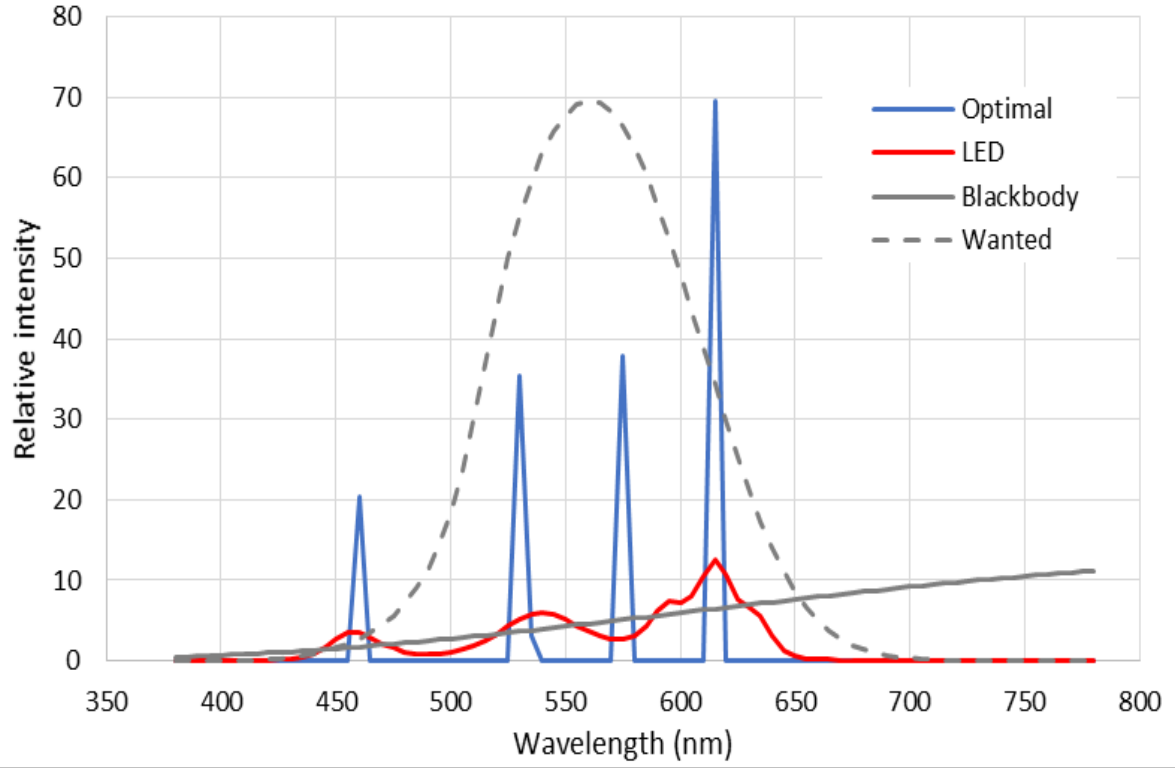
No-Blue Light

Optimization- General Approach



Maximum LER

- **To maximize energy efficiency**



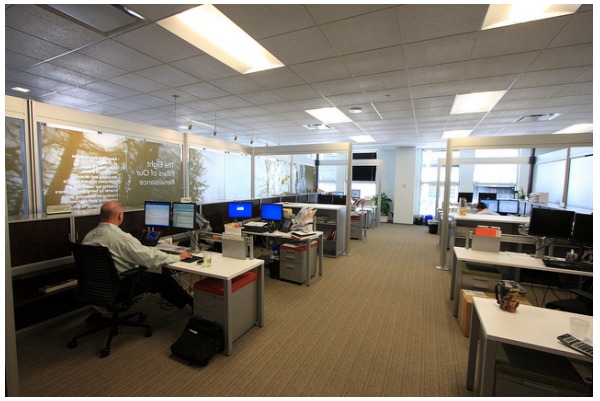
Condition:

CCT: 2856K

D_{uv}: 0

CRI: 90

$$\max\left[\frac{\int L(\lambda)\cdot V(\lambda)d\lambda}{\int L(\lambda)\cdot d\lambda}\right]$$



