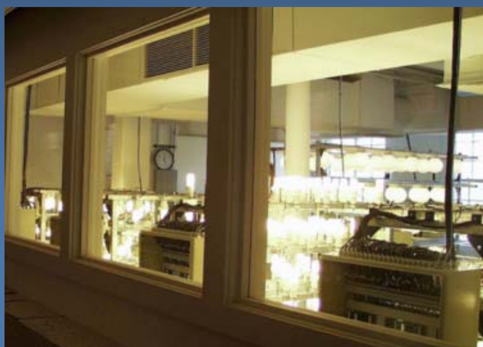
# Demonstration of Outdoor Lighting for Maximizing Perceptions of Safety and Security

Lighting Research Center,
Rensselaer Polytechnic Institute, Troy, NY
Lighting Design Lab, Seattle, WA
Seattle City Light, Seattle, WA
University of Washington, Seattle, WA

# Lighting Research Center (LRC) in its 28th year

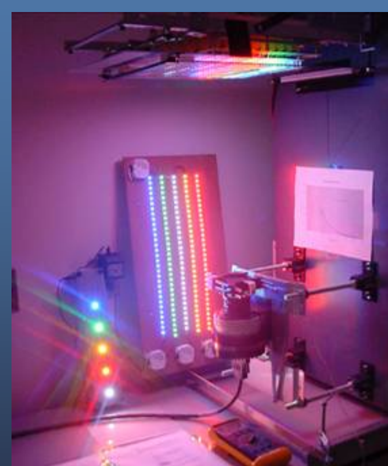
*Advancing the effective use of light, thereby creating a positive legacy for society and the environment.*



NVLAP-accredited
testing laboratory

30,000 sq. ft. near
Rensselaer campus
Troy, New York


40-60 concurrent projects in field and lab



Research & education revenue = $7 M/year

34 full-time faculty and staff

15 graduate students

# Some of our recent sponsors

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- Advance Transformer Co.
- Aero Farm Systems LLC
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- California Energy Co
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- Gerry Foundation
- Hella
- Illuminating Engineer (IESNA)
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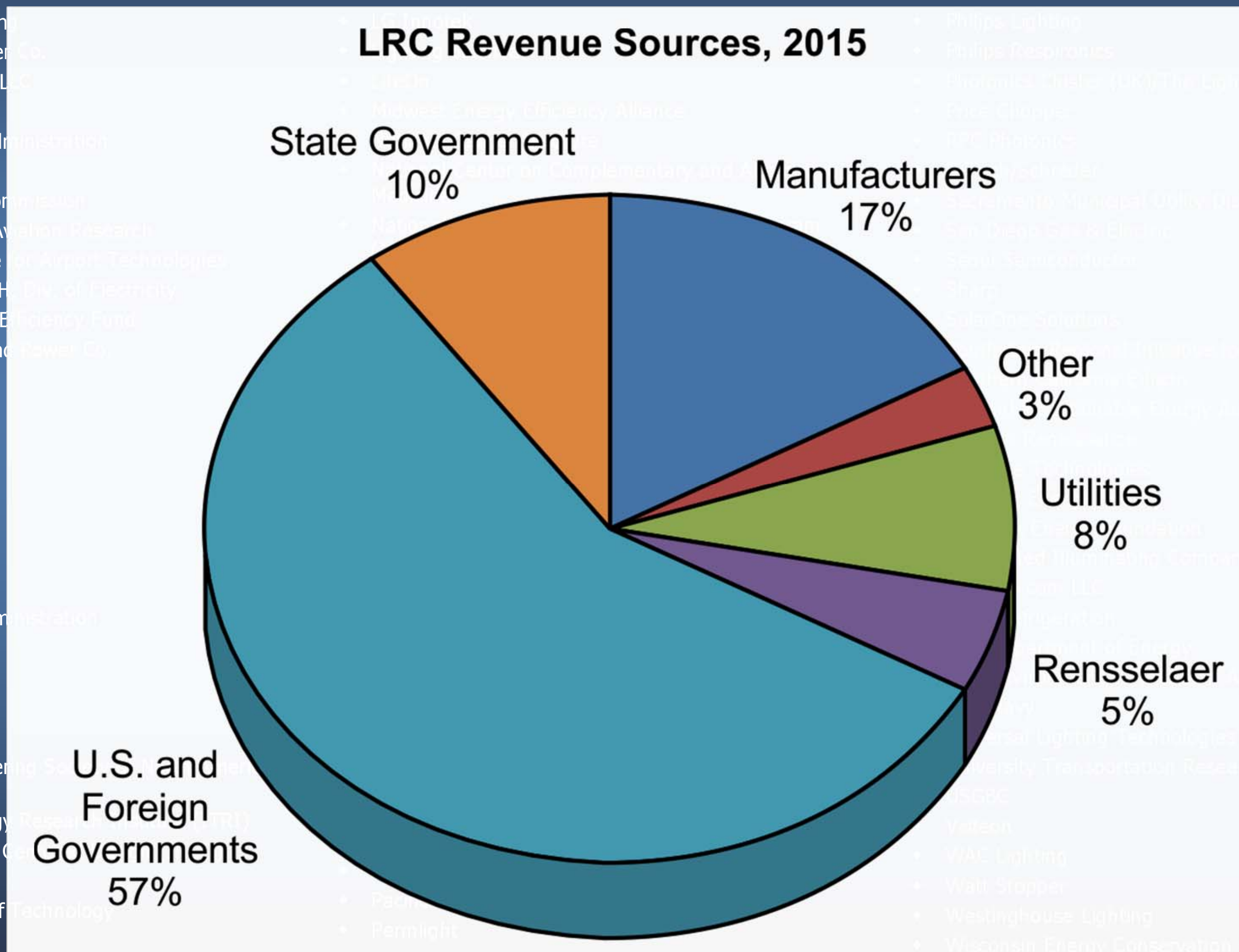
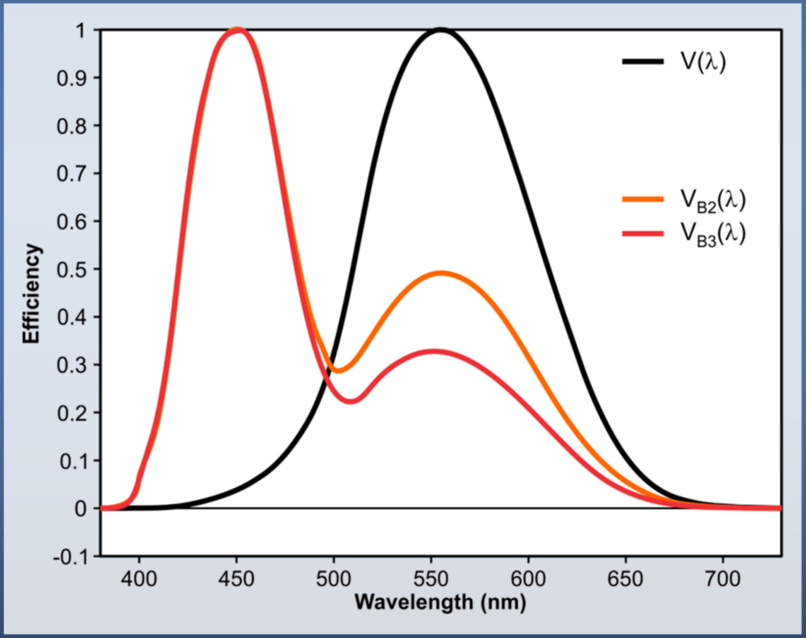
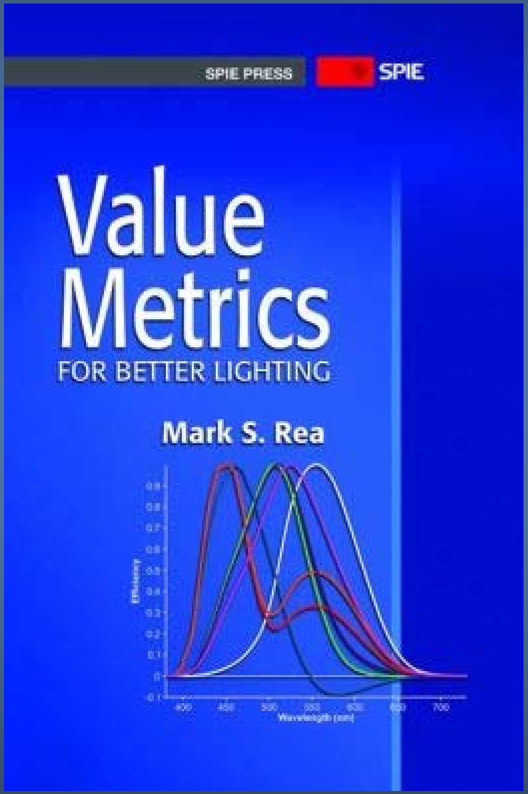


# Background

- Brightness as a benefit metric for lighting

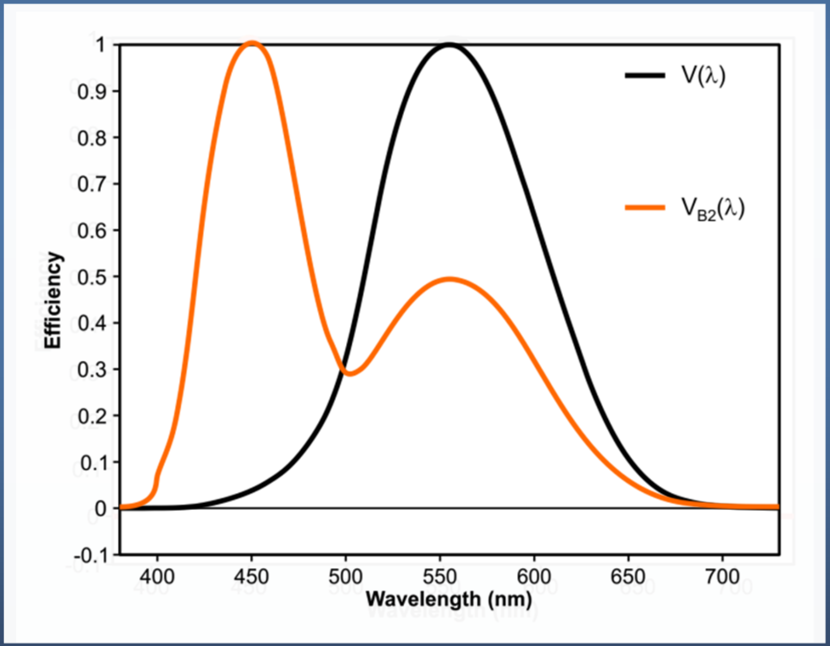


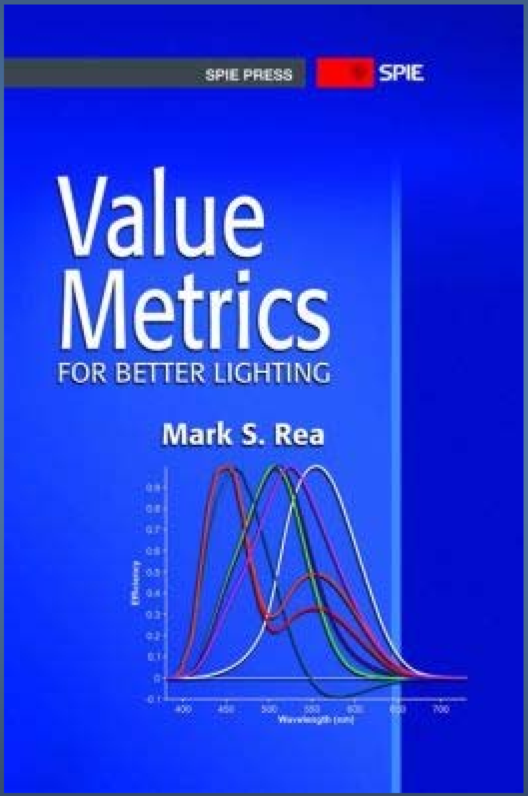




Rea M. 2013.
*Value Metrics for Better Lighting.*
SPIE Press Monograph PM228.

