CORM 2008

CORM Council for Optical Radiation Measurements

What over Watts?

Mark S. Rea

June 10, 2008

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Ban the bulb!

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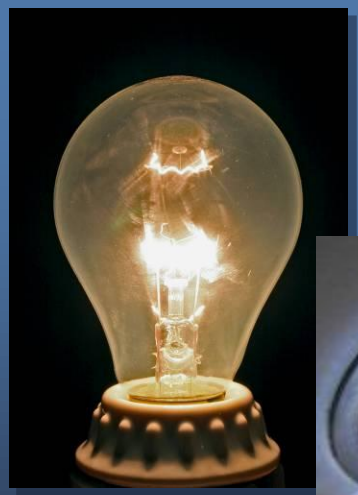
Lighting Research Center

Rensselaer

What over watts?

- We use luminous efficacy (lm/W) to compare the effectiveness of lighting systems



12 lm/W

35 lm/W

55 lm/W

100 lm/W

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What over watts?

- Simple, fundamental questions
  - What do we mean by efficacy (as opposed to efficiency)?
  - In general, efficacy is benefit/cost
  - In lighting, efficacy is lumens/watt
  - What does lumens/watt really mean?

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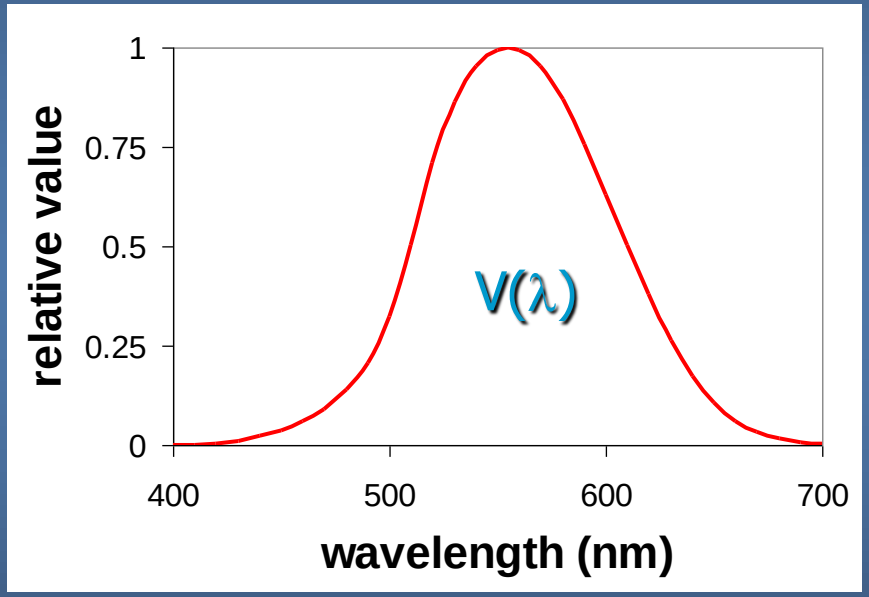
What does lumens/watt really mean?

- Conceptual definition
  - Radiant energy capable of creating a visual sensation
- Official definition
  - Radiant energy weighted by the photopic luminous efficiency function, V(λ)



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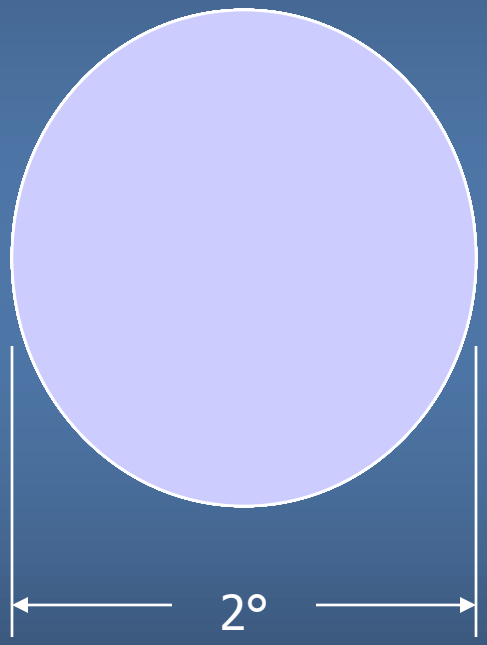
What is V(λ)?

- Basis for V(λ)
  - Flicker photometry (mainly)



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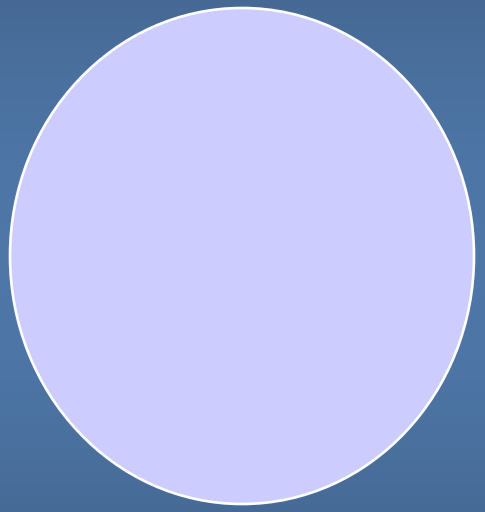
What is V(λ)?

- Why flicker?
  - Precision and repeatability (CIE, 1924)
  - Related to speed of visual performance
    - Societally important in early 20th century



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V(λ)-like responses

- Reaction times
  - Also appears to capture response speed (Lennie et al., 1993)
- Visual performance (Smith and Rea, 1980)
- Visual acuity (Luckiesh, 1912)
- Minimally distinct border (Boynton and Kaiser,1968)
  - Different visual channel (high spatial resolution, longer integration time)
  - But rely on same photoreceptors (foveal cones)

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What over watts?

Source	lm/W
Incandescent	12
CFL 2700 K	55
T8 fluorescent 3000 K	100
T8 fluorescent 4100 K	100
T8 fluorescent 6500 K	90
T12 fluorescent 7500 K	55
Metal halide	95
White LED	35

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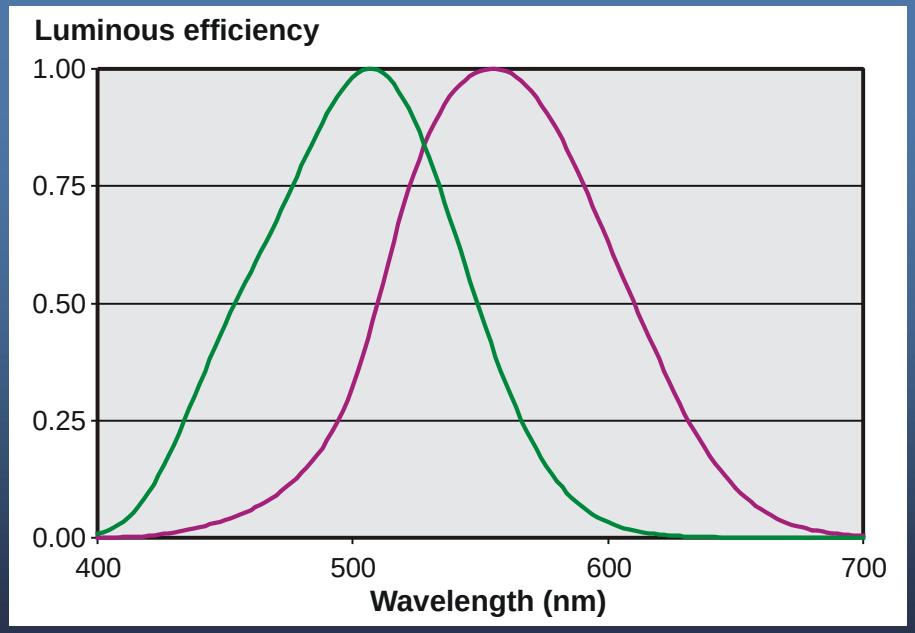
Lumens per watt

- But there are actually two formal definitions of light
  - Photopic and scotopic