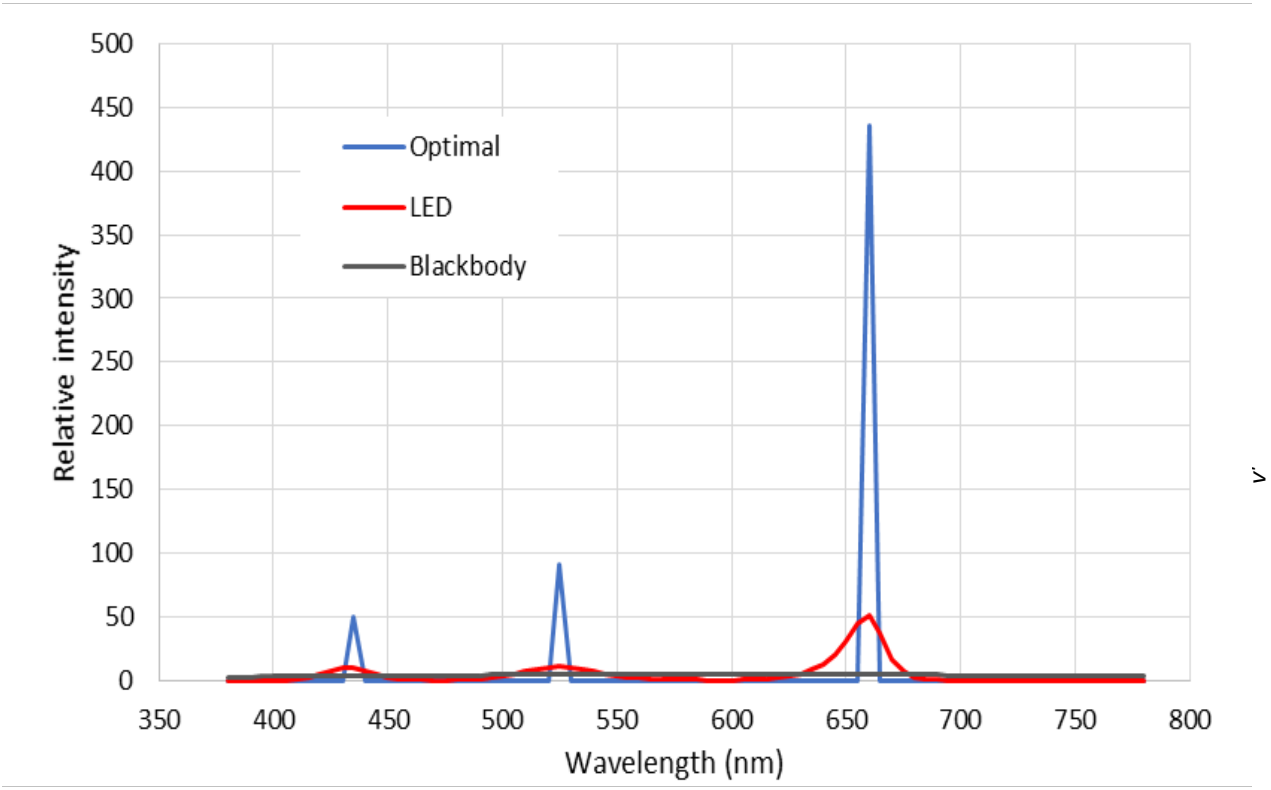
Tgldenver, flickr.com

Type	LER (lm/W)
Optimal	410
LED	379
Blackbody*	154

*** Calculated in 380-780 nm**

Maximum Color Gamut

- **To show the object colors appear saturated**

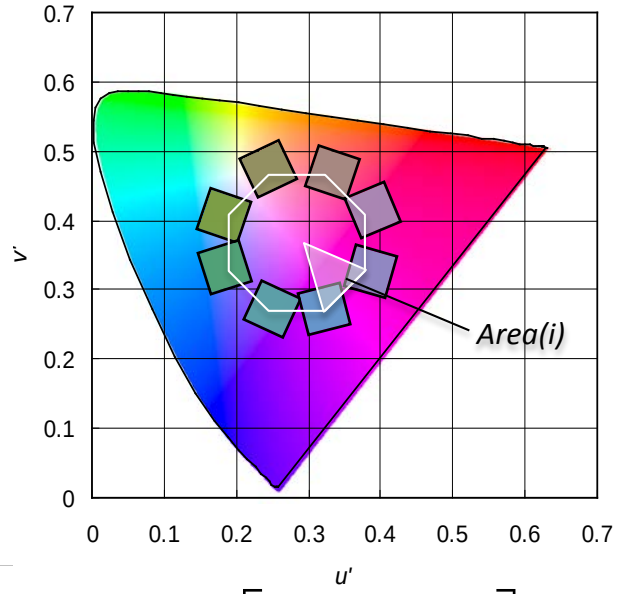


Condition:

CCT: 5000K

D_{uv}: 0

CRI: (do-not-care)



