CORM 2008

CORM Council for Optical Radiation Measurements

The unified system of photometry: A model of mesopic vision

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Rensselaer

What is photometry?

- A simple, mathematically precise system of measuring and specifying light agreed to by an international community involved with its commerce and specification

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Why is photometry important?

- Promotes international trade
- Provides a quantitative language for communicating between stakeholders
- There must be a strong commercial reason for photometry to change

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What are the strengths and limitations of the current system of photometry?

- Strengths
  - Based on visual response: V_λ and V'_λ
  - CIE Standard Observer: V_λ and V'_λ are additive
  - Several visual responses have spectral sensitivity close to V_λ and V'_λ and are additive, or nearly so (Lennie et al., 1993)

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What are the strengths and limitations of the current system of photometry?

- Limitations
  - Judd correction needed for fovea (V_m)
  - $V_{10\lambda}$ needed for off-axis
  - Can't accurately characterize brightness
  - Can't accurately characterize visual performance
    - "More light, better light" – but only for small or low contrast targets
    - Interaction between stimulus variables
  - Mesopic: Which to use, V_λ or V'_λ?

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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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Unified system of photometry—
Spans photopic and scotopic through mesopic

- A unified system of photometry should:
  I. Be based upon studies of human vision
  II. Preserve Abney's law of additivity
  III. Preserve both the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions
  IV. Be practical to use

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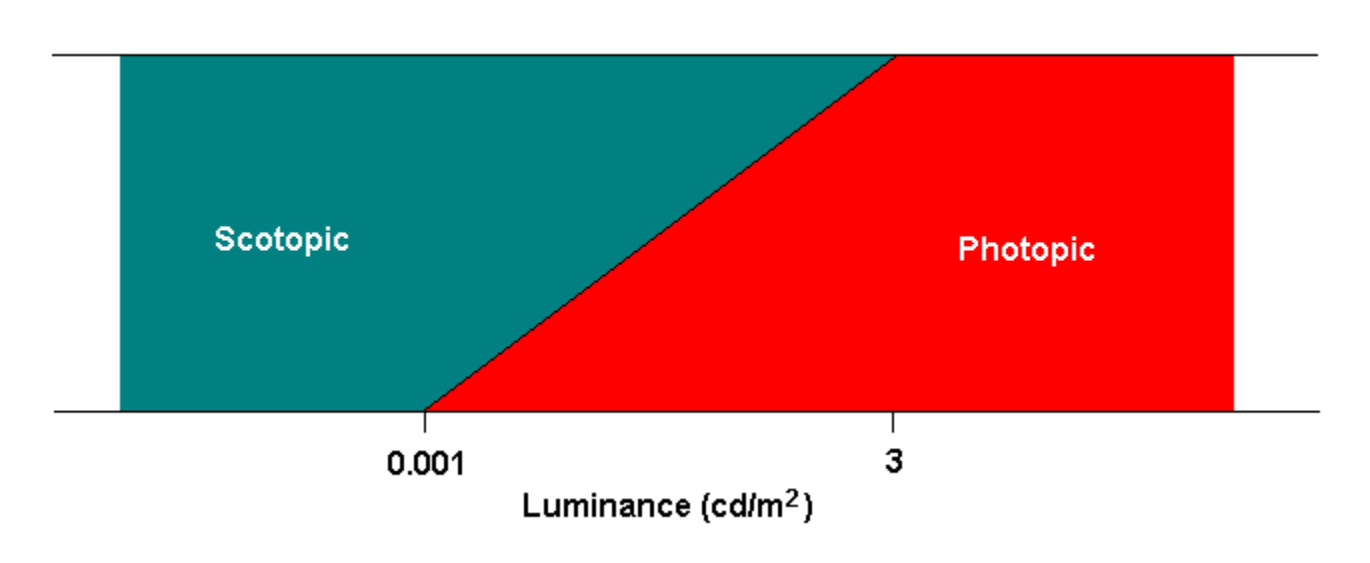
I. Based on human vision