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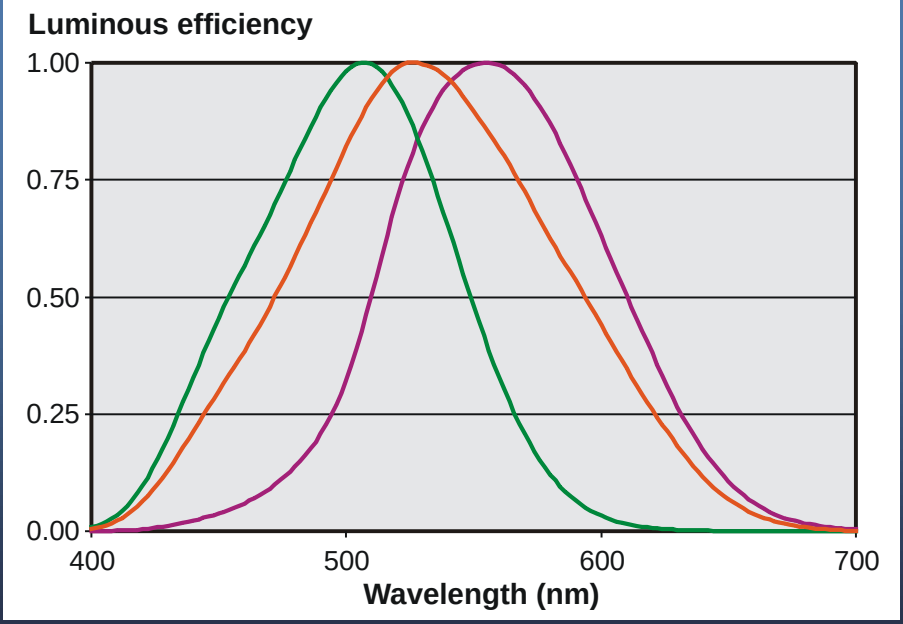
Lumens per watt

- From a lighting perspective scotopic doesn't matter much, but mesopic (photopic + scotopic) does



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Dynamic range of human vision compared to range of electric lighting

Luminance (cd/m²)	Physical Description	Human Response	
10^{10}	Sun's surface at noon	Damaging	
10^{9}			
10^{8}			
10^{7}		Photopic	
10^{6}	100 W lamp filament		
10^{5}			
10^{4}	Paper under sun		
10^{3}			
10^{2}	Paper in office		Interior lighting recommend-ations
10			
1		Mesopic	Exterior lighting recommend-ations
10^{-10}			
10^{-2}	Paper under moon		
10^{-3}		Scotopic	
10^{-4}	Paper under stars		
10^{-5}			
10^{-6}			

Adapted from
Sekuler and Blake, 1990

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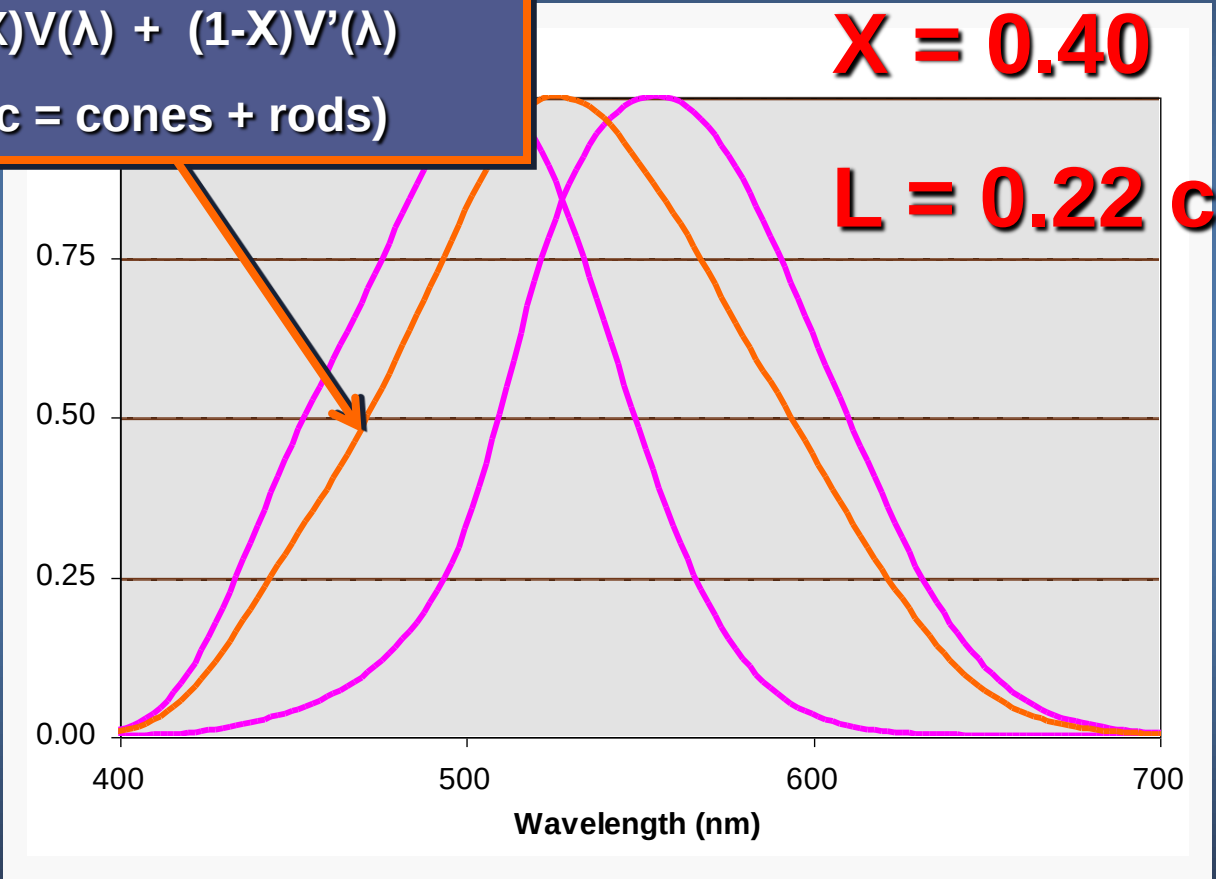
Mesopic luminous efficiency functions

$V_{mes} = (X)V(\lambda) + (1-X)V'(\lambda)$

(mesopic = cones + rods)



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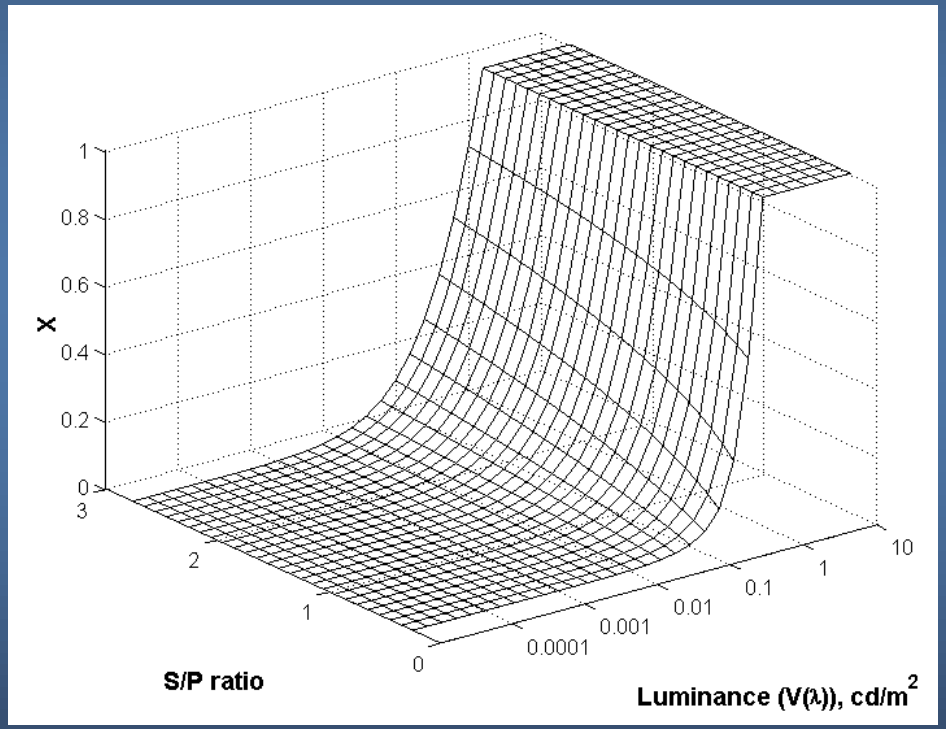
Unified System of Photometry