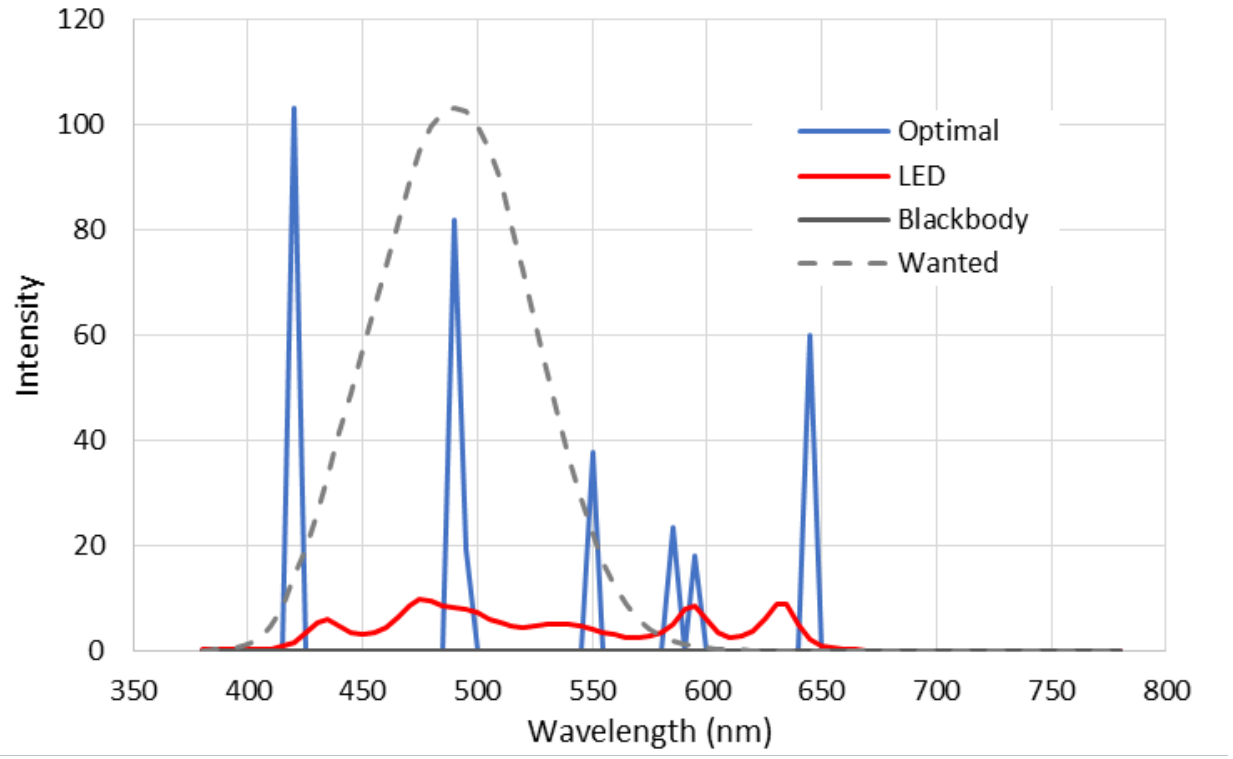
$$\max\left[\sum_{i=1}^{8} Area(i)\right]$$

Tim Murtaugh, flickr.com

Type	Gamut size
Optimal	179%
LED	156%
Blackbody	100% (ref.)

Maximum Impact on ipRGC

- To “wake-up”



Condition:

CCT: 6500K

D_{uv}: 0

CRI: 80

$$\max\left[\frac{\int L(\lambda)\cdot ipRGC(\lambda)d\lambda}{\int L(\lambda)\cdot V(\lambda)d\lambda}\right]$$