- Could simply draw a line from 3 cd/m² to 0.001 cd/m² to define mesopic vision



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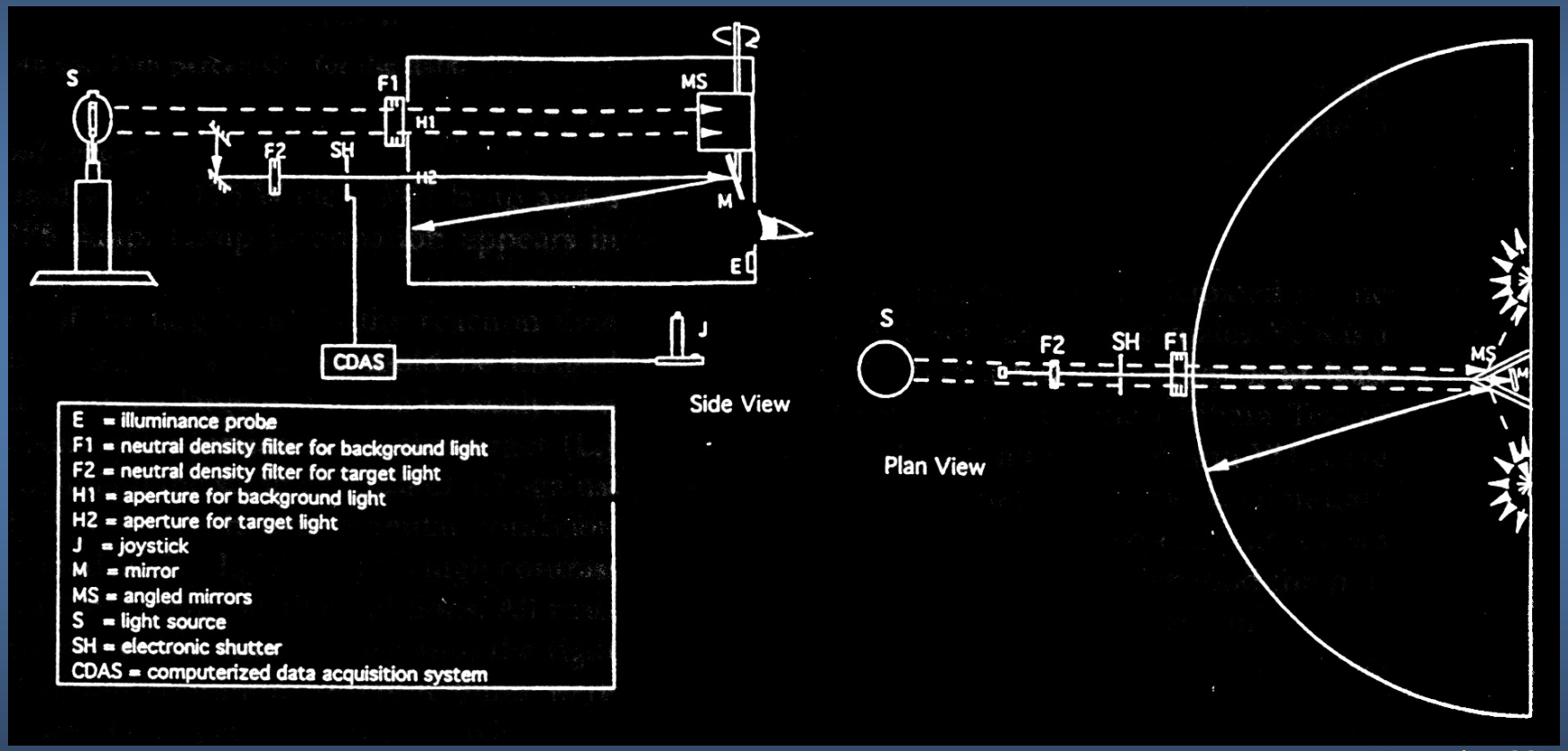
I. Based on human vision