- Values of X for $V_{mes} = X\,V_\lambda + (1–X)\,V'_\lambda$ different light levels in terms of photopic (V_λ) luminance (cd/m²), and different light source spectral power distributions in terms of S/P (ratio of scotopic [V'_λ] to photopic [V_λ] lumens)



Rea et al., 2004

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Mesopic lumens per watt

- Illuminance [V(λ)] and normalized power requirements for different light sources needed to provide equivalent values of X (ref: 400 W HPS @ 0.6, 0.3 and 0.1 cd/m²; 0.07 reflectance)

Light source (S/P ratio)	X = 1.00 @ 0.6 cd/m²		X = 0.44 @ 0.3 cd/m²		X = 0.12 @ 0.1 cd/m²	
	Illuminance (lux)	Power (%)	Illuminance (lux)	Power (%)	Illuminance (lux)	Power (%)
180W LPS (0.25)	26.9	69%	16.0	82%	7.6	118%
400 W HPS (0.66)	26.9	100%	13.5	100%	4.5	100%
400 W MH (1.57)	26.9	119%	10.0	88%	2.4	63%
Fl. 6500 K (2.19)	26.9	130%	8.5	82%	1.8	52%

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What over watts?

Source	lm/W	Mesopic/W*
Incandescent	12	12
CFL 2700 K	55	47
T8 fluorescent 3000 K	100	86
T8 fluorescent 4100 K	100	109
T8 fluorescent 6500 K	90	122
T12 fluorescent 7500 K	55	79
Metal halide	95	108
White LED	35	52

* X = 0.15

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Brightness perception

- In many spaces, brightness appearance can be as or more important than visual performance
  - Museums, art galleries, lobbies
- Luminance ≠ brightness
- Brightness is nonlinear (1+1≠2!)
  - Dresler (1953); Alman (1977); Ware and Cowan (1983)

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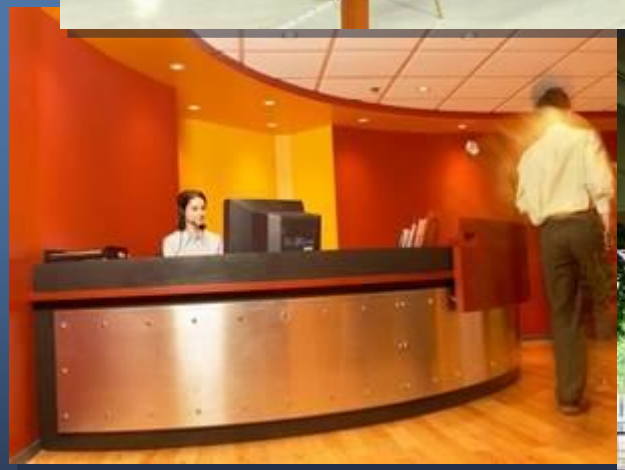
Brightness perception



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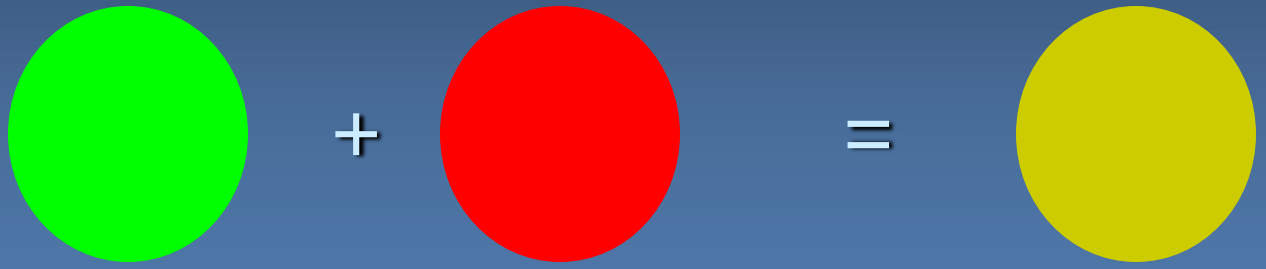
Luminance is linear



L(g) + L(r) = L(y)

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Brightness is nonlinear!

$B(g) + B(r) \neq B(y)$

In fact…

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Brightness is nonlinear!

B(g) or B(r) > B(y) !!!

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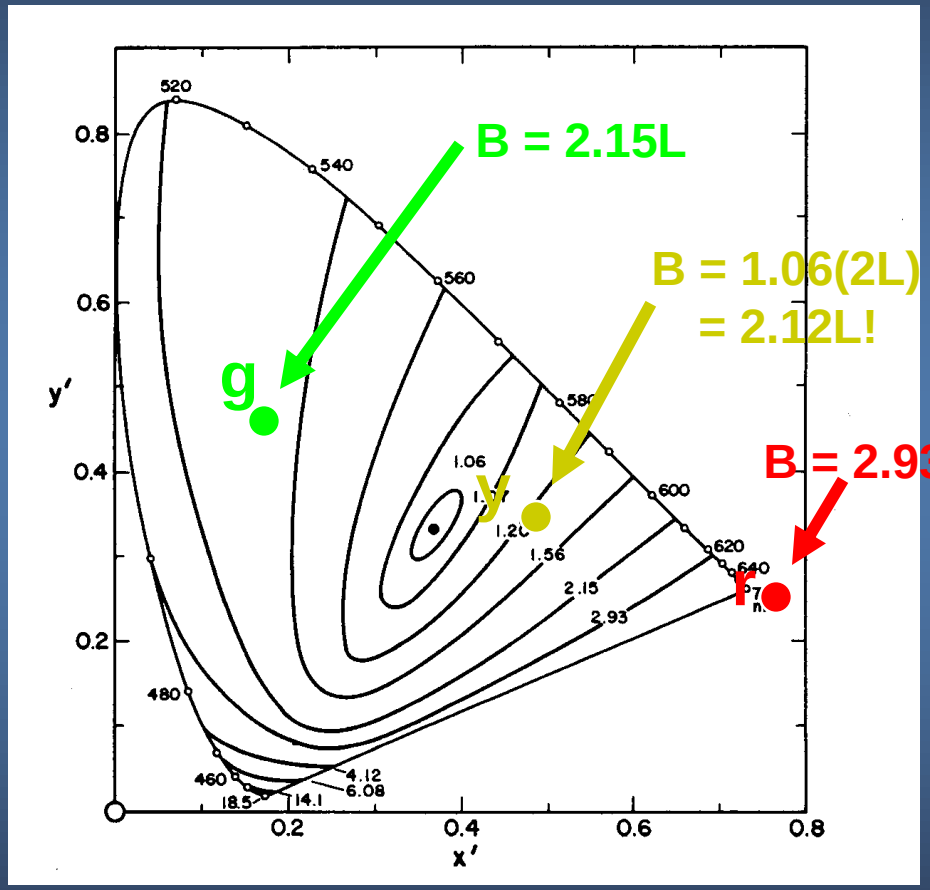
Brightness/luminance ratios

- Assuming r and g have the same luminance (L):
  - B(r) = 2.93L
  - B(g) = 2.15L
  - B(y) = 1.06(2L) = 2.12L



Guth et al. (1980)