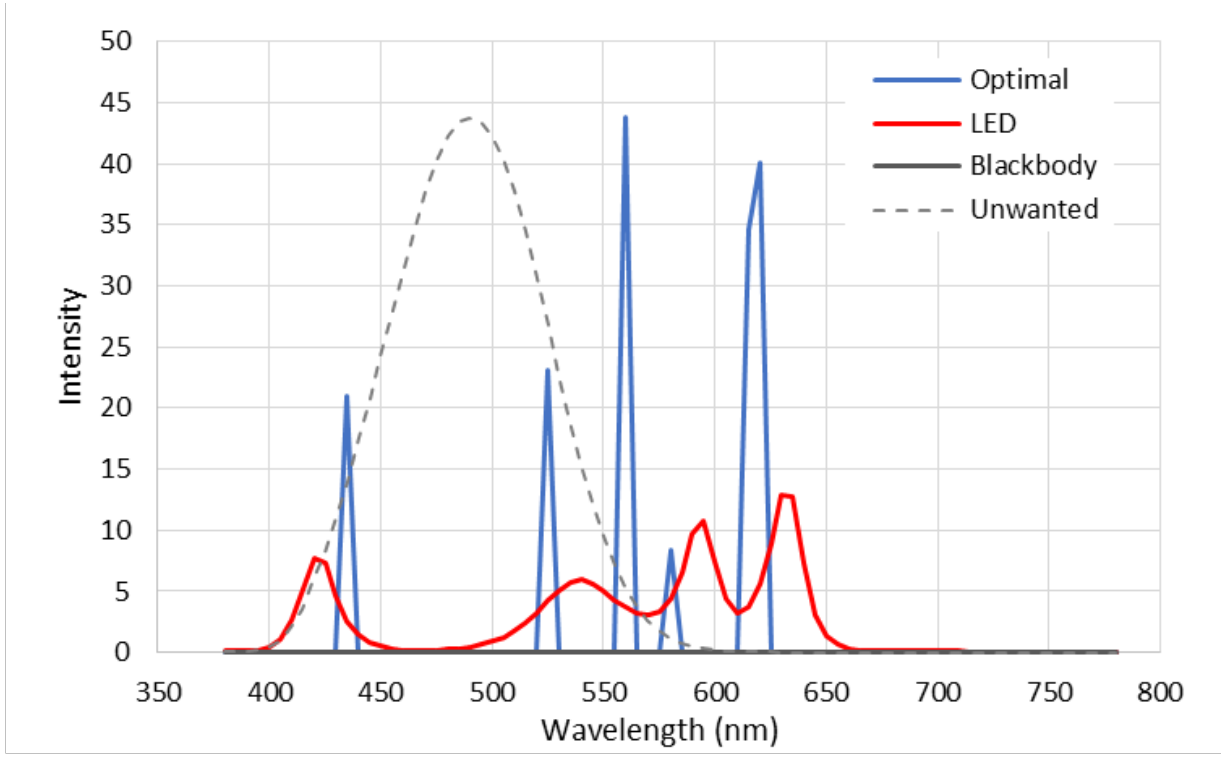
With LER concerned

Doug, flickr.com

Type	Impact (D65 ref.)
Optimal	140%
LED	120%
Blackbody	100% (ref.)

Minimum Impact on ipRGC

- **Not to disturb circadian rhythm / to keep pupils open**



Condition:

CCT: 2856K

D_{uv}: 0

CRI: 80

$$\min\left[\frac{\int L(\lambda)\cdot ipRGC(\lambda)d\lambda}{\int L(\lambda)\cdot V(\lambda)d\lambda}\right]$$

With LER concerned

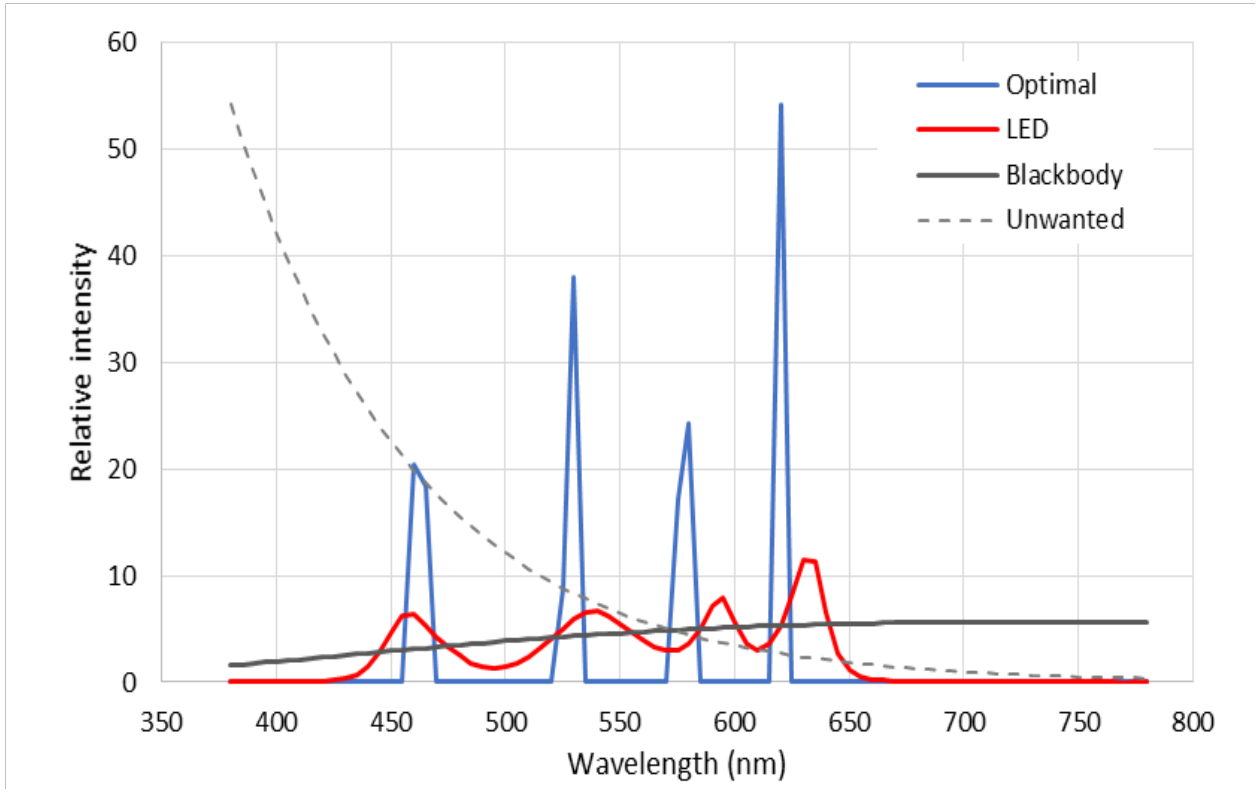
http://www.defense.gov/dodcmsshare/newsphoto/1999-08/990831-N-1056R-001.jpg