He et al., 1997

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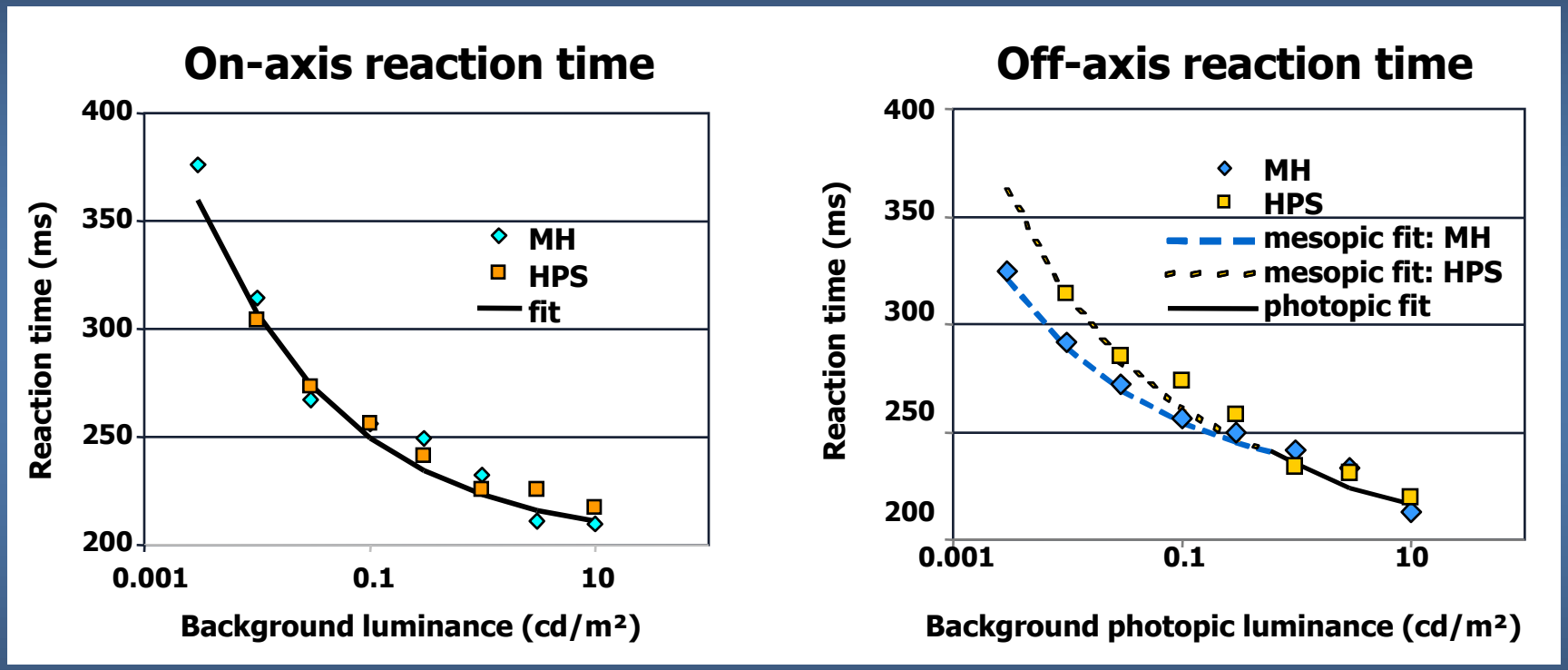
I. Based on human vision



He et al., 1997

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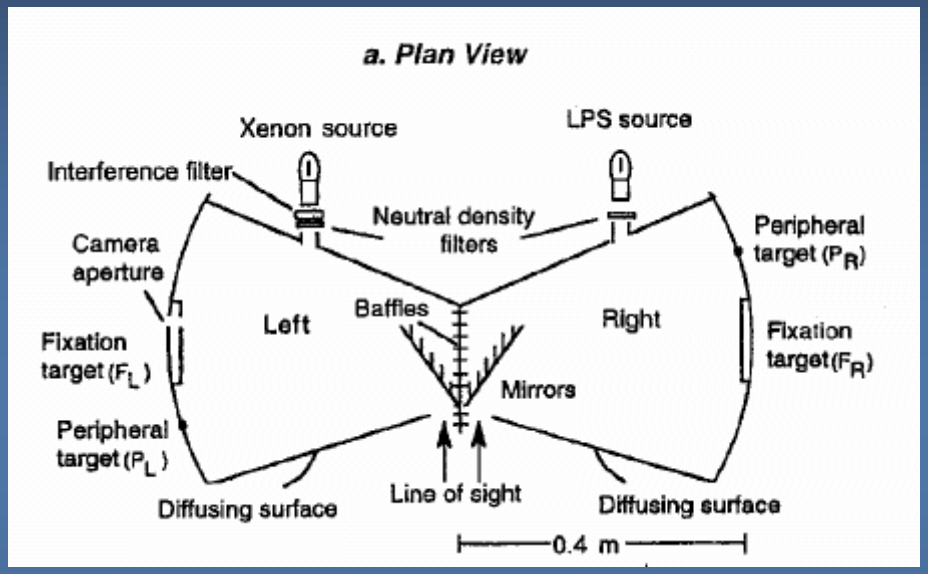
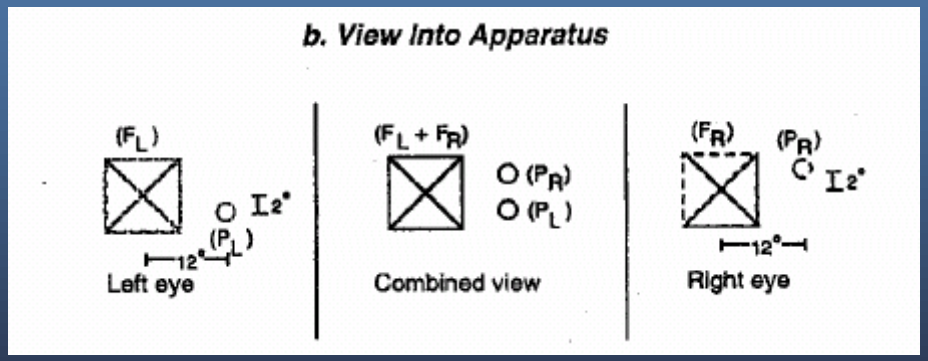
I. Based on human vision