# Background

- Brightness as a benefit metric for lighting




Rea M. 2013.
*Value Metrics for Better Lighting.*
SPIE Press Monograph PM228.

# Brightness in illuminant mode

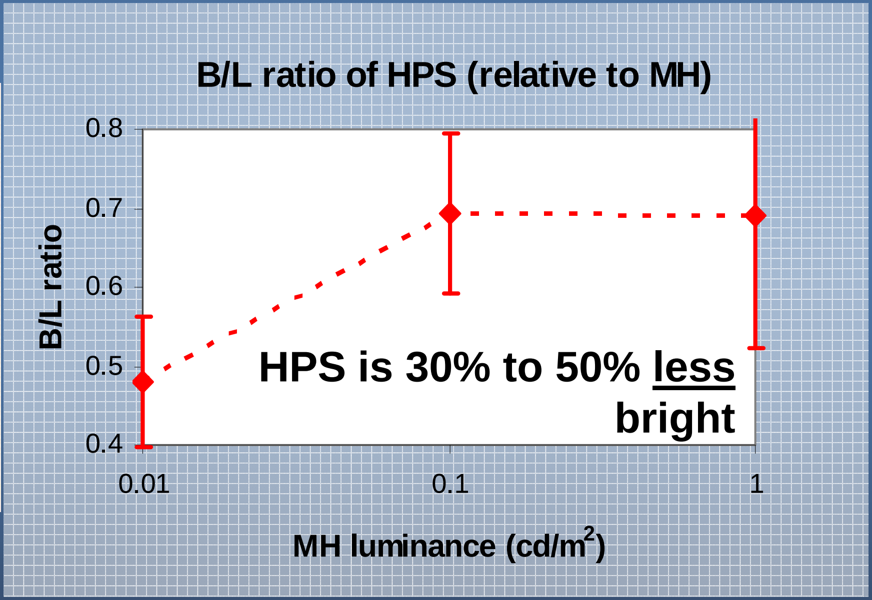
- Often, we judge the lighting of a scene with respect to its overall brightness
- Both light level and light spectrum affect brightness perception

- Scene brightness affects our sense of safety and security

# Illuminant mode of viewing

High Pressure Sodium

Metal Halide



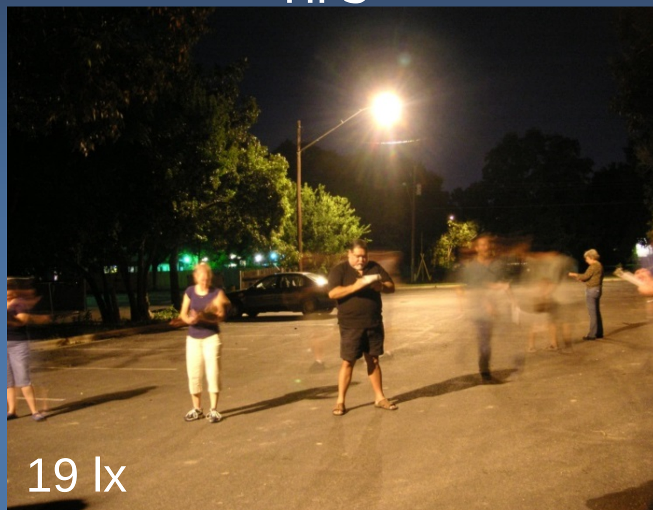

Rea 1996

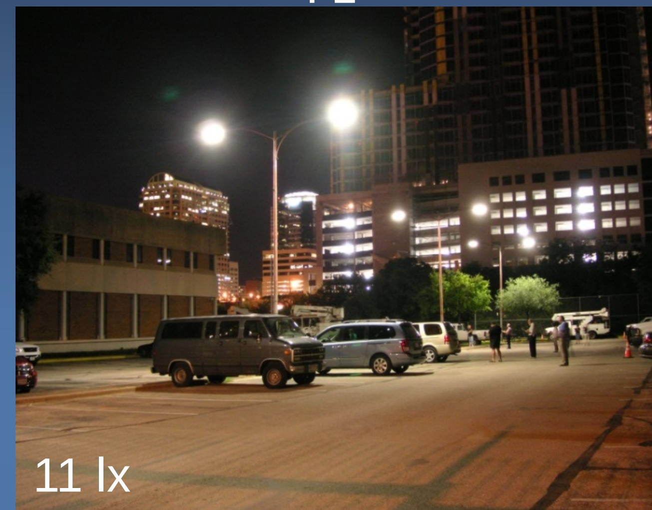
# Field demonstration: Austin, TX

Morante et al. 2007

HPS | FL

High




Low



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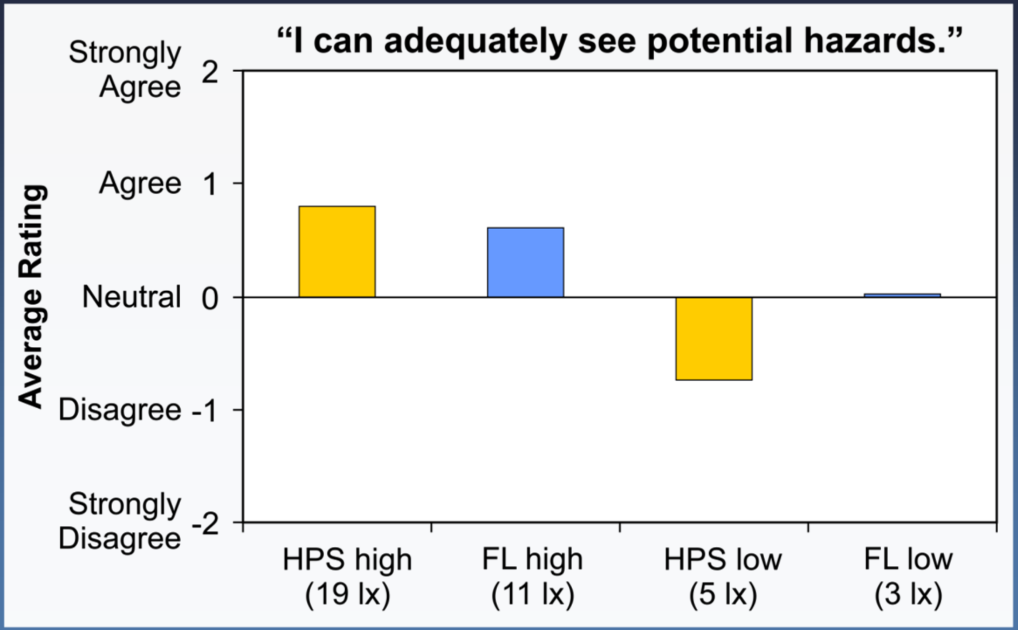
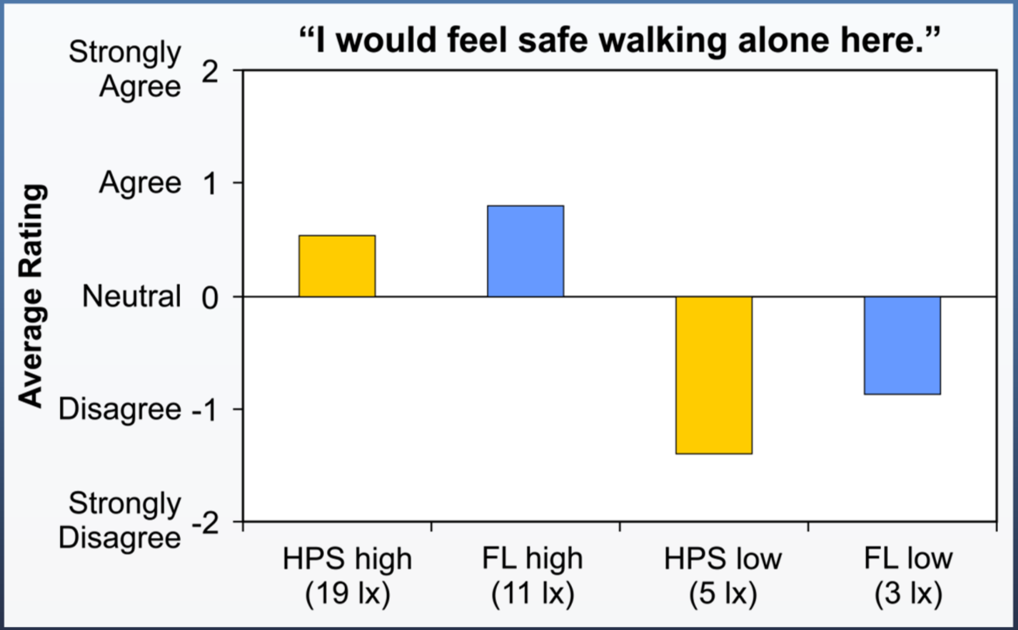
Morante et al. 2007

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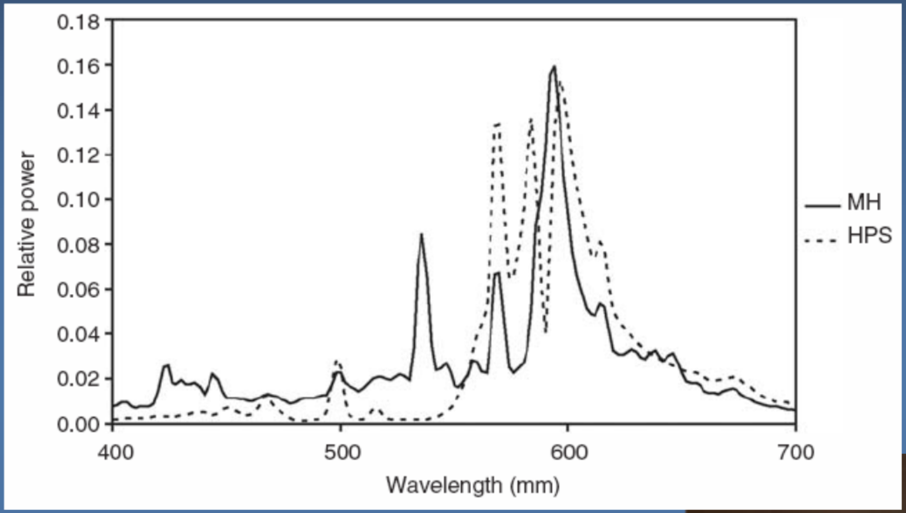
# Field test: High pressure sodium vs. metal halide street lighting