Type	Impact	Impact (D65 ref.)
Optimal	71%	30%
LED	84%	35%
Blackbody	100% (ref.)	42%

CIE TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry

Museum Light

- **To prevent fading of artifacts**



Condition:

CCT: 4000K

D_{uv}: 0

CRI: 95

dee_dee_creamer, flickr.com

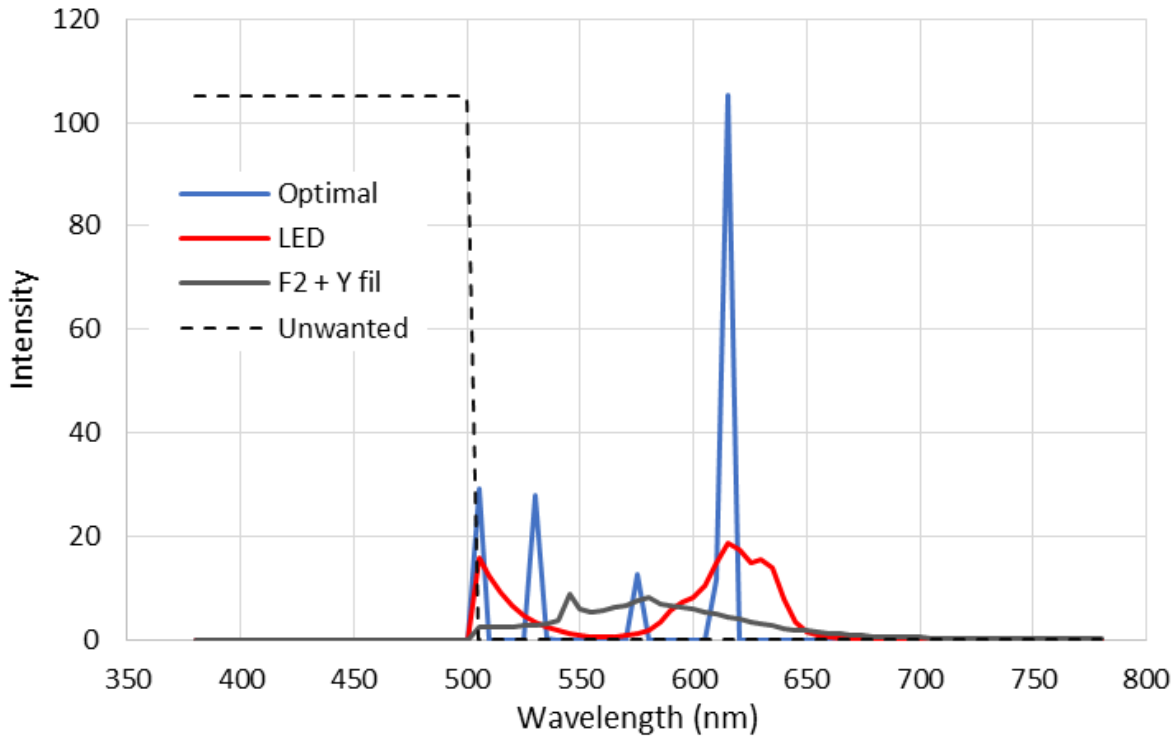
$$\min\left[\frac{\int L(\lambda)\cdot damage(\lambda)d\lambda}{\int L(\lambda)\cdot V(\lambda)d\lambda}\right]$$

Type	Impact
Optimal	57%
LED	64%
Blackbody	100% (ref.)