Bierman et al., 1998; He et al., 1998

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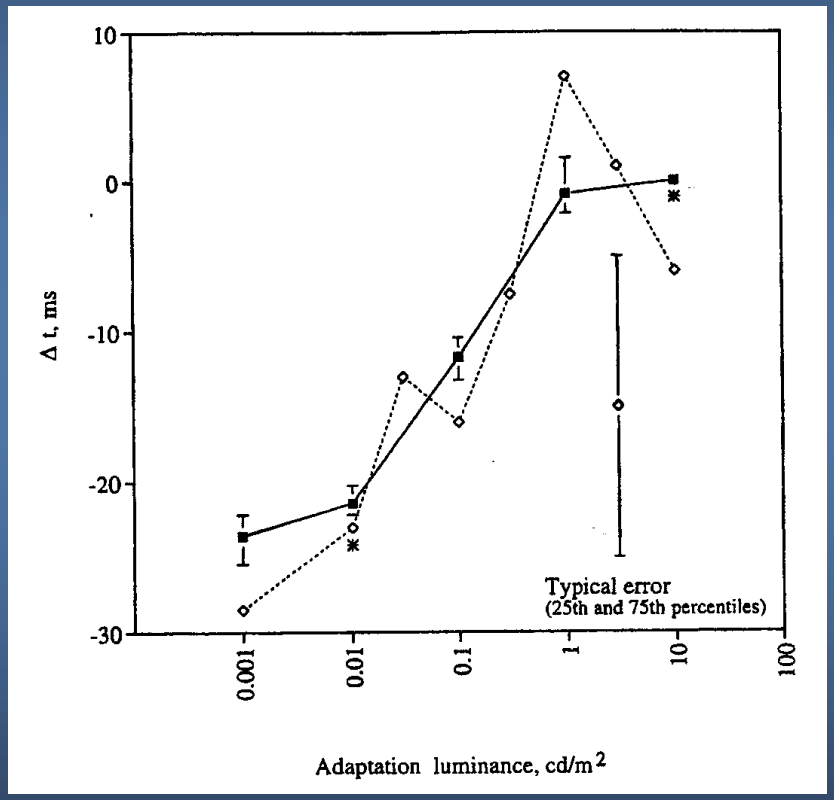
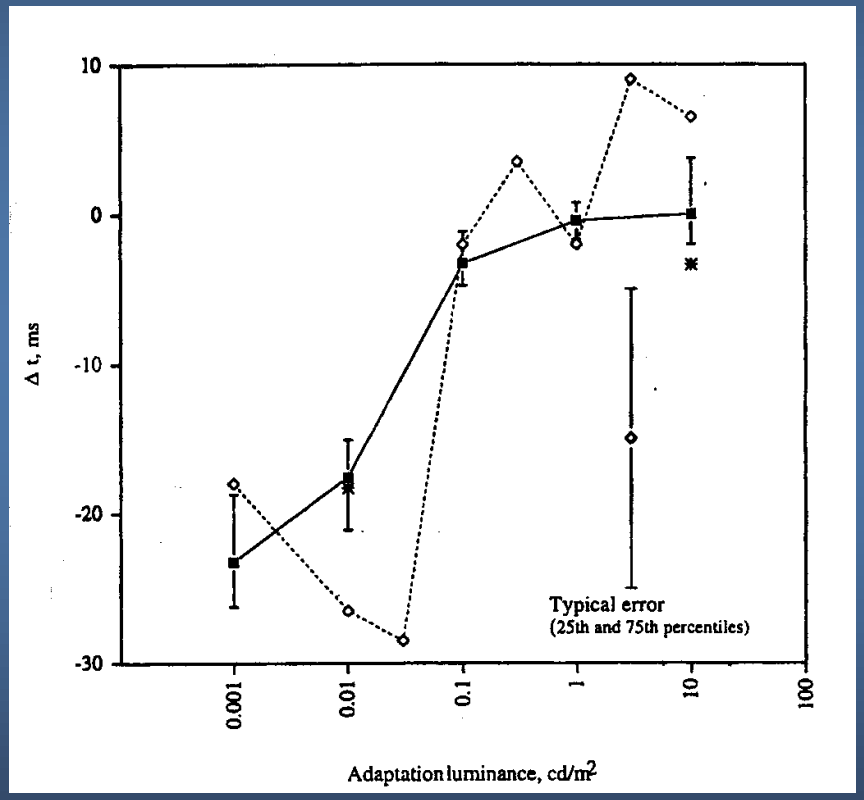
I. Based on human vision