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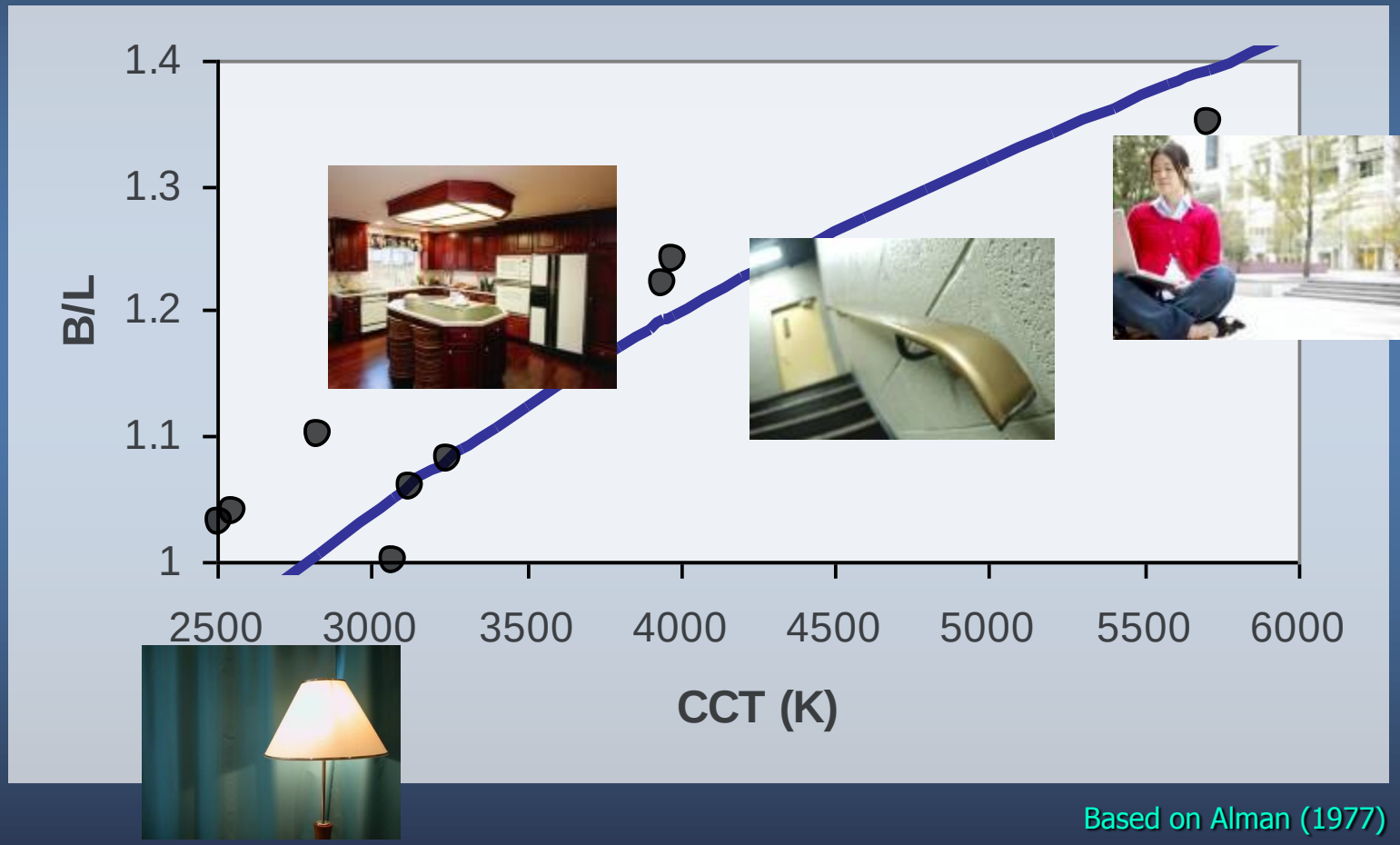
Brightness/luminance ratios for white light sources



Based on Alman (1977)

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Warm white vs. cool white

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What over watts?

Source	lm/W	Mesopic/W	Brightness/W
Incandescent	12	12	12
CFL 2700 K	55	47	56
T8 fluorescent 3000 K	100	86	101
T8 fluorescent 4100 K	100	109	101
T8 fluorescent 6500 K	90	122	99
T12 fluorescent 7500 K	55	79	64
Metal halide	95	108	97
White LED	35	52	41

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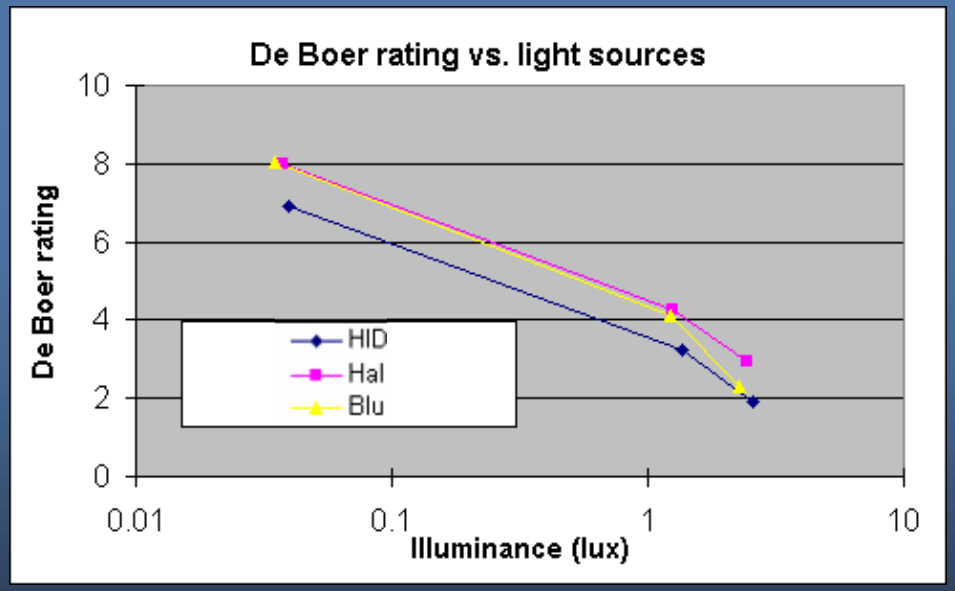
Discomfort glare and headlights

- For example, high intensity discharge headlamps are rated as more uncomfortable than halogen headlights



Bullough et al. (2002)

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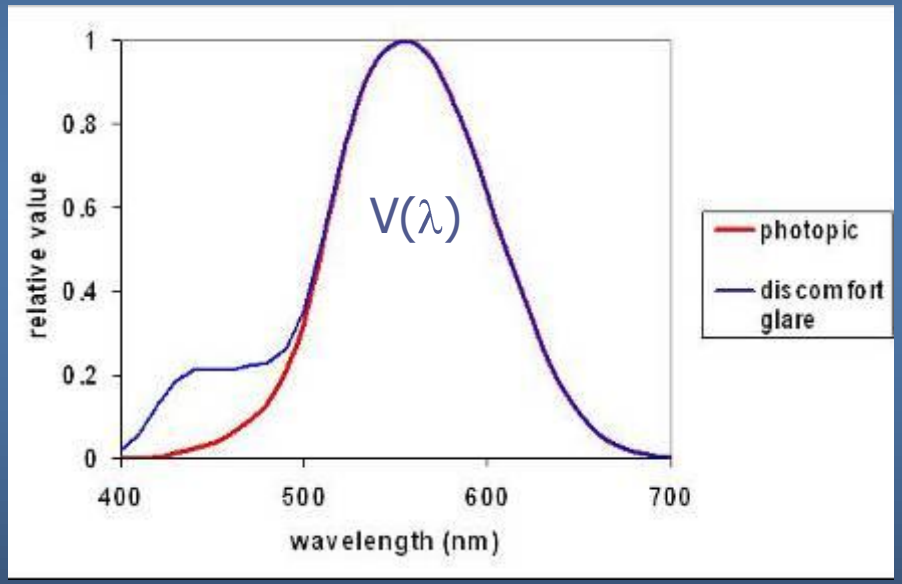
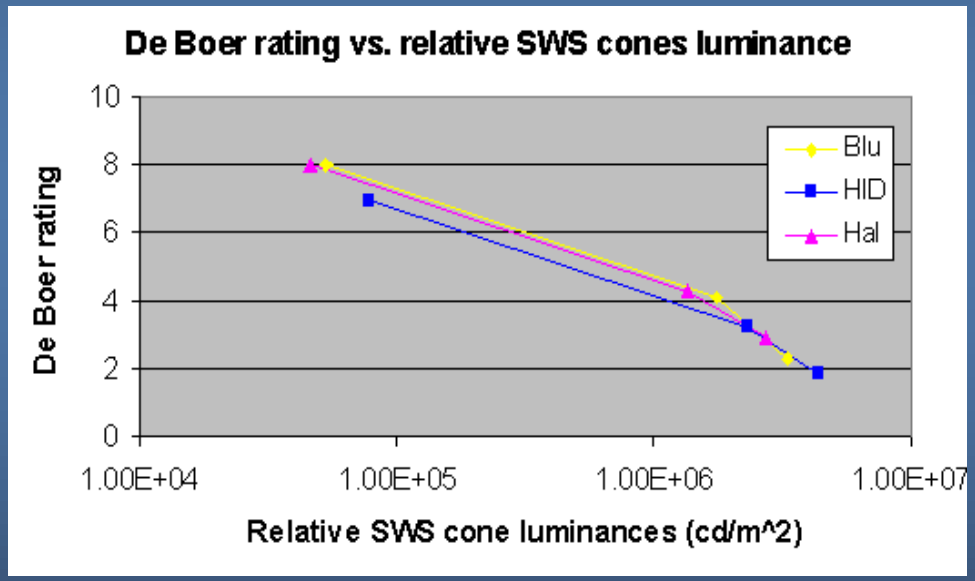
Discomfort glare spectral effects

- $V_{DG} = V_{Discomfort\ Glare}$





Bullough et al. (2002)

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What over watts?