CIE publication 157 Damage function

No-blue Light

- **No power below 500nm to avoid exposure to photoresist**



Condition:

CCT: 2000K

D_{uv}: 0.005

CRI: 45

$$\min\left[\frac{\int L(\lambda)\cdot blue\_region(\lambda)d\lambda}{\int L(\lambda)\cdot V(\lambda)d\lambda}\right]$$

Megan,Laver, flickr.com

Type	CCT	D_{uv}	CRI-Ra	CRI-R9
Optimal	2000	0.005	45	20
LED + Y filter	2000	0.005	45	75
F2 + Y filter	3235	0.034	33	-127

Color Appearances Under 6 SPDs

- Note: Camera spectral sensitivity does not match color matching functions of human eye

Maximum LER

Maximum Color Gamut

Maximum Impact on ipRGC

Minimum Impact on ipRGC

Museum Light

No-Blue Light

Result of Optimization

End up with spiky spectrum while color rendering is kept.

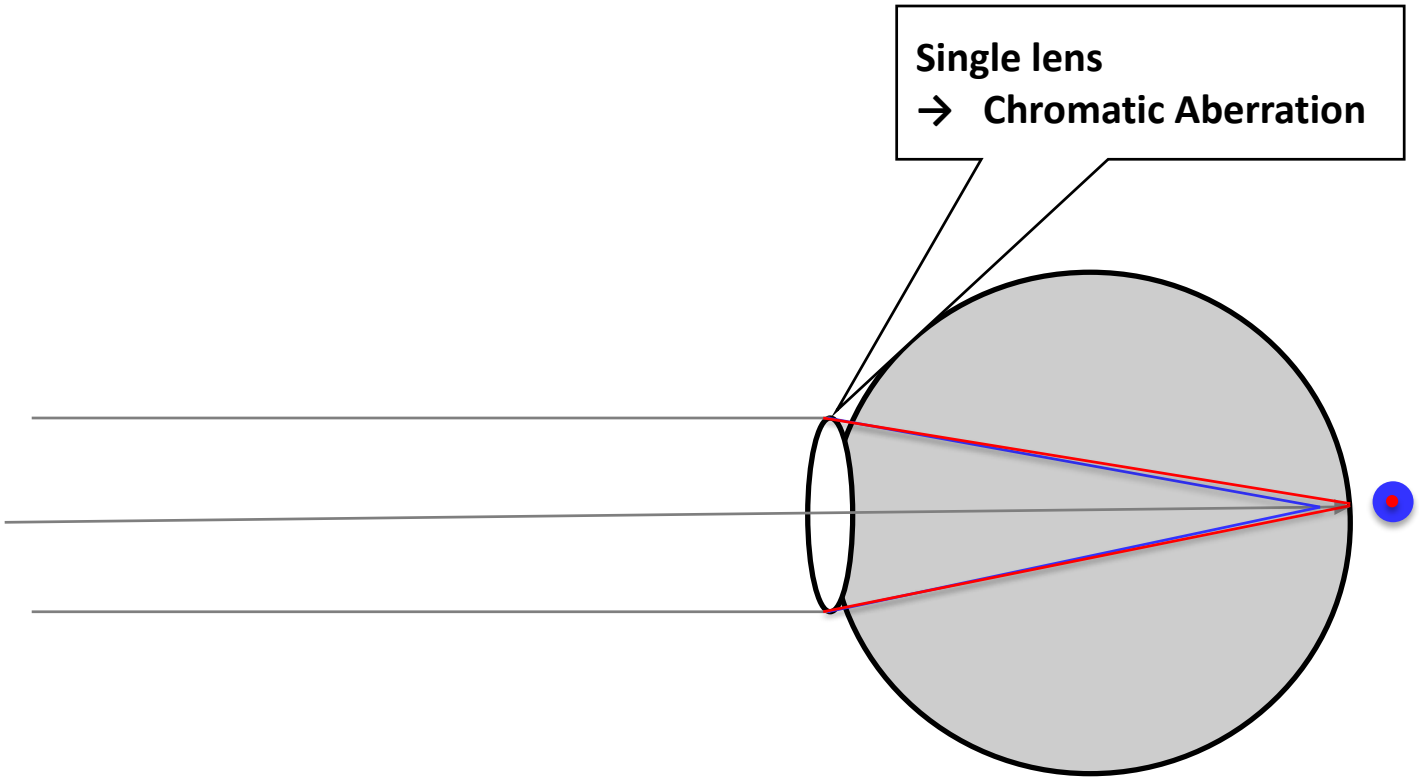
Why?