Hypothesis: Higher short-wavelength energy for metal halide results in greater perceived brightness

Sponsor: Philips Lighting

Rea et al. 2009

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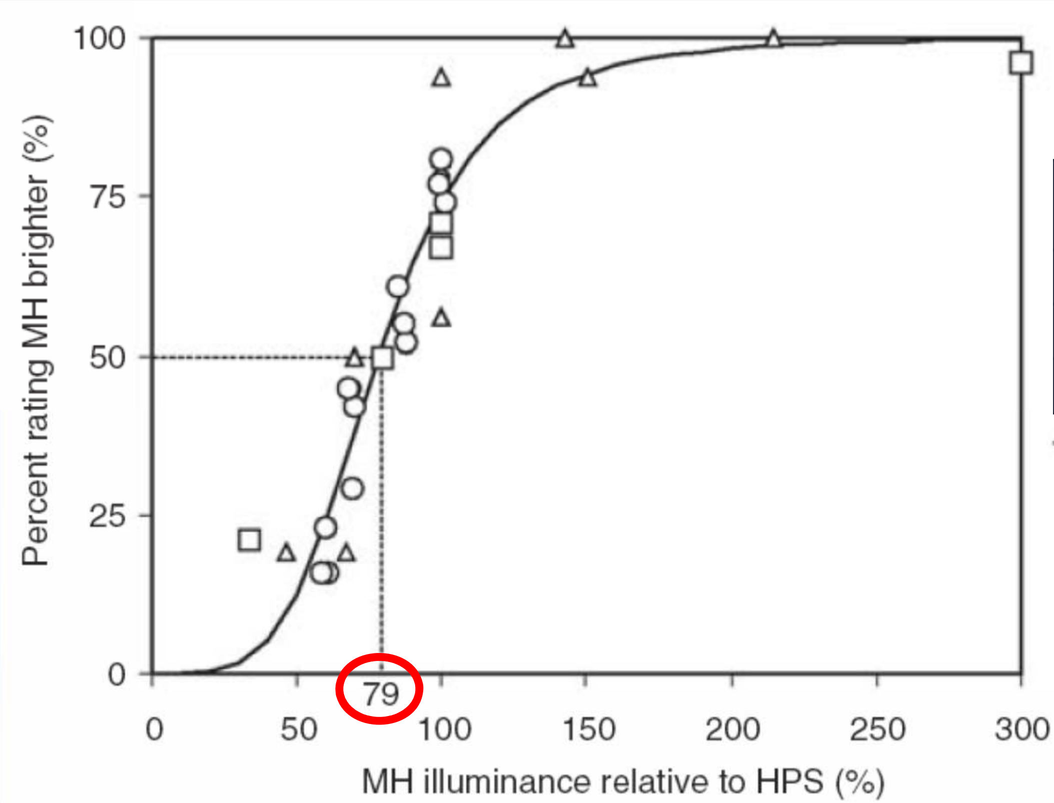
# Field test: High pressure sodium vs. metal halide street lighting



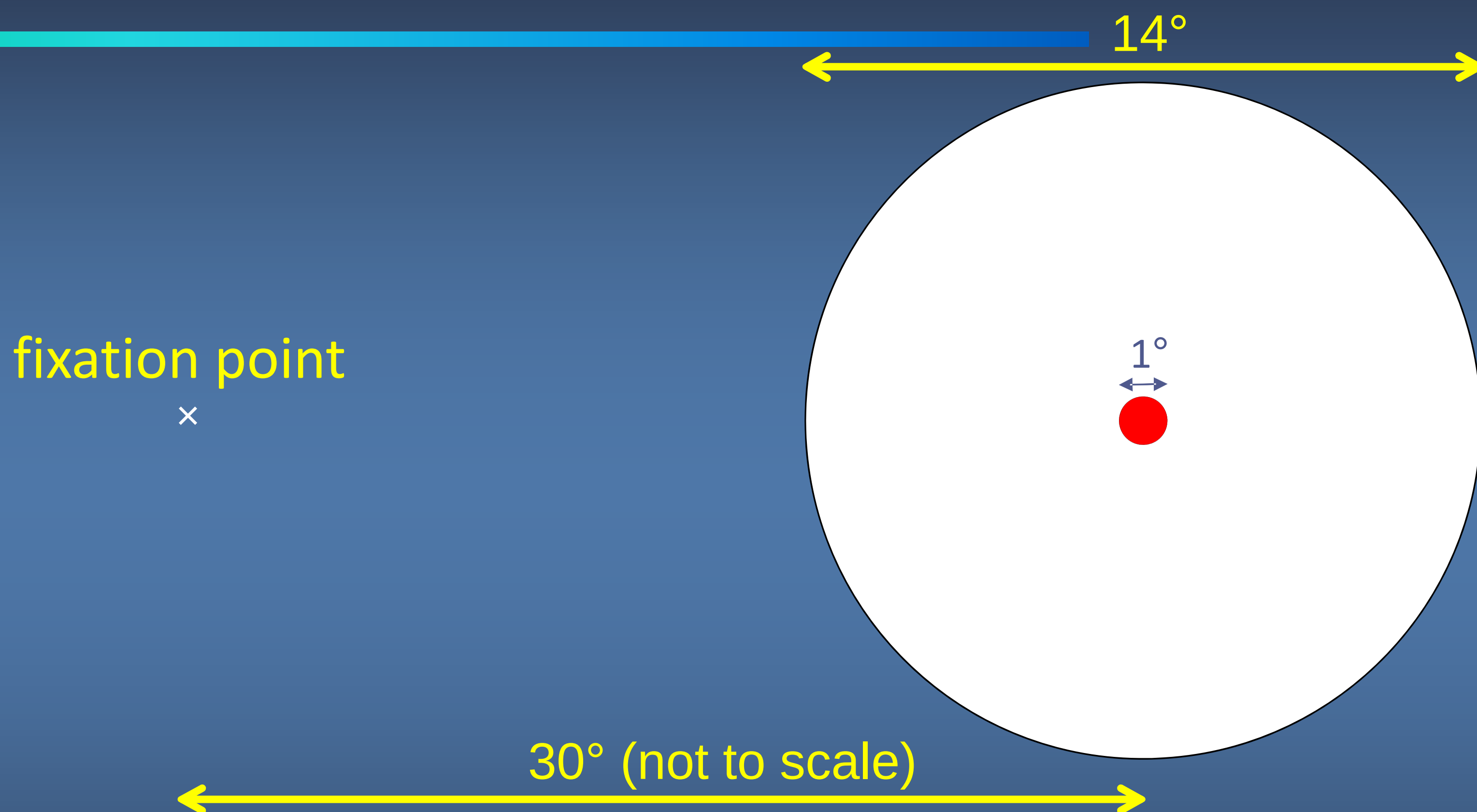

| | n | HPS (lx) | MH (lx) |
|---|---|---|---|
| □ Experiment 1 | 24 | 5-15 | 5-15 |
| △ Experiment 2 | 16 | 7-15 | 7-15 |
| ○ Experiment 3 | 31 | 5-15 | 3-15 |

— Fit

Sponsor: Philips Lighting

Rea et al. 2009

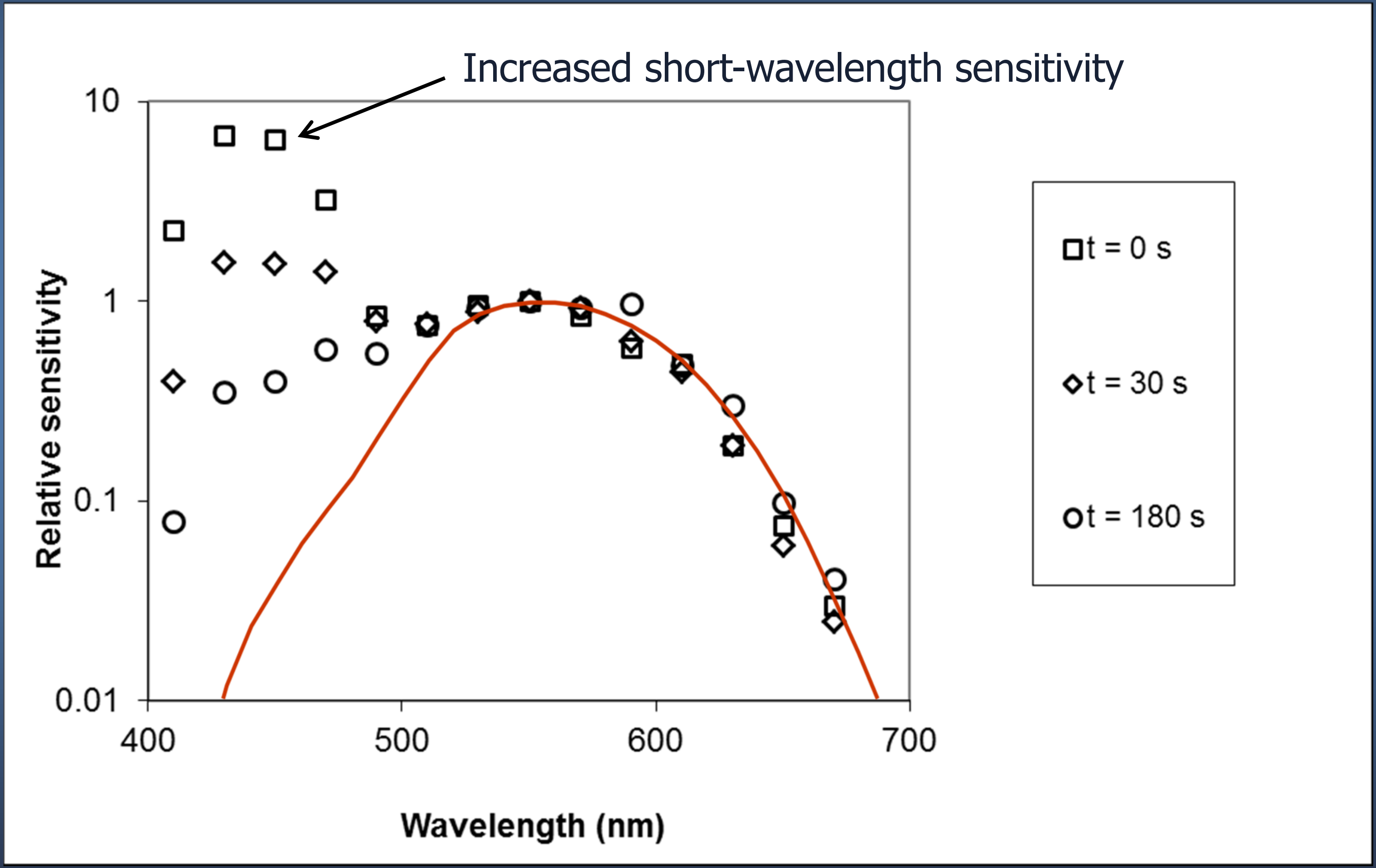
# Modeling brightness




The 3000 K, 14° adapting field had an initial luminance of 17,000 cd/m² before extinction at time = 0 s. The small central field varied in wavelength and luminance to determine the threshold of a 190-ms increment, either with the adapting field in place or following extinction.