Source	lm/W	Mesopic/W	Brightness/W	V_{DG}/W
Incandescent	12	12	12	12
CFL 2700 K	55	47	56	55
T8 fluorescent 3000 K	100	86	101	99
T8 fluorescent 4100 K	100	109	101	107
T8 fluorescent 6500 K	90	122	99	98
T12 fluorescent 7500 K	55	79	64	59
Metal halide	95	108	97	97
White LED	35	52	41	38

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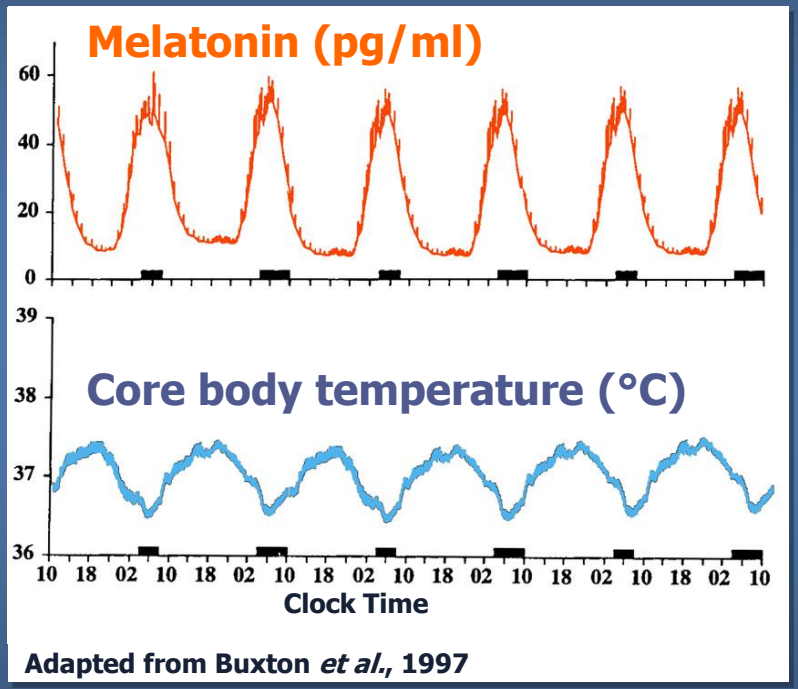
Light isn't just for vision anymore!



Adapted from Buxton *et al.*, 1997

- Circadian rhythms are hormonal, biological, or behavioral changes over an approximately 24-hour cycle that repeat over successive days (circa = about; dies = day)
- Circadian rhythms are influenced by internal and external factors (zeitgebers)
- Light is the most important external zeitgeber to the circadian system

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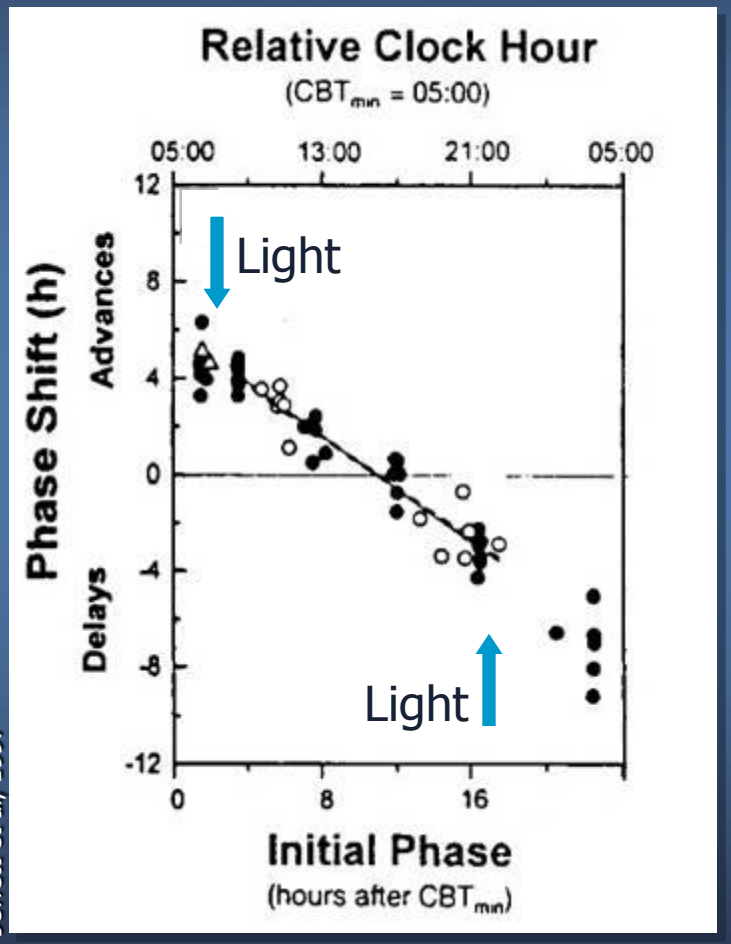
Timing



Jewett et al, 1997

5-hr pulse of 7,000 to 13,000 lux

Phase advance

Wake up earlier

Phase delay

Go to bed later

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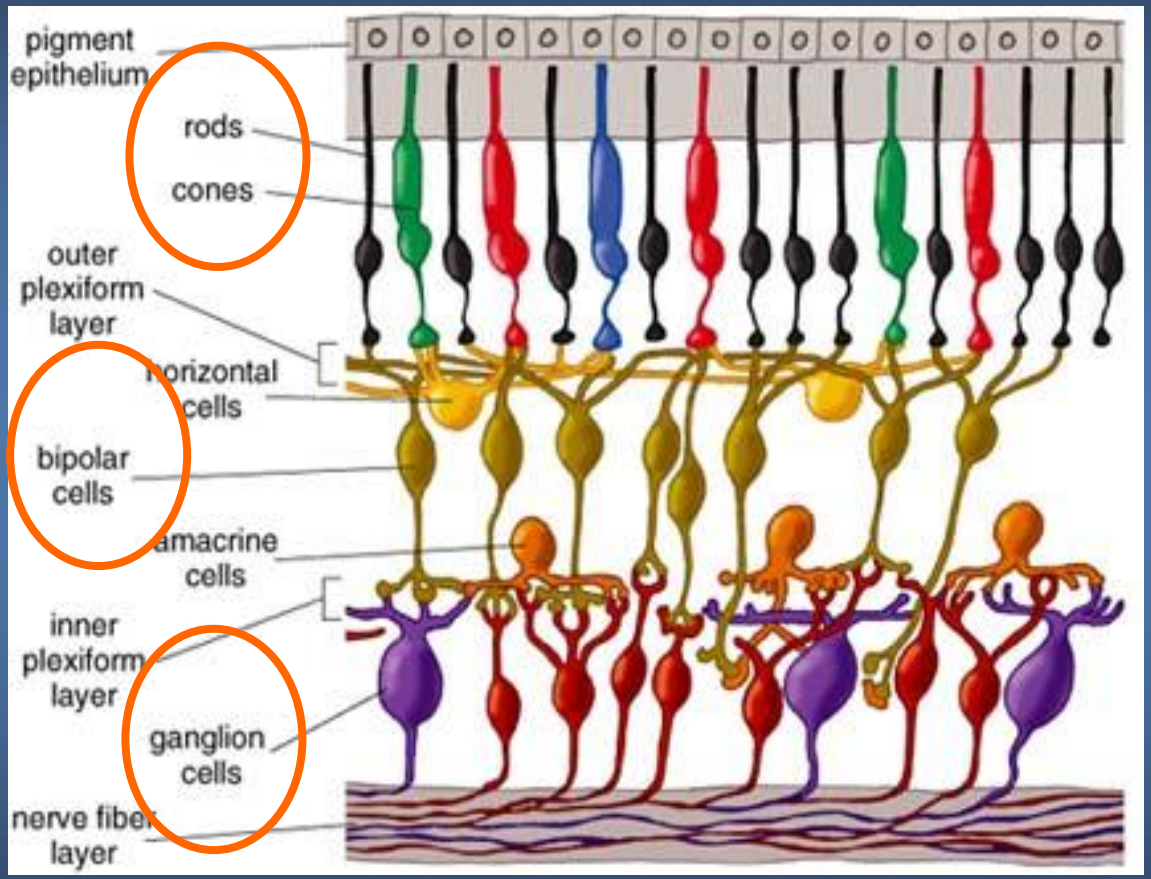
Cross-section of retina