Relative differences in response times for HPS and MH





Bierman et al. (1998)

Binocular simultaneity method provides greater precision than reaction times

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I. Based on human vision

- The relative proportion of photopic ($V_{10\lambda}$) and scotopic (V'_{λ}) luminous efficiency for peripheral vision at a given (mesopic) light level (He et al., 1997; 1998)
  - At high light levels, x = 1
  - At very low levels, x = 0
- $V_{mes} = (x)\, V_{10\lambda} + (1 - x)\, V'_{\lambda}$

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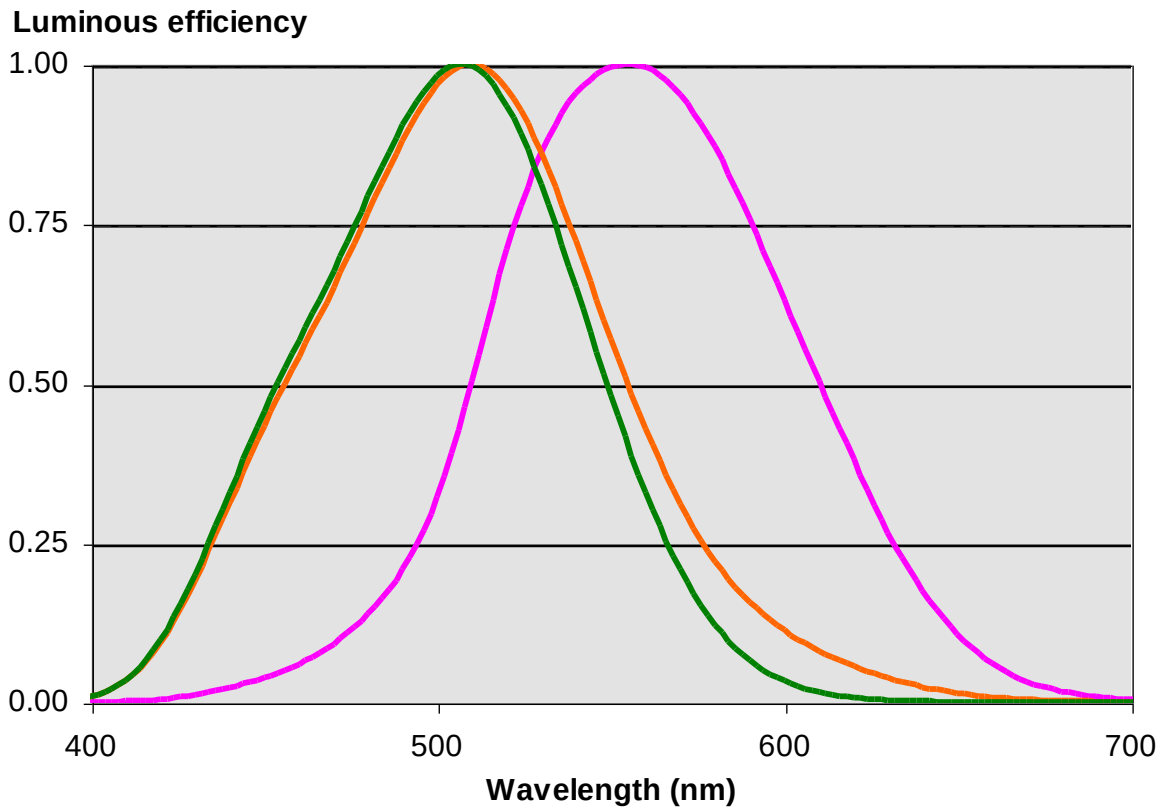
I. Based on human vision