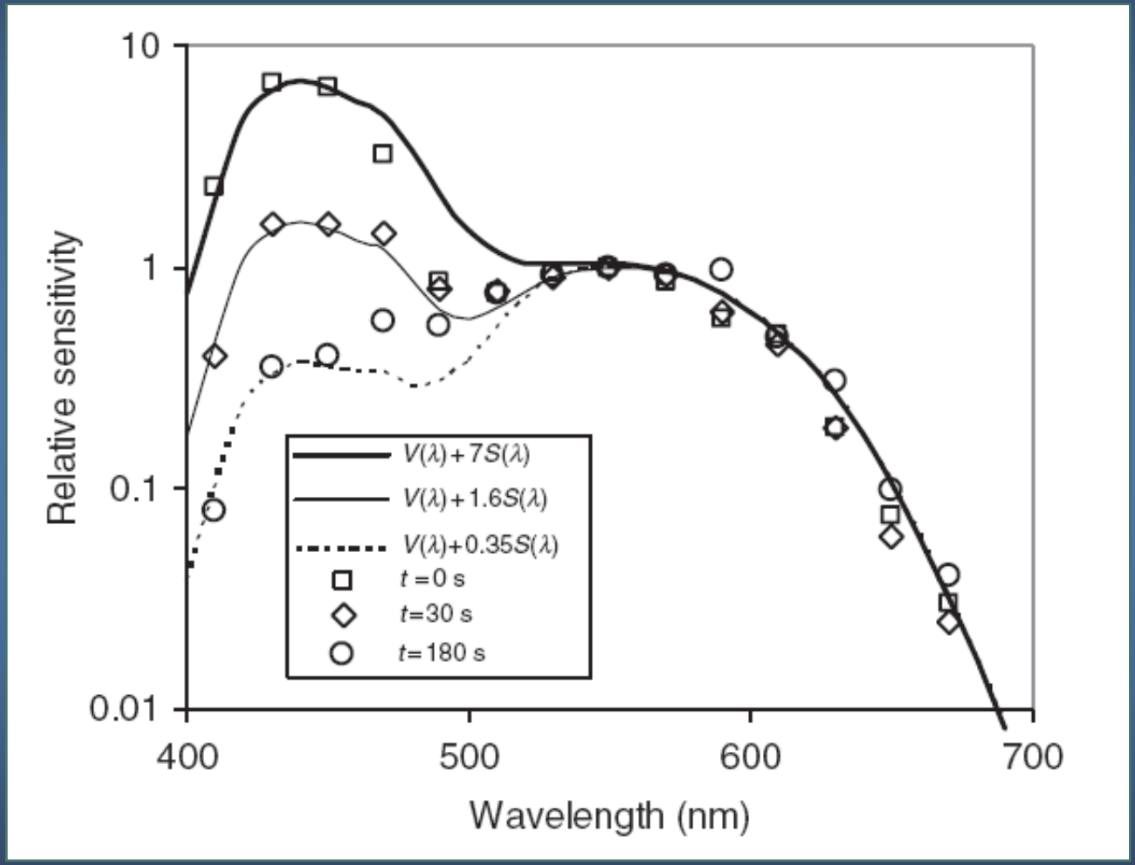
Wooten et al. 1975

# Modeling brightness




Wooten et al. 1975

# Modeling brightness




$$V_B(\lambda) = V(\lambda) + 0.5Mel(\lambda) + g_2S(\lambda)$$

Wooten et al. 1975

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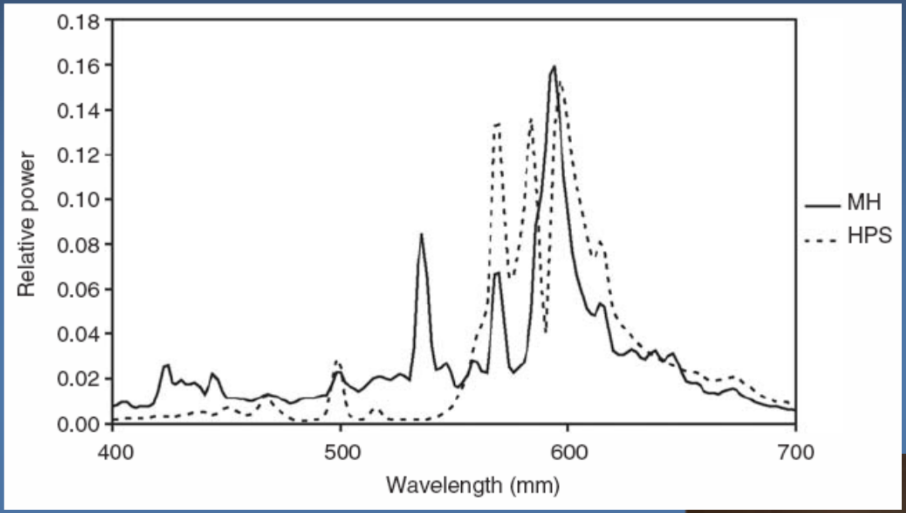
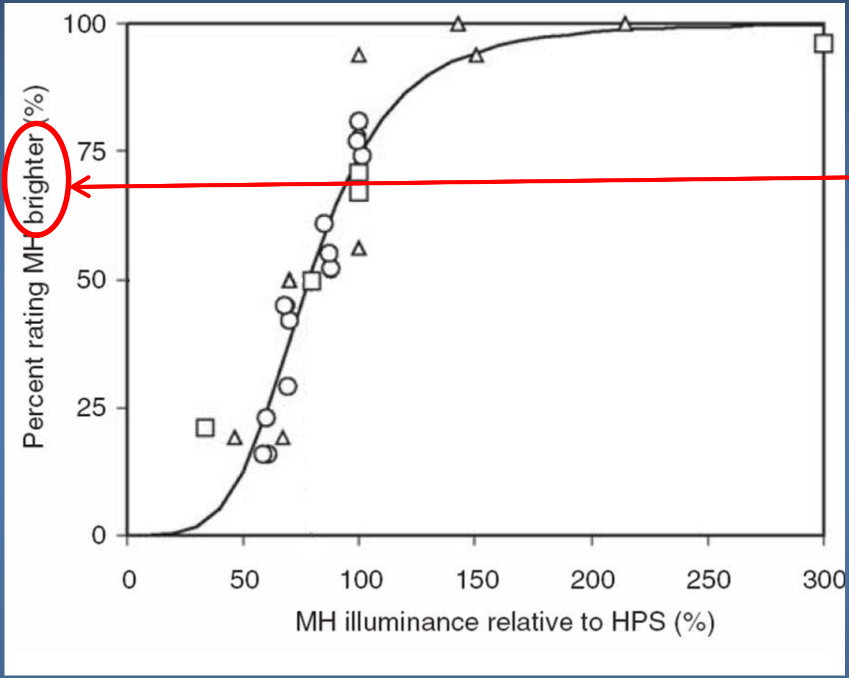
# Field test: High pressure sodium vs. metal halide street lighting

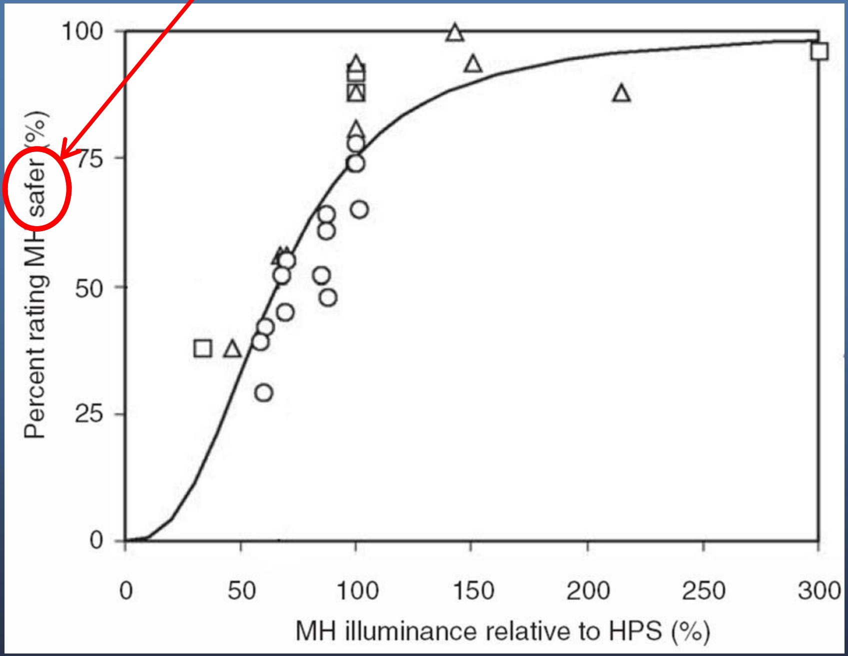



Hypothesis: Higher short-wavelength energy for metal halide results in greater sense of safety and security