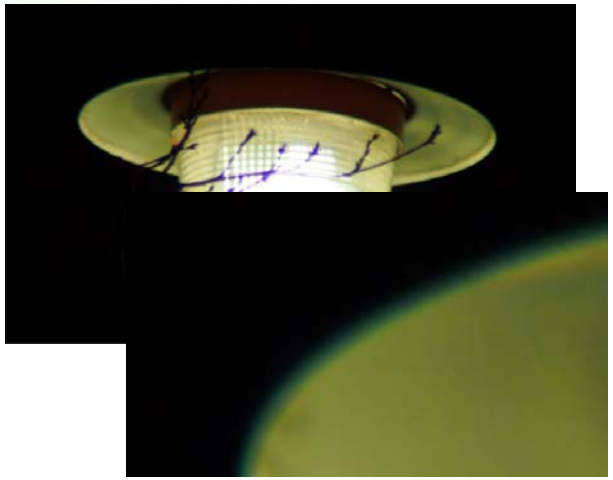
- **Optimization creates “extreme” spectrum**
- **Usual reflective materials have a commonality in spectrum domain**
  - **5-6 principle components can produce almost any spectral reflectance**

Possible Disadvantages of Spiky Spectra

- Chromatic aberration
- Bad color reproduction by camera

Possible Disadvantage: Chromatic Aberration





Possible disadvantage: Bad Color Reproduction by Camera

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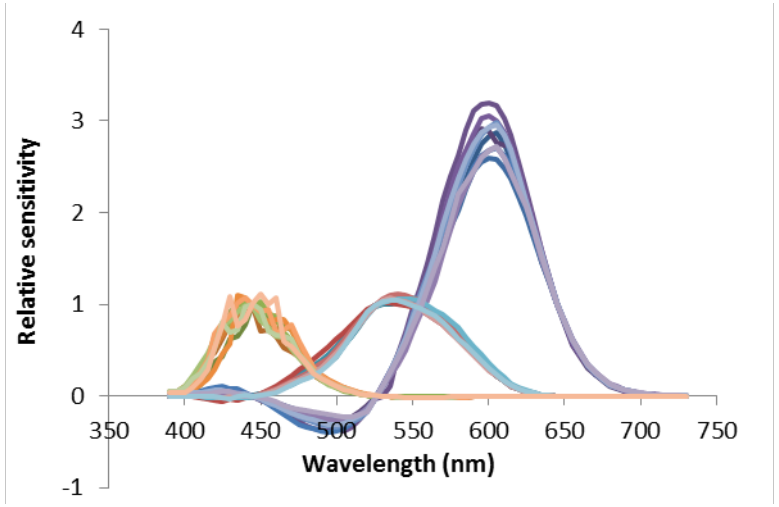
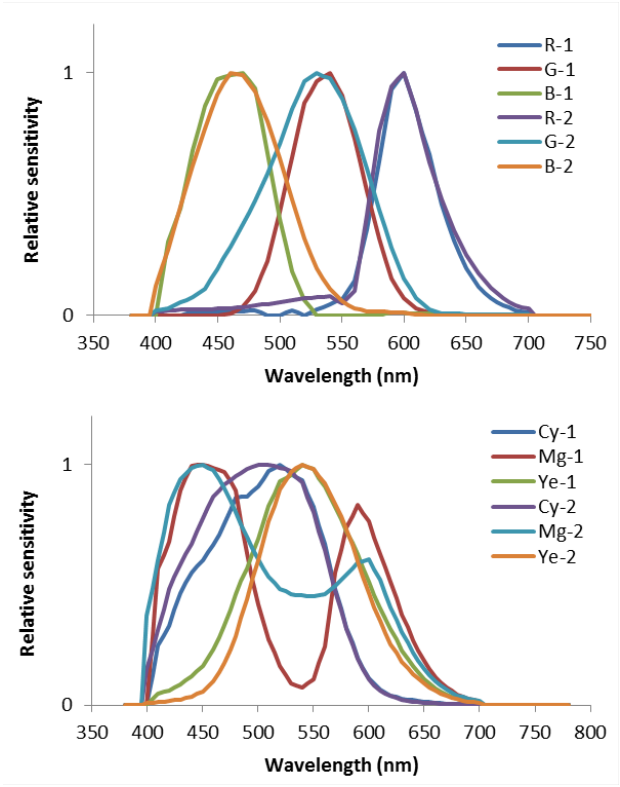
Simulation