x = 0,09

L = 0,02 cd/m²

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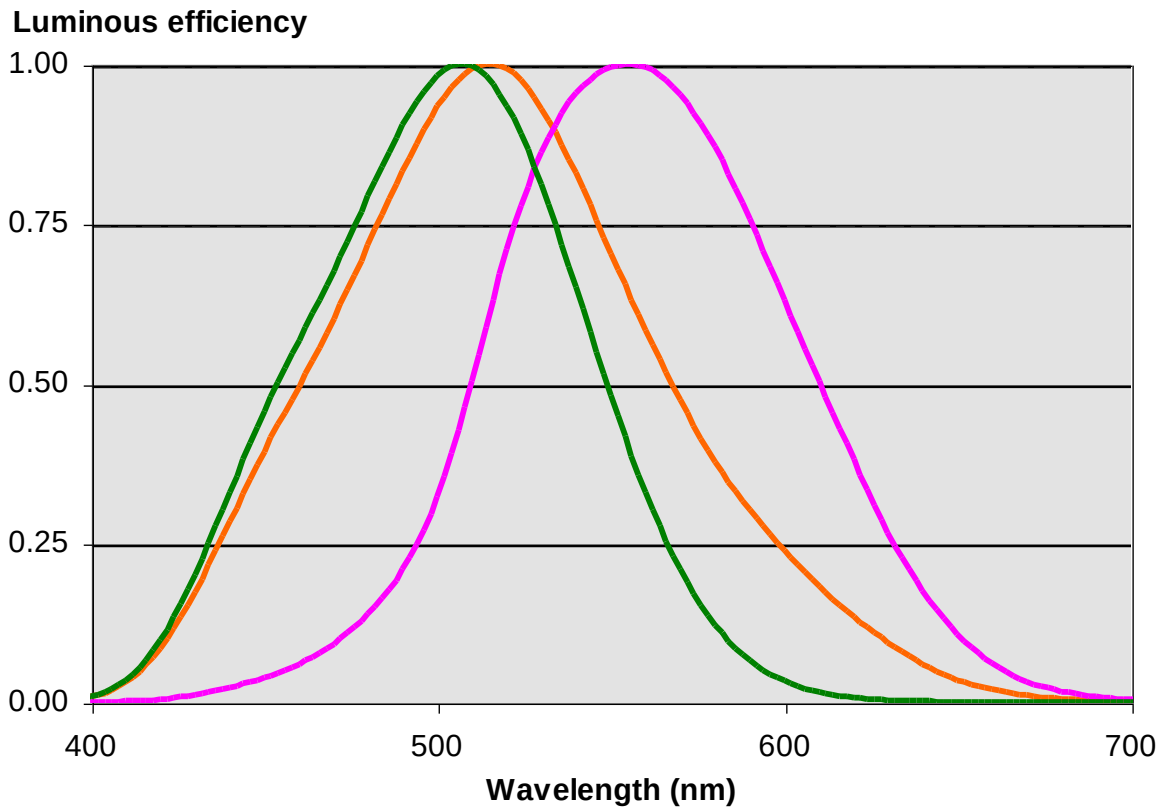
I. Based on human vision