Sponsor: Philips Lighting

# What is the value of increased scene brightness at night?




**Locations that look brighter also feel safer**

Correlation = 0.89

Rea et al. 2009

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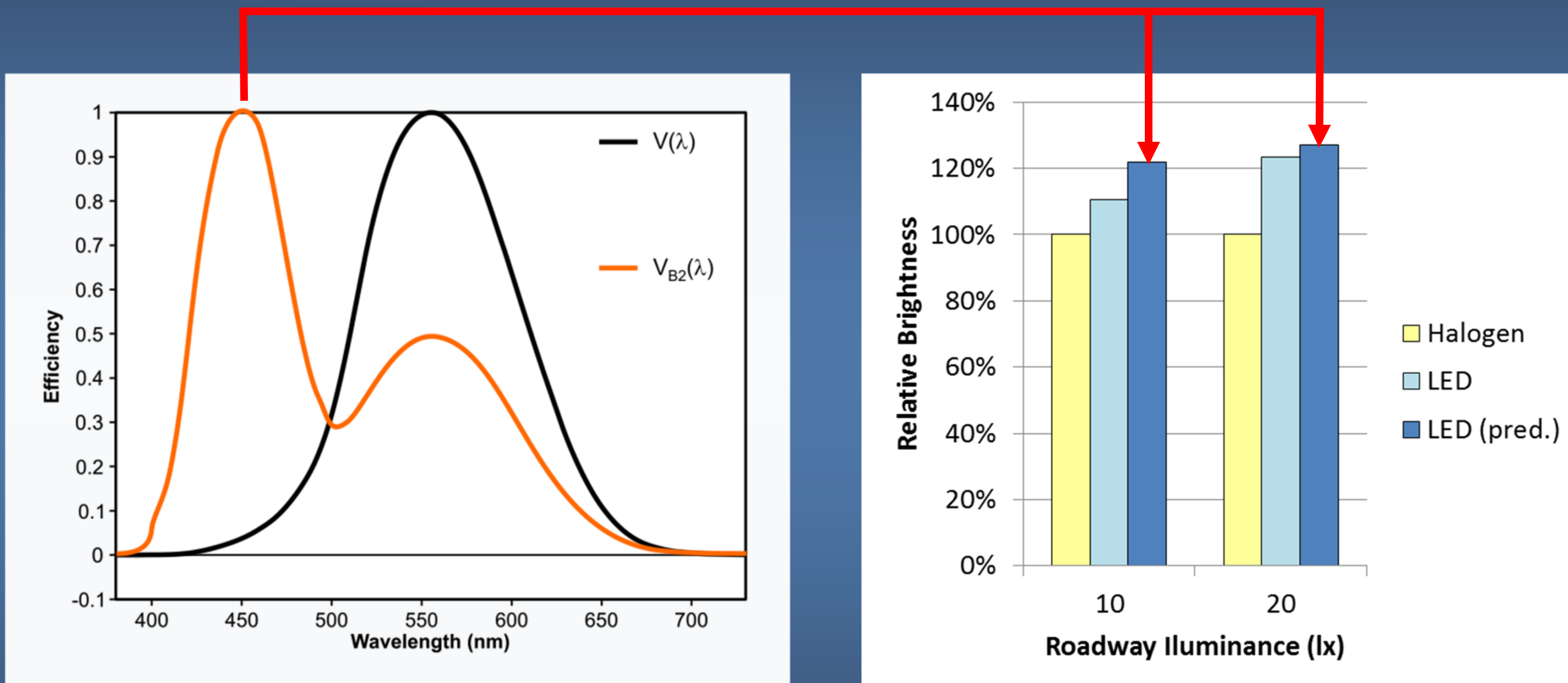
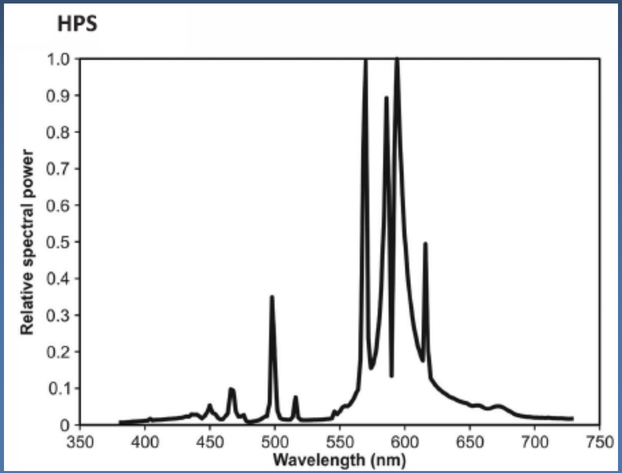
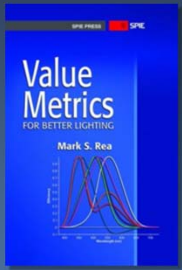
# Brightness prediction: Automobile forward lighting

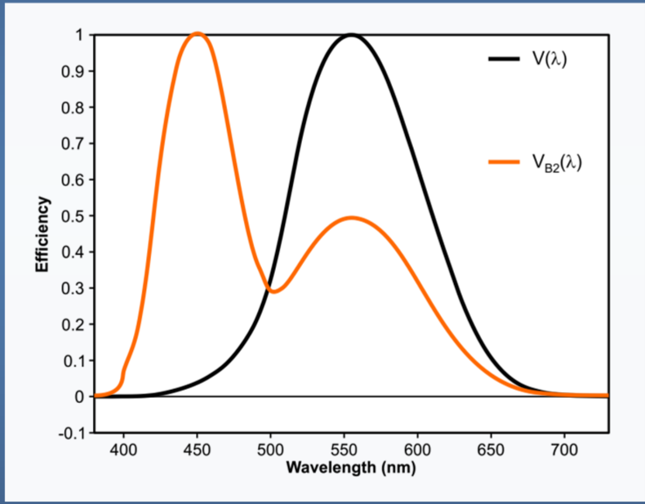


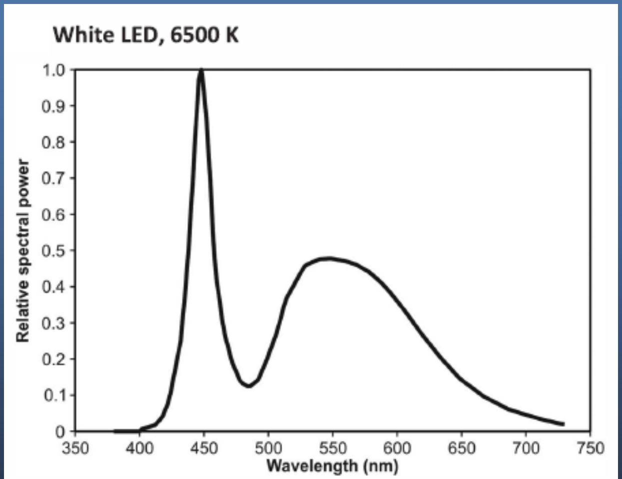

Hamm 2011

# Brightness predictions: HPS vs. 6500 K LED




To be judged **equally bright**, the LED illuminance is predicted to be **54 %** of the HPS illuminance (Rea 2013).

# BPA project, December 2014

- University of Washington, Seattle
- Three campus parking lots
- 18 subjects
- Team members
  - LRC
    - Mark Rea
    - Jennifer Brons
    - Mariana Figueiro
    - John Bullough
  - Seattle LDL
    - Kurt Nielsen
    - Jeff Robbins
    - Eric Strandberg
  - Seattle City Light
    - Edward Smalley

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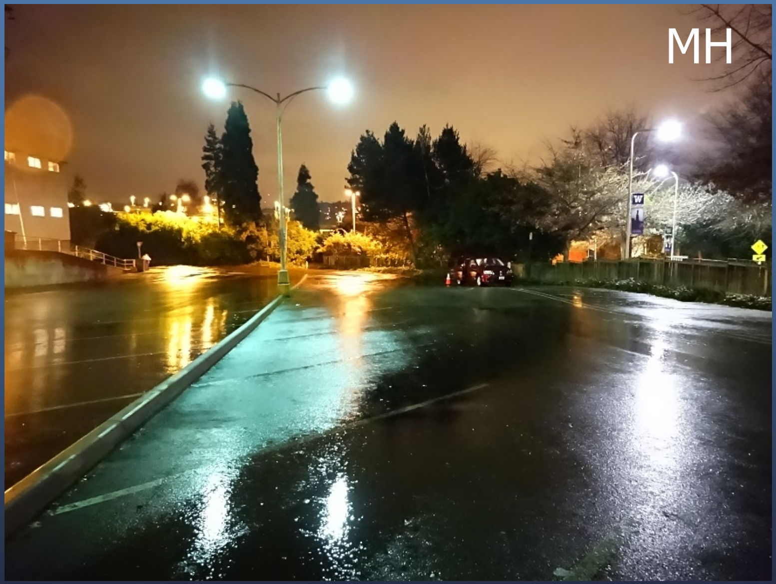
# BPA project, December 2014

- Three parking lots evaluated
  - Sound Transit Lot: Light-emitting diode (LED) luminaires on 37′ poles
  - W-35: High pressure sodium (HPS) luminaires on 27′ poles
  - W-12: Metal halide (MH) luminaires on 27′ poles



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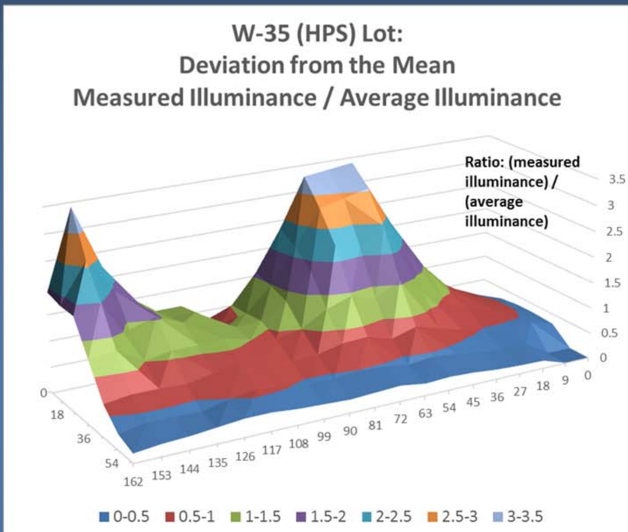
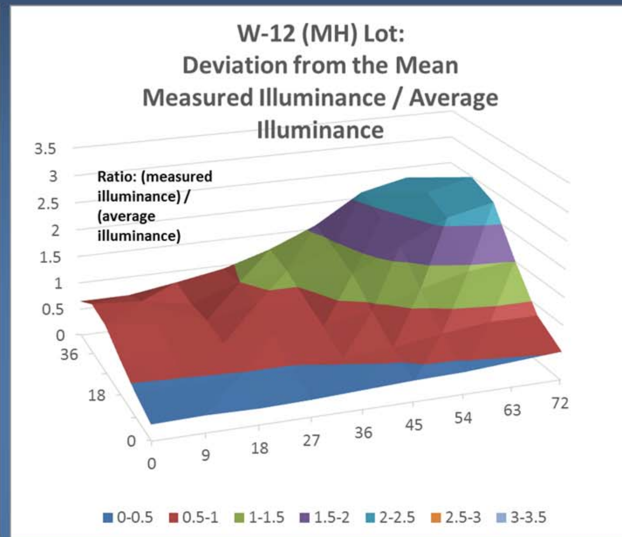
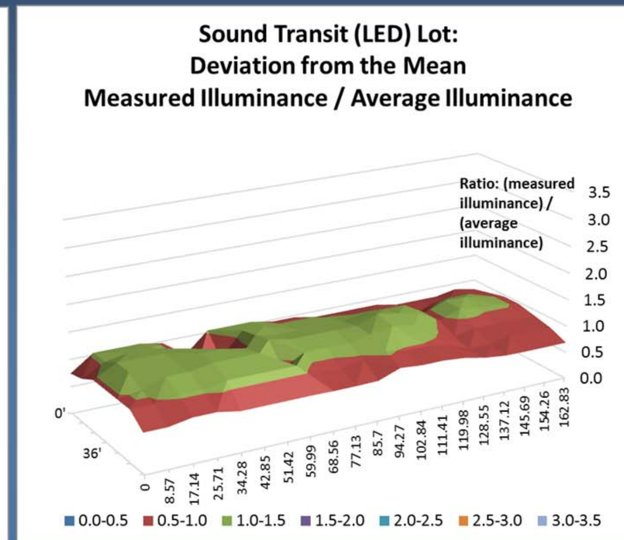
# Light level measurements