Kolb et al., 2003

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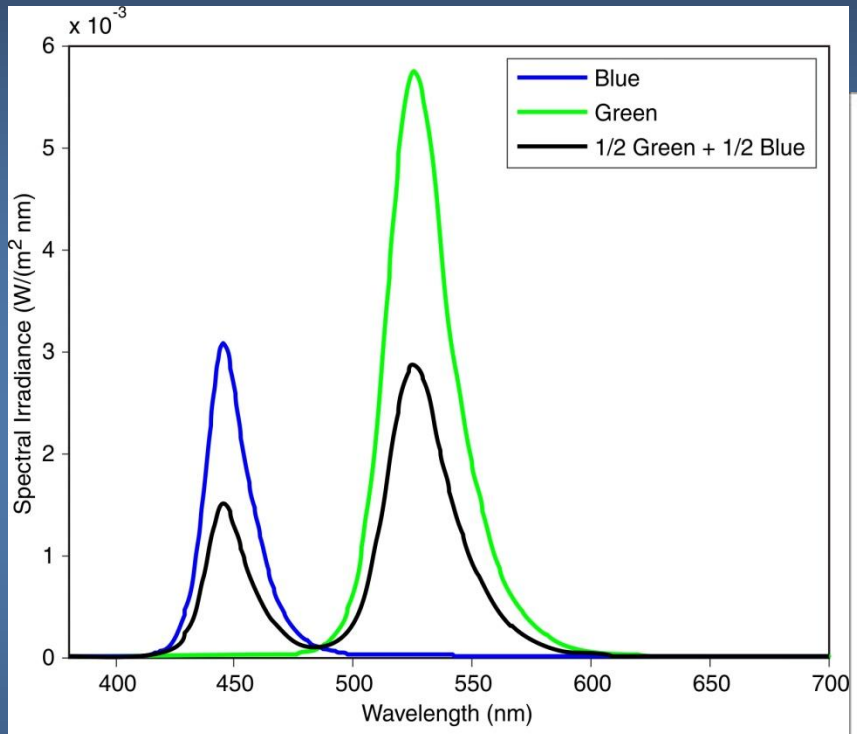
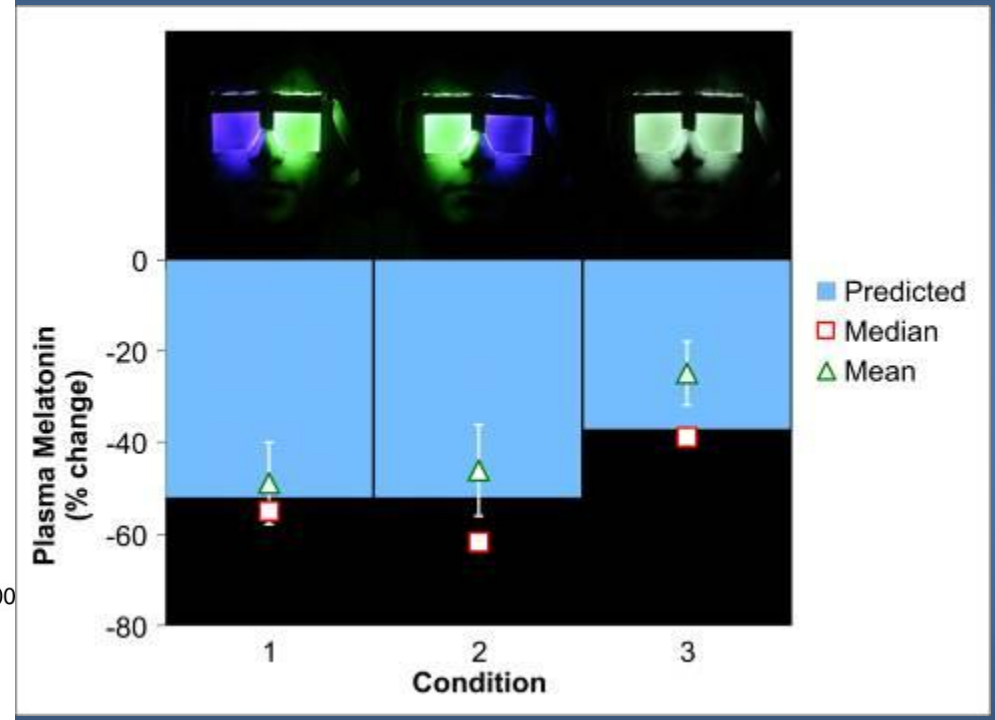
Spectral opponency



Monocular Stimulus	Illuminance (lux)	Irradiance (W/m²)
Blue	3.0	0.077
Green	113.2	0.211
1/2 Blue + 1/2 Green	57.7	0.142



Figueiro et al., in press

Sponsor: James D. Watson Investigator Award - NYSTAR

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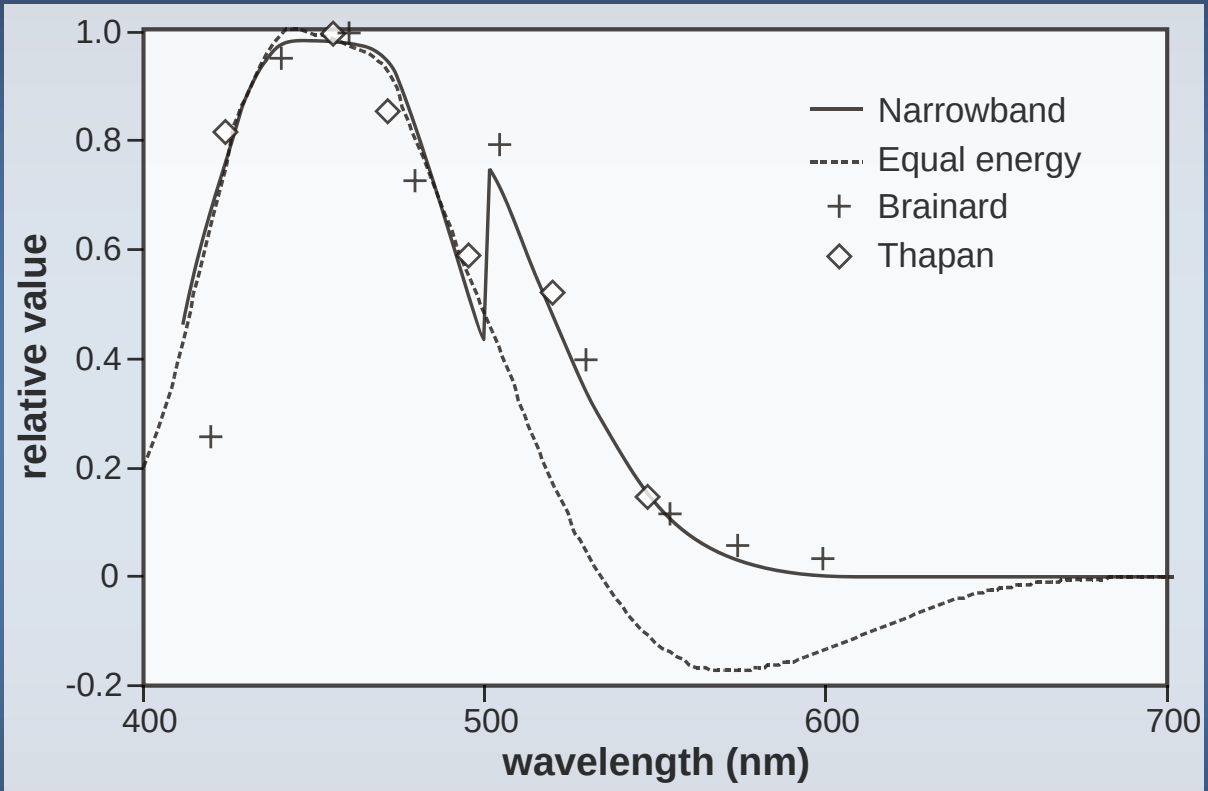
Circadian response to light