x = 0,16

L = 0,05 cd/m²

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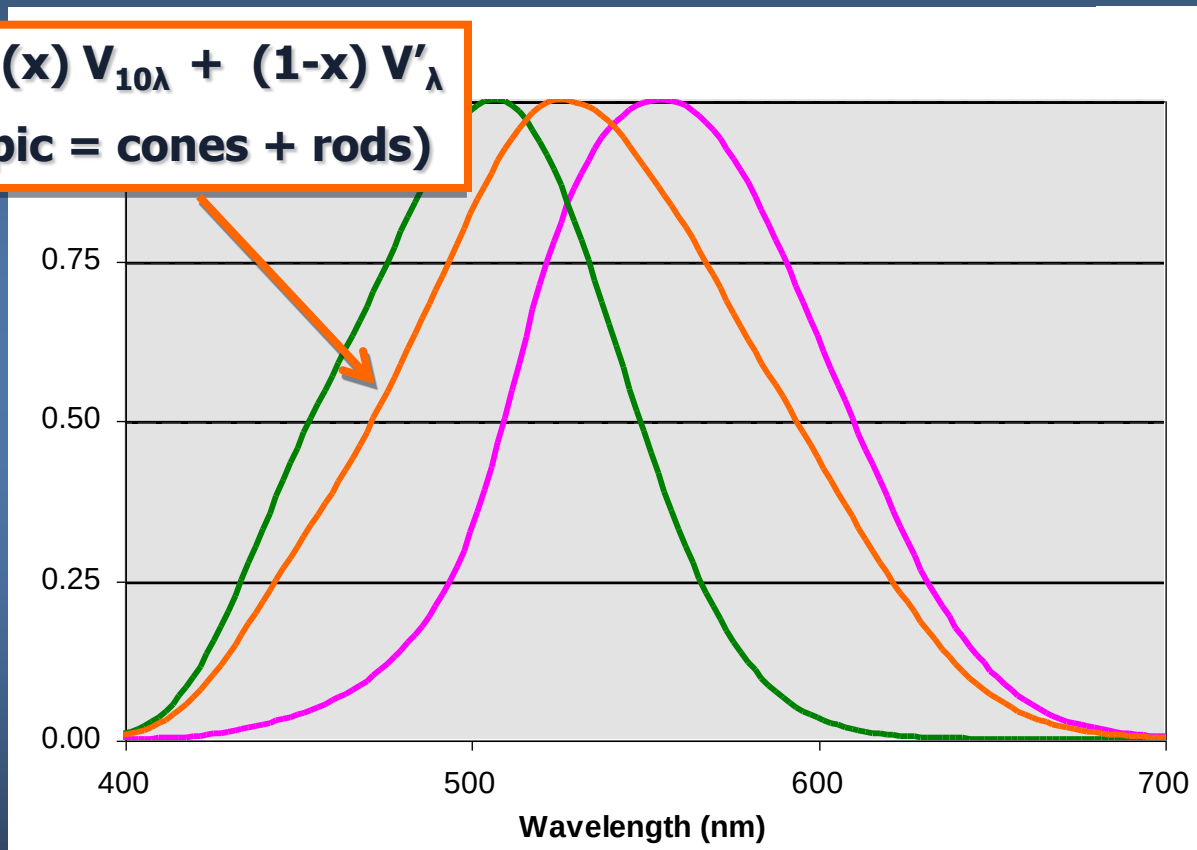
I. Based on human vision

$V_{mes} = (x)\, V_{10\lambda} + (1-x)\, V'_{\lambda}$

(mesopic = cones + rods)