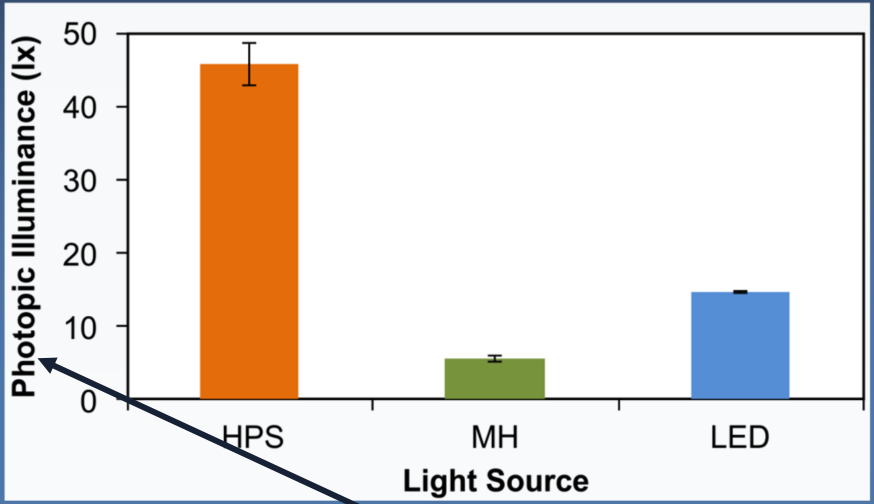


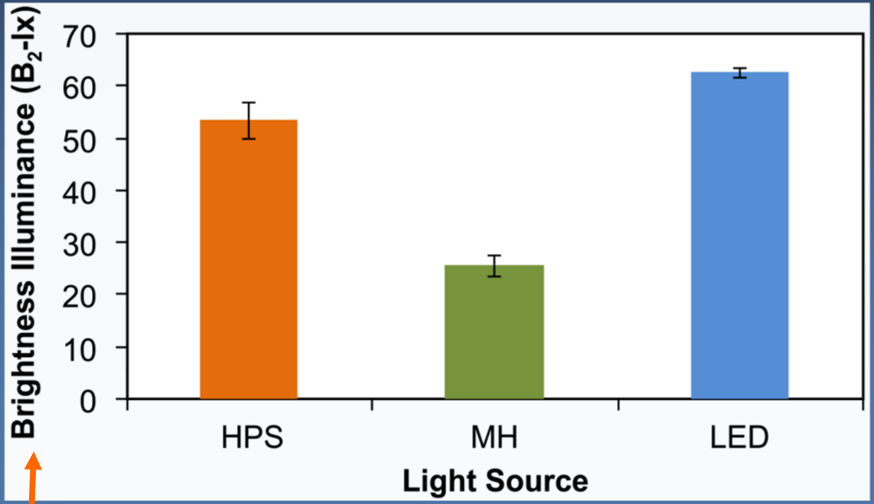



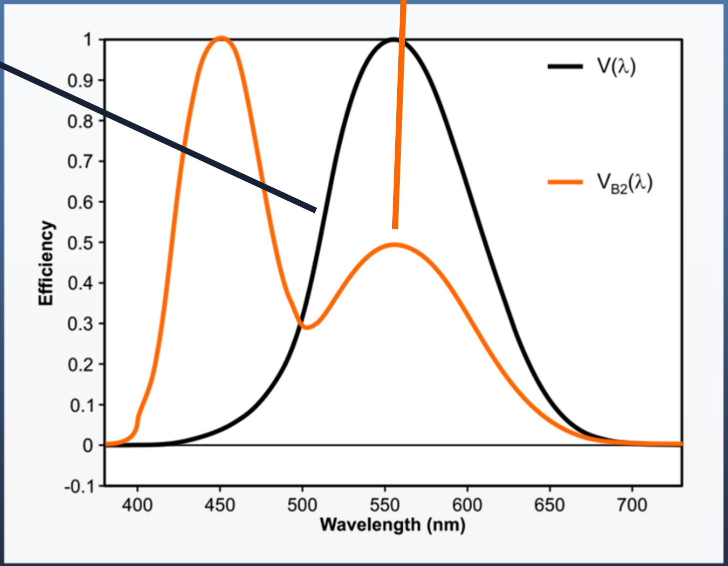




| | Photopic Illuminance (lx) | | | | | Brightness Illuminance ($B_2$-lx) | | | | | Ratios | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Mean | Median | Std. Dev. | Max. | Min. | Mean | Median | Std. Dev. | Max. | Min. | Max:Min | Avg:Min |
| LED | 14.5 | 15.1 | 2.5 | 19.4 | 8.6 | 62.6 | 65.0 | 10.8 | 83.6 | 37.2 | 2.3 | 1.7 |
| HPS | 45.9 | 37.1 | 33.8 | 157.1 | 7.0 | 53.7 | 43.4 | 39.5 | 183.6 | 8.2 | 22.5 | 6.6 |
| MH | 5.6 | 4.6 | 3.4 | 14.0 | 1.6 | 25.6 | 21.1 | 15.6 | 63.7 | 7.3 | 8.7 | 3.5 |

# Comparison of photopic illuminance and brightness illuminance







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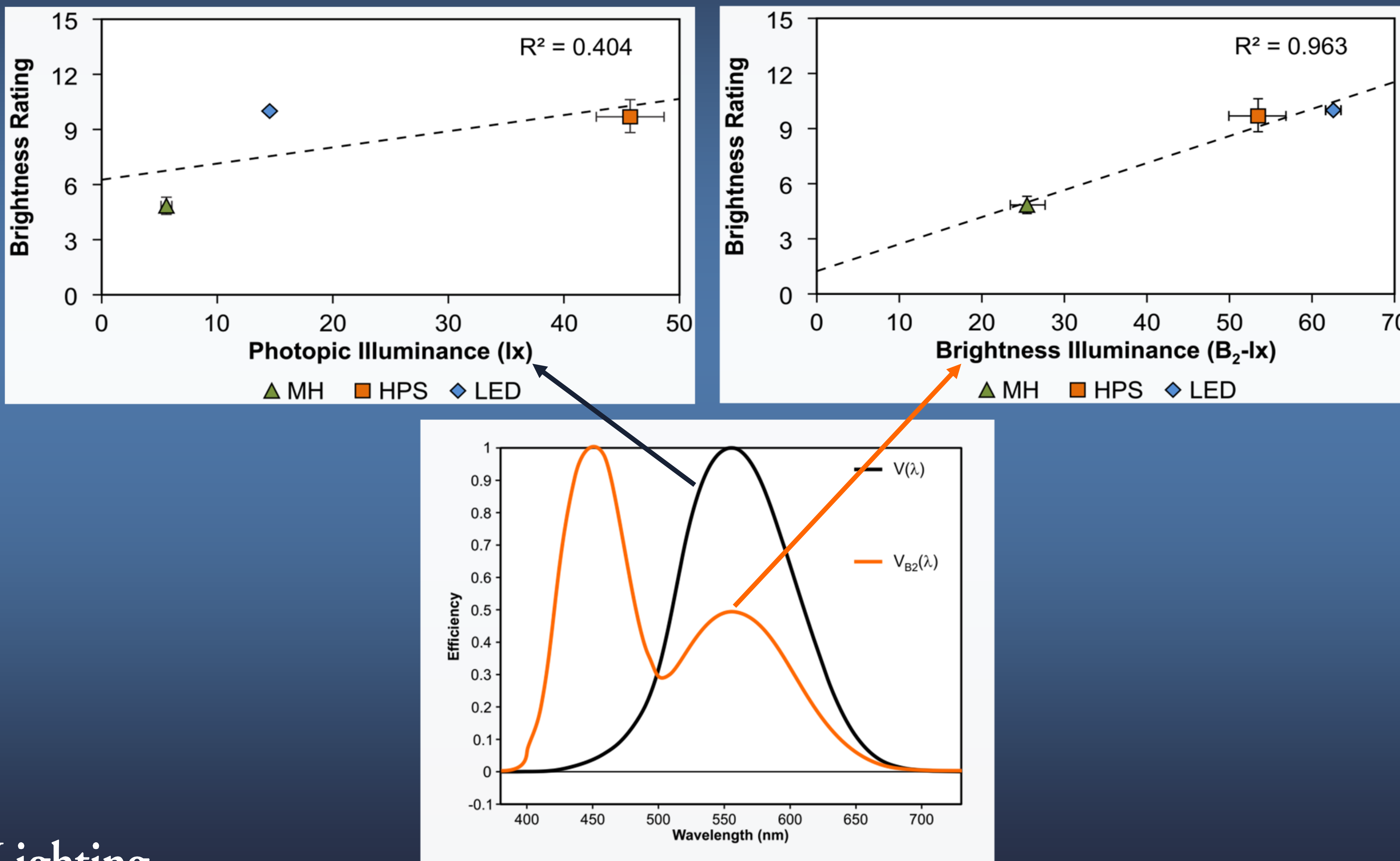
# Brightness judgments

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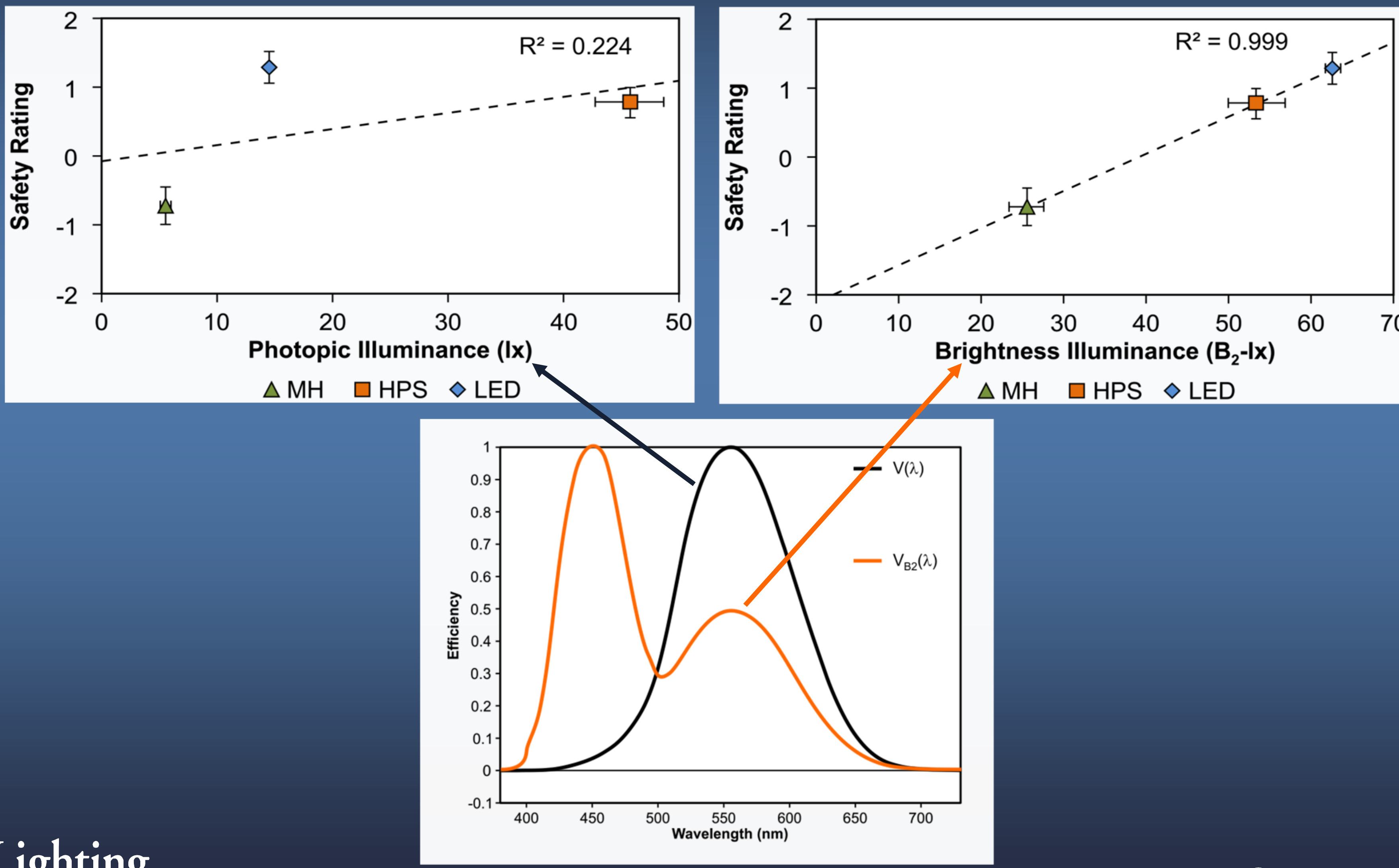
# Safety judgments