- Spectrum

- LRC developed and published a model for human circadian phototransduction (*Rea et al., 2005*)



Rea et al., 2005; Figueiro et al., 2004

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What over watts?

Source	lm/W	Mesopic/W	Brightness/W	V_{DG}/W	CircadianStimulus/W
Incandescent	12	12	12	12	12
CFL 2700 K	55	47	56	55	37
T8 fluorescent 3000 K	100	86	101	99	74
T8 fluorescent 4100 K	100	109	101	107	65
T8 fluorescent 6500 K	90	122	99	98	152
T12 fluorescent 7500 K	55	79	64	59	86
Metal halide	95	108	97	97	84
White LED	35	52	41	38	81

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Application efficacy

- Some lamps (e.g., reflector lamps) direct light strongly in a particular direction while other (e.g., fluorescent lamps) direct light in all directions
- The most efficacious (lm/W) lamp can waste energy if used in the wrong application
- It is important to consider the light distribution pattern of a lamp in order to select the one that distributes light to the area where it is needed

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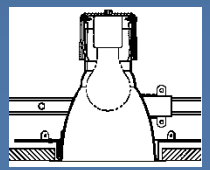
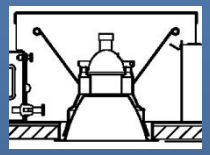
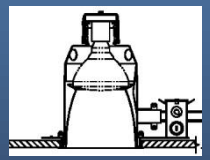
Application efficacy

Lamp Type	Fixture Efficacy	Application Efficacy	Illuminance at 6’
 A-lamp downlight, 50 W	**8 lm/W**	**10 cd/W**	**15 fc**
 MR 16 lamp, 50 W	**11 lm/W**	**39 cd/W**	**54 fc**
 PAR 30 lamp, 50 W	**12 lm/W**	**54 cd/W**	**74 fc**
CFL, 18 W	37 lm/W	32 cd/W	16 fc

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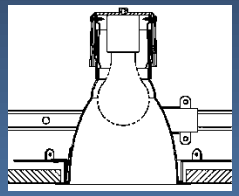
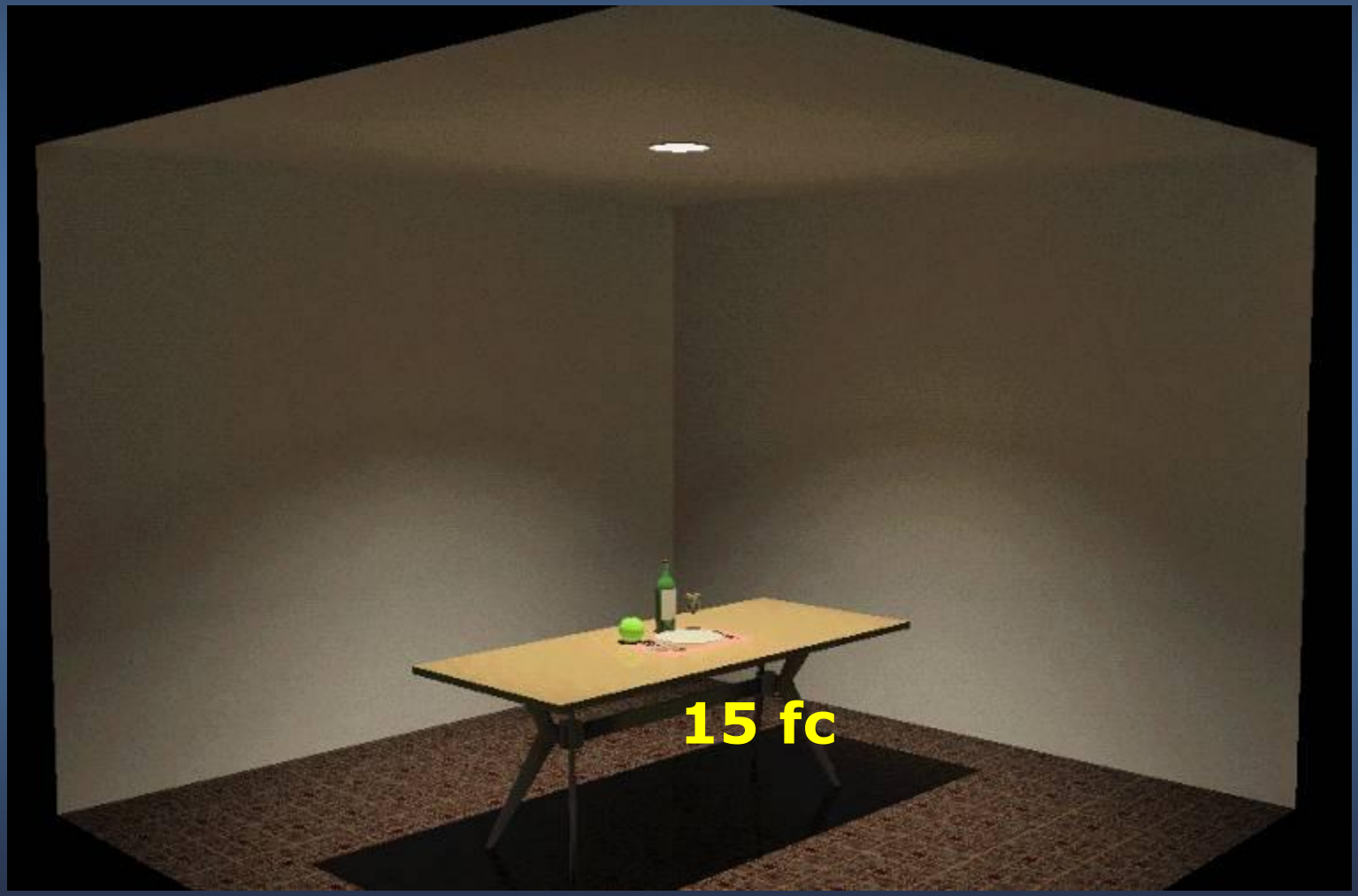
A-lamp downlight, 50 W