x = 0,40

L = 0,22 cd/m²

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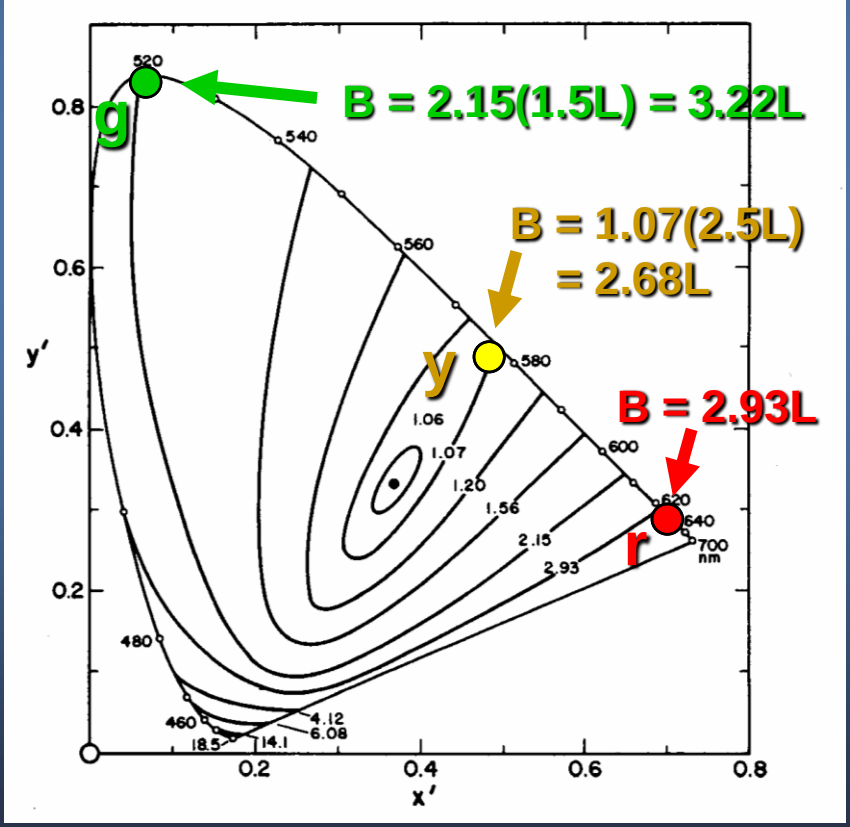
II. Preserve Abney's law of additivity

- Methods using brightness do not obey Abney's law of additivity



Guth et al., 1980

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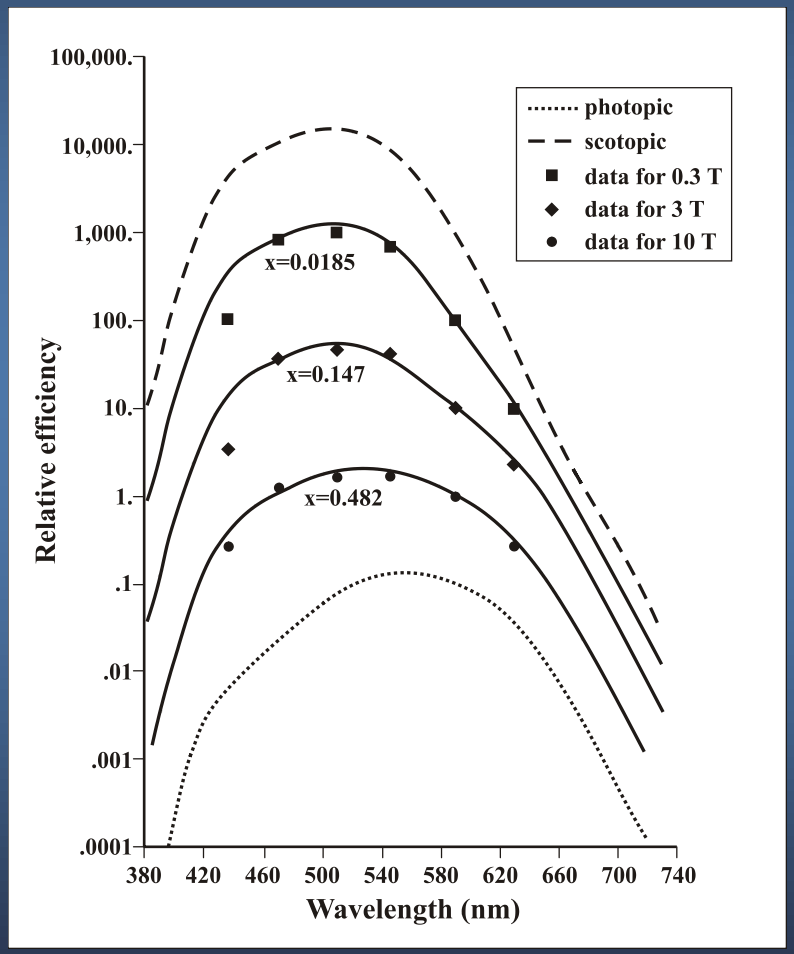