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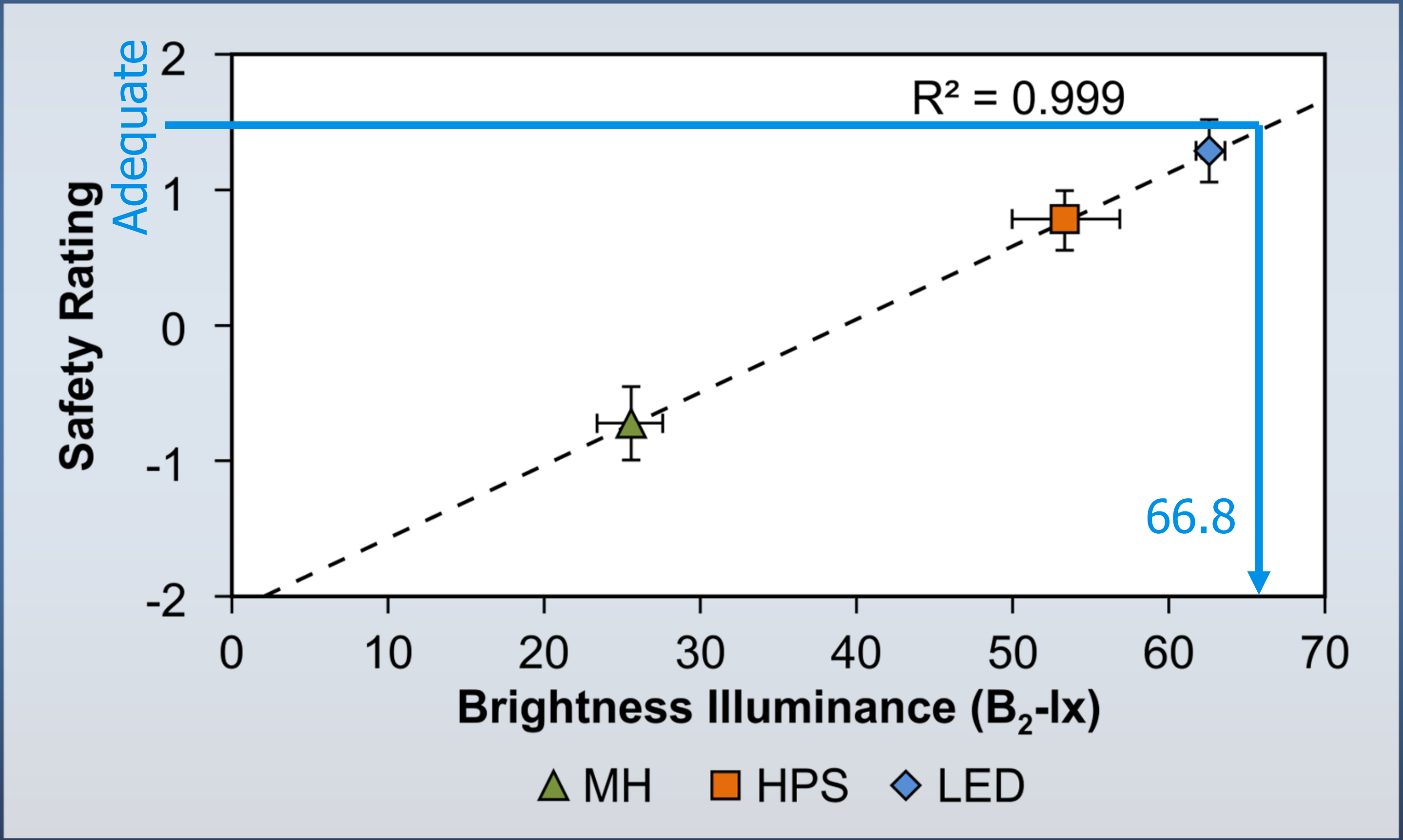
# Brightness illuminance for adequate safety and security







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# Design specifications

| Light Source | Brightness Illuminance ($B_2$-lx) | Photopic Illuminance (lx) | Power Density: Existing (W/ft$^2$) | Power Density: New (W/ft$^2$) | Power Density: After 5 Years (W/ft$^2$) |
|---|---|---|---|---|---|
| HPS | 66.8 | 57.1 | 0.09 | 0.09 | 0.11 |
| MH | 66.8 | 14.7 | 0.14 | 0.03 | 0.05 |
| LED | 66.8 | 15.5 | 0.03 | 0.03 | 0.04 |

conversion table

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# Design procedure

**Preliminary Design Procedure**

Formulae for calculating photopic illuminance and electrical power demand ratios for lighting specifications based on perceived scene brightness are given below.

Step 1. Determine the spectral power scaling factor needed for achieving the same perceived scene brightness by solving for the scaling constant, $a$, that equates the brightness flux of the LED SPD to the brightness flux of the HPS SPD:

$$\int_{400}^{750} V_{B2}(\lambda)P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda = a\int_{400}^{750} V_{B2}(\lambda)P_{Rel\,LED}(\lambda)\mathrm{d}\lambda$$

$$a = \frac{\int_{400}^{750} V_{B2}(\lambda)P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda}{\int_{400}^{750} V_{B2}(\lambda)P_{Rel\,LED}(\lambda)\mathrm{d}\lambda} \approx \frac{\sum_i V_{B2\,i}P_{Rel\,HPS\,i}\Delta\lambda}{\sum_i V_{B2\,i}P_{Rel\,LED\,i}\Delta\lambda} = \frac{0.845}{1.57} = 0.537$$

In these equations, $V_{B2}(\lambda)$ is the benefit luminous efficiency function from Rea[13] and is tabulated in 5 nm increments in Table A1. $P_{Rel\ HPS}(\lambda)$ and $P_{Rel\ LED}(\lambda)$ are the relative SPDs of the HPS and LED sources, respectively. In the approximations to the integrals, $V_{B2\ i}$, $P_{Rel\ HPS\ i}$ and $P_{Rel\ LED\ i}$ are the values of $V_{B2}(\lambda)$, $P_{Rel\ HPS}(\lambda)$ and $P_{Rel\ LED}(\lambda)$ for the $i$th row of the tabulated values in Table A1 and $\Delta\lambda$ is the wavelength increment of 5 nm.

Note that the starting SPDs can be relative, that is, not in absolute radiometric units. In this example, the SPDs in Table A1 are normalised to produce 1000 photopic lumens.

Step 2. Calculate the photopic flux of each SPD ($\Phi_{HPS}$ and $\Phi_{LED}$) when scaled for equal perceived scene brightness:

$$\Phi_{HPS} = 683\int_{400}^{750} V(\lambda)P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda \approx 683\sum_i V_i P_{Rel\,HPS\,i}\Delta\lambda = 1000\,\text{lumens}$$

$$\Phi_{LED} = 683a\int_{400}^{750} V(\lambda)P_{Rel\,LED}(\lambda)\mathrm{d}\lambda \approx 683a\sum_i V_i P_{Rel\,LED\,i}\Delta\lambda = 537\,\text{lumens}$$

$$\text{Luminous flux ratio} = \frac{\Phi_{LED}}{\Phi_{HPS}} = \frac{537}{1000} = 0.537$$

In these equations, $V(\lambda)$ is the photopic luminous efficiency function from Table A1. In the approximations to the integrals, $V_i$ is the value of $V(\lambda)$ for the $i$th row of the tabulated values in Table A1 and $\Delta\lambda$ is the wavelength increment of 5 nm.

Step 3. Determine the electrical power, $W_{HPS}$ and $W_{LED}$ (in watts), required to operate each light source as given by the luminous efficacy, $\eta_{HPS}$ and $\eta_{LED}$ (in lumens/watt), of each light source:

$$W_{HPS} = \frac{\Phi_{HPS}}{\eta_{HPS}} = \frac{1000}{96} = 10.4\,\text{watts},$$

$$W_{LED} = \frac{\Phi_{LED}}{\eta_{LED}} = \frac{537}{80} = 6.71\,\text{watts}$$

Step 4. Compute the electrical power ratio:

$$\text{Electric power ratio} = \frac{W_{LED}}{W_{HPS}} = \frac{6.71}{10.4} = 0.645$$