- Color Matching Function (CMF) by Stiles and Burch (=10 sets)
- RGB filter and CMY filter camera (=4 sets)



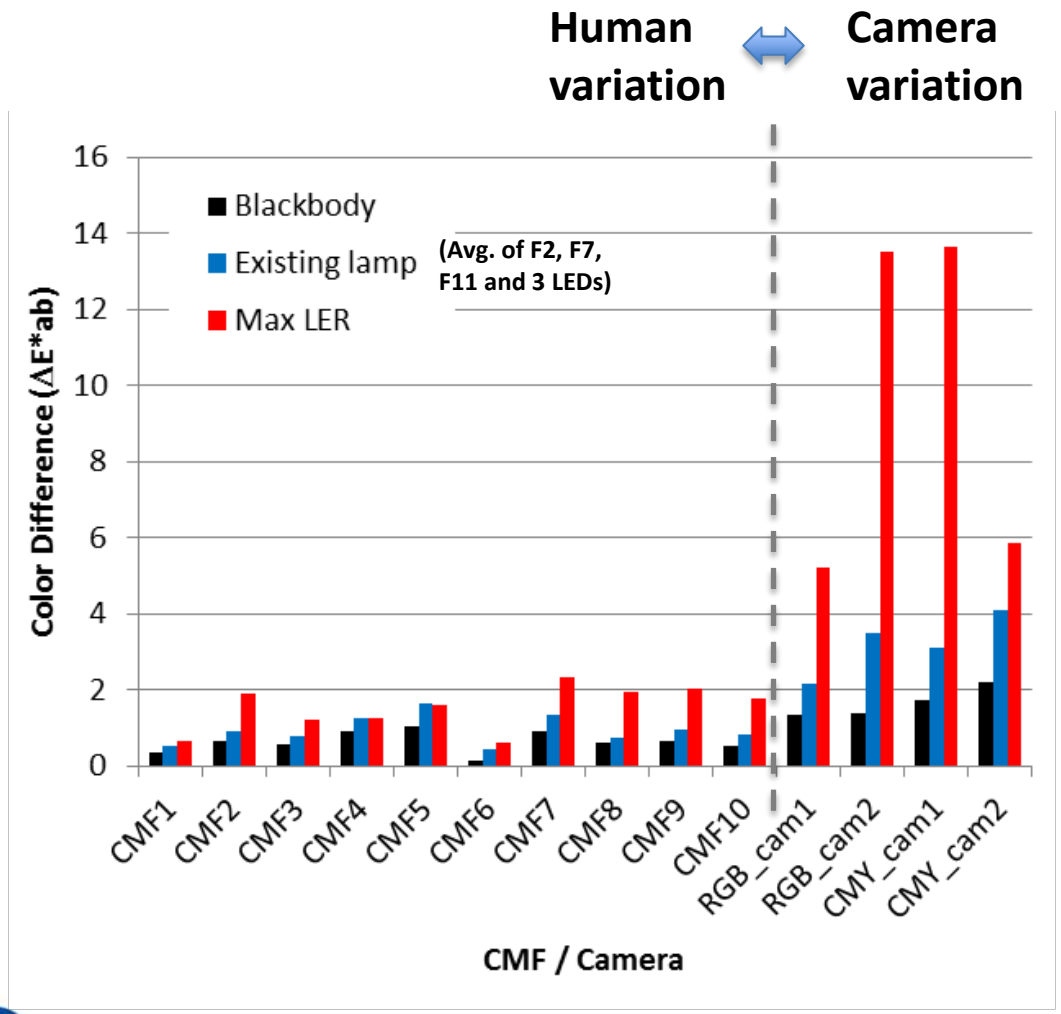
Eye variation



Camera variation (RGB/CMY)

Possible disadvantage: Bad Color Reproduction by Camera

- **Camera may give larger color reproduction errors by spiky light sources**



Summary / Future

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◆Optimization is possible for any application:

- Better result while keeping a moderate color reproduction
- Action spectrum or color gamut can be used
- Spectrum will be spiky

◆Possible disadvantages caused by spiky spectrum:

- May emphasize chromatic aberration for eyes
- May cause bad color reproductions by cameras

However…

More & New Values by Tuning Spectrum

Acknowledgements

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