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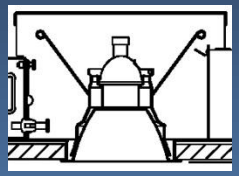
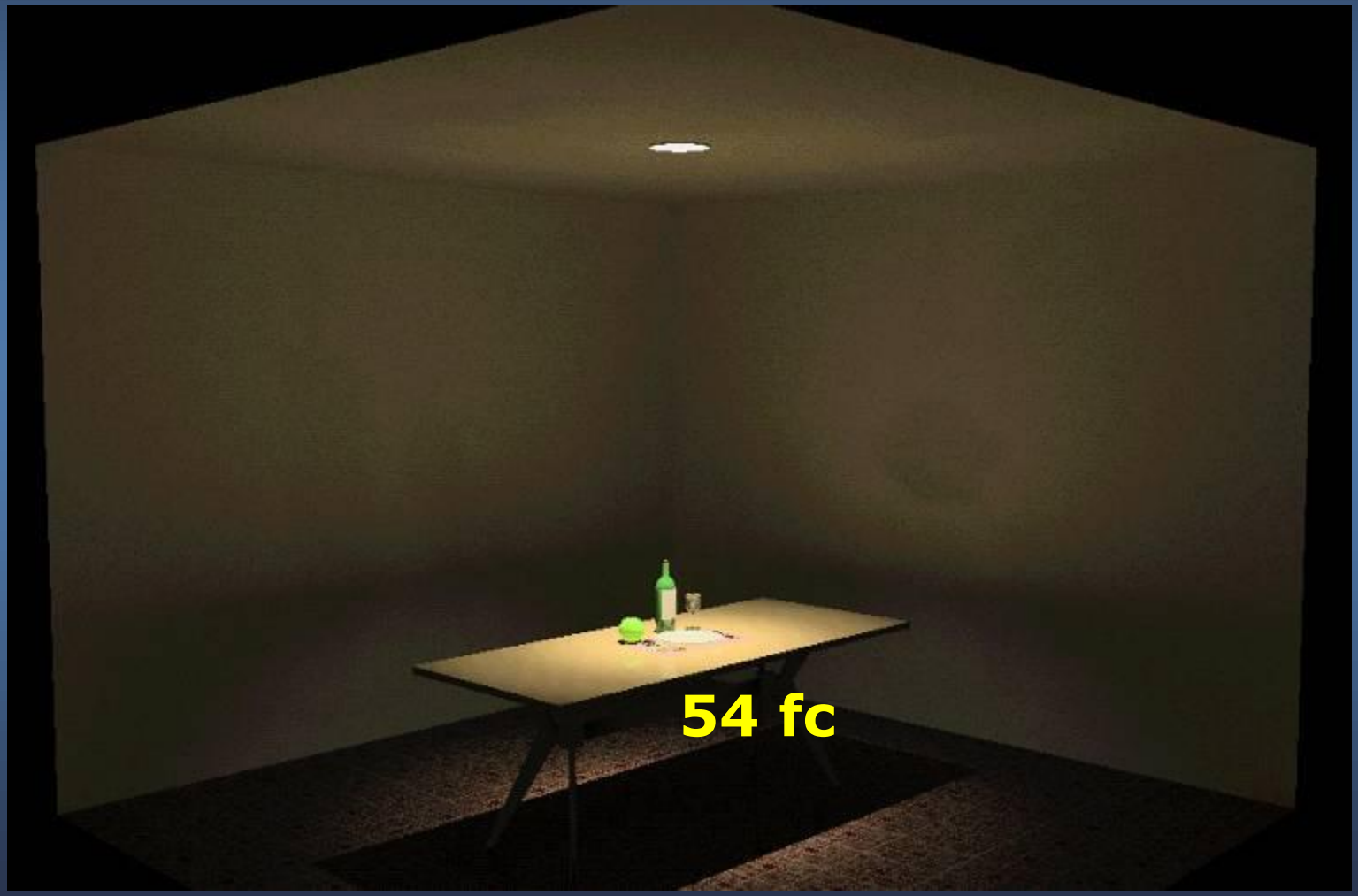
MR-16 lamp, 50 W





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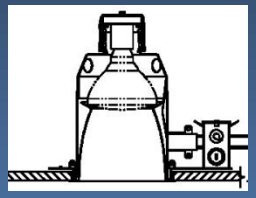
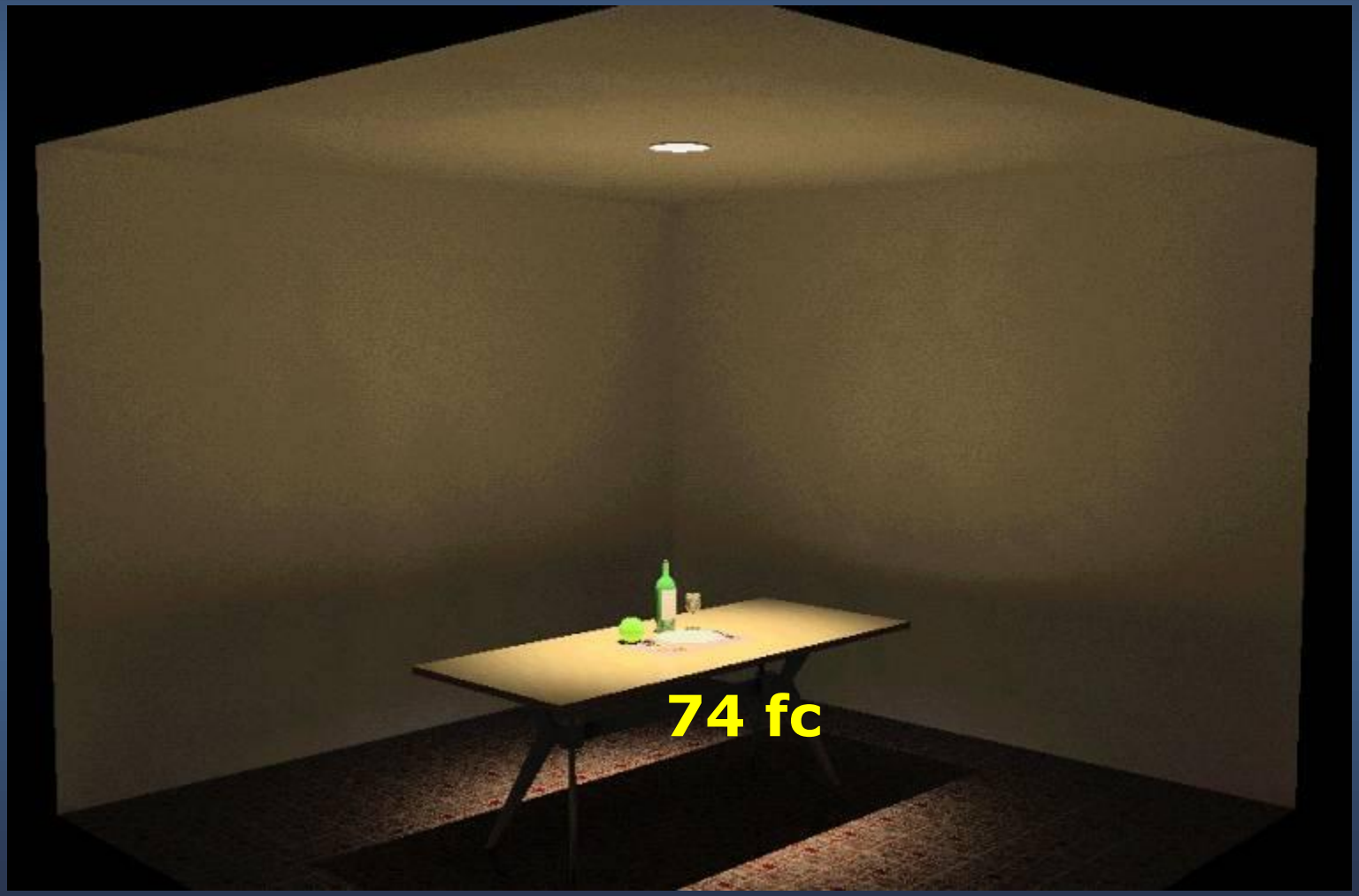
PAR-30 lamp, 50 W





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Undercabinet lighting

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What over watts?

- And here it gets a little fuzzy…
  - Sparkle/watt?
  - Cognitive dissonance/watt?
  - Visual interest/watt?
  - Excitement/watt?
  - Economic development/watt?

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Sparkle/watt?

Sparkle/watt?

Cognitive
dissonance/watt?

Crown Fountains
Millenium Park, Chicago

Visual interest/watt?

Basketball Hall of Fame
Springfield, MA
Excitement/watt?

Economic development/watt?

Main messages

- Efficacy is more than lumens per watt
- Generally, efficacy is lighting benefit per watt
- Good intentions to save the environment should be understood in a technical-social-psychological context
- The *value* of lighting is more complex (and interesting) than simply banning the incandescent light bulb
- Metrology is essential for delivering that value to society

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Thank you.

Acknowledgements

- John Bullough
- Mariana Figueiro
- Dennis Guyon

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