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# Design procedure

**Table A1** Spectral values for HPS and 6500 K LED light sources together with the photopic luminous efficiency function [$V(\lambda)$][25] and one benefit efficiency function based upon perceived scene brightness from Rea[13] [$V_{B2}(\lambda)$]

| Wavelength (nm) | $P_{Rel\,HPS}(\lambda)$ (W/nm) | $P_{Rel\,LED}(\lambda)$ (W/nm) | $V(\lambda)$ | $V_{B2}(\lambda)$ |
|---|---|---|---|---|
| 400 | 0.0008 | 0.0002 | 0.0004 | 0.0667 |
| 405 | 0.0010 | 0.0003 | 0.0006 | 0.1273 |
| 410 | 0.0010 | 0.0005 | 0.0012 | 0.1935 |
| 415 | 0.0011 | 0.0010 | 0.0022 | 0.3350 |
| 420 | 0.0012 | 0.0021 | 0.0040 | 0.5027 |
| 425 | 0.0013 | 0.0043 | 0.0073 | 0.6547 |
| 430 | 0.0015 | 0.0075 | 0.0116 | 0.8139 |
| 435 | 0.0018 | 0.0129 | 0.0169 | 0.8915 |
| 440 | 0.0020 | 0.0217 | 0.0230 | 0.9742 |
| 445 | 0.0015 | 0.0322 | 0.0298 | 0.9844 |
| 450 | 0.0038 | 0.0330 | 0.0380 | 1.0000 |
| 455 | 0.0018 | 0.0241 | 0.0481 | 0.9973 |
| 460 | 0.0011 | 0.0146 | 0.0600 | 0.9611 |
| 465 | 0.0046 | 0.0101 | 0.0740 | 0.8703 |
| 470 | 0.0027 | 0.0076 | 0.0910 | 0.7803 |
| 475 | 0.0018 | 0.0058 | 0.1127 | 0.6396 |
| 480 | 0.0006 | 0.0046 | 0.1390 | 0.5397 |
| 485 | 0.0007 | 0.0043 | 0.1695 | 0.4571 |
| 490 | 0.0013 | 0.0048 | 0.2081 | 0.3741 |
| 495 | 0.0029 | 0.0058 | 0.2589 | 0.3321 |
| 500 | 0.0128 | 0.0074 | 0.3231 | 0.2935 |
| 505 | 0.0012 | 0.0091 | 0.4075 | 0.2910 |
| 510 | 0.0010 | 0.0111 | 0.5031 | 0.3040 |
| 515 | 0.0035 | 0.0131 | 0.6083 | 0.3356 |
| 520 | 0.0010 | 0.0142 | 0.7101 | 0.3696 |
| 525 | 0.0009 | 0.0153 | 0.7931 | 0.4044 |
| 530 | 0.0010 | 0.0162 | 0.8622 | 0.4328 |
| 535 | 0.0010 | 0.0164 | 0.9148 | 0.4558 |
| 540 | 0.0011 | 0.0167 | 0.9542 | 0.4722 |
| 545 | 0.0019 | 0.0167 | 0.9803 | 0.4837 |
| 550 | 0.0026 | 0.0167 | 0.9951 | 0.4895 |
| 555 | 0.0037 | 0.0166 | 1.0000 | 0.4915 |
| 560 | 0.0048 | 0.0165 | 0.9952 | 0.4886 |
| 565 | 0.0098 | 0.0163 | 0.9786 | 0.4803 |
| 570 | 0.0711 | 0.0160 | 0.9522 | 0.4670 |
| 575 | 0.0116 | 0.0157 | 0.9154 | 0.4490 |
| 580 | 0.0192 | 0.0153 | 0.8702 | 0.4267 |
| 585 | 0.0524 | 0.0147 | 0.8163 | 0.4003 |
| 590 | 0.0096 | 0.0141 | 0.7572 | 0.3712 |
| 595 | 0.0650 | 0.0134 | 0.6950 | 0.3407 |
| 600 | 0.0366 | 0.0126 | 0.6311 | 0.3093 |
| 605 | 0.0229 | 0.0118 | 0.5669 | 0.2779 |
| 610 | 0.0155 | 0.0110 | 0.5031 | 0.2466 |
| 615 | 0.0239 | 0.0101 | 0.4413 | 0.2163 |
| 620 | 0.0092 | 0.0093 | 0.3811 | 0.1867 |
| 625 | 0.0074 | 0.0085 | 0.3211 | 0.1573 |
| 630 | 0.0063 | 0.0077 | 0.2651 | 0.1298 |
| 635 | 0.0055 | 0.0070 | 0.2172 | 0.1063 |
| 640 | 0.0049 | 0.0063 | 0.1750 | 0.0857 |
| 645 | 0.0044 | 0.0056 | 0.1383 | 0.0677 |
| 650 | 0.0039 | 0.0050 | 0.1070 | 0.0524 |
| 655 | 0.0038 | 0.0045 | 0.0817 | 0.0400 |
| 660 | 0.0035 | 0.0040 | 0.0610 | 0.0299 |
| 665 | 0.0032 | 0.0036 | 0.0447 | 0.0218 |
| 670 | 0.0036 | 0.0032 | 0.0320 | 0.0157 |
| 675 | 0.0035 | 0.0029 | 0.0233 | 0.0114 |
| 680 | 0.0027 | 0.0025 | 0.0170 | 0.0083 |
| 685 | 0.0021 | 0.0022 | 0.0120 | 0.0058 |
| 690 | 0.0017 | 0.0020 | 0.0082 | 0.0040 |
| 695 | 0.0015 | 0.0018 | 0.0057 | 0.0028 |
| 700 | 0.0014 | 0.0016 | 0.0041 | 0.0020 |
| 705 | 0.0014 | 0.0014 | 0.0029 | 0.0014 |
| 710 | 0.0014 | 0.0012 | 0.0021 | 0.0010 |
| 715 | 0.0013 | 0.0011 | 0.0015 | 0.0007 |
| 720 | 0.0013 | 0.0009 | 0.0010 | 0.0005 |
| 725 | 0.0012 | 0.0008 | 0.0007 | 0.0004 |
| 730 | 0.0012 | 0.0007 | 0.0005 | 0.0003 |
| 735 | 0.0012 | 0.0006 | 0.0000 | 0.0002 |
| 740 | 0.0012 | 0.0006 | 0.0000 | 0.0001 |
| 745 | 0.0011 | 0.0005 | 0.0000 | 0.0001 |
| 750 | 0.0011 | 0.0005 | 0.0000 | 0.0001 |

# Design procedure

**Preliminary Design Procedure**

Formulae for calculating photopic illuminance and electrical power demand ratios for lighting specifications based on perceived scene brightness are given below.

Step 1. Determine the spectral power scaling factor needed for achieving the same perceived scene brightness by solving for the scaling constant, $a$, that equates the brightness flux of the LED SPD to the brightness flux of the HPS SPD:

$$\int_{400}^{750} V_{B2}(\lambda) P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda = a\int_{400}^{750} V_{B2}(\lambda) P_{Rel\,LED}(\lambda)\mathrm{d}\lambda$$

$$a = \frac{\int_{400}^{750} V_{B2}(\lambda) P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda}{\int_{400}^{750} V_{B2}(\lambda) P_{Rel\,LED}(\lambda)\mathrm{d}\lambda} \approx \frac{\sum_i V_{B2\,i} P_{Rel\,HPS\,i}\Delta\lambda}{\sum_i V_{B2\,i} P_{Rel\,LED\,i}\Delta\lambda} = \frac{0.845}{1.57} = 0.537$$

In these equations, $V_{B2}(\lambda)$ is the benefit luminous efficiency function from Rea[13] and is tabulated in 5 nm increments in Table A1. $P_{Rel\ HPS}(\lambda)$ and $P_{Rel\ LED}(\lambda)$ are the relative SPDs of the HPS and LED sources, respectively. In the approximations to the integrals, $V_{B2\ i}$, $P_{Rel\ HPS\ i}$ and $P_{Rel\ LED\ i}$ are the values of $V_{B2}(\lambda)$, $P_{Rel\ HPS}(\lambda)$ and $P_{Rel\ LED}(\lambda)$ for the $i$th row of the tabulated values in Table A1 and $\Delta\lambda$ is the wavelength increment of 5 nm.

Note that the starting SPDs can be relative, that is, not in absolute radiometric units. In this example, the SPDs in Table A1 are normalised to produce 1000 photopic lumens.

Step 2. Calculate the photopic flux of each SPD ($\Phi_{HPS}$ and $\Phi_{LED}$) when scaled for equal perceived scene brightness:

$$\Phi_{HPS} = 683\int_{400}^{750} V(\lambda) P_{Rel\,HPS}(\lambda)\mathrm{d}\lambda \approx 683\sum_i V_i P_{Rel\,HPS\,i}\Delta\lambda = 1000\,\text{lumens}$$

$$\Phi_{LED} = 683a\int_{400}^{750} V(\lambda) P_{Rel\,LED}(\lambda)\mathrm{d}\lambda \approx 683a\sum_i V_i P_{Rel\,LED\,i}\Delta\lambda = 537\,\text{lumens}$$

$$\text{Luminous flux ratio} = \frac{\Phi_{LED}}{\Phi_{HPS}} = \frac{537}{1000} = 0.537$$

In these equations, $V(\lambda)$ is the photopic luminous efficiency function from Table A1. In the approximations to the integrals, $V_i$ is the value of $V(\lambda)$ for the $i$th row of the tabulated values in Table A1 and $\Delta\lambda$ is the wavelength increment of 5 nm.

Step 3. Determine the electrical power, $W_{HPS}$ and $W_{LED}$ (in watts), required to operate each light source as given by the luminous efficacy, $\eta_{HPS}$ and $\eta_{LED}$ (in lumens/watt), of each light source:

$$W_{HPS} = \frac{\Phi_{HPS}}{\eta_{HPS}} = \frac{1000}{96} = 10.4\,\text{watts},$$

$$W_{LED} = \frac{\Phi_{LED}}{\eta_{LED}} = \frac{537}{80} = 6.71\,\text{watts}$$

Step 4. Compute the electrical power ratio:

$$\text{Electric power ratio} = \frac{W_{LED}}{W_{HPS}} = \frac{6.71}{10.4} = 0.645$$

# Design specifications

| Light Source | Brightness Illuminance ($B_2$-lx) | Photopic Illuminance (lx) | Power Density: Existing (W/ft$^2$) | Power Density: New (W/ft$^2$) | Power Density: After 5 Years (W/ft$^2$) |
|---|---|---|---|---|---|
| HPS | 66.8 | 57.1 | 0.09 | 0.09 | 0.11 |
| MH | 66.8 | 14.7 | 0.14 | 0.03 | 0.05 |
| LED | 66.8 | 15.5 | 0.03 | 0.03 | 0.04 |

$\Delta$ = 0.07 W/ft$^2$

# Cost

- The amount of light needed to deliver an “adequate for safety” level of light would be 66.8 $B_2$-lx for any light source.
- The incremental power density needed by the HPS lighting system over the LED lighting system after 5 years, taking into account lumen depreciation, is 0.07 W/ft².
- The system cost to break even after 5 years is based upon the hours of use as well as the incremental energy (power x time) costs of the HPS relative to the LED systems to deliver 66.8 $B_2$-lx at 5 years.
  - Electricity would be used (12 h/day x 365 day/y) 21,900 h for 5 y.
  - The incremental energy savings over 5 years is 1.5 kWh/ft².
- At an estimated utility rate, including use and demand charges, of $0.10/kWh, the energy cost savings over 5 years from the LED lighting system would be $0.15/ft².

- Example: 50,000 ft² parking lot
  - For the 5 year payback, the initial cost of the LED system should not be more than $7,500 over the HPS system.

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# Expected benefits of brightness engineering

- Adopting the design methodology would lead to significant power and capital cost reductions in parking lots relative to existing practice while providing pedestrians with an “adequate for safety” level of light.
- Relative to existing HPS technology, high CCT LEDs can reduce energy consumption by approximately 50% in parking lot applications. During the winter, peak demand in the evening and the morning would also be reduced.
- Because these results have been shown empirically and theoretically in previous published studies, the findings from this demonstration project can be confidently and immediately implemented.

# Thank you

- Bonneville Power Administration
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- University of Washington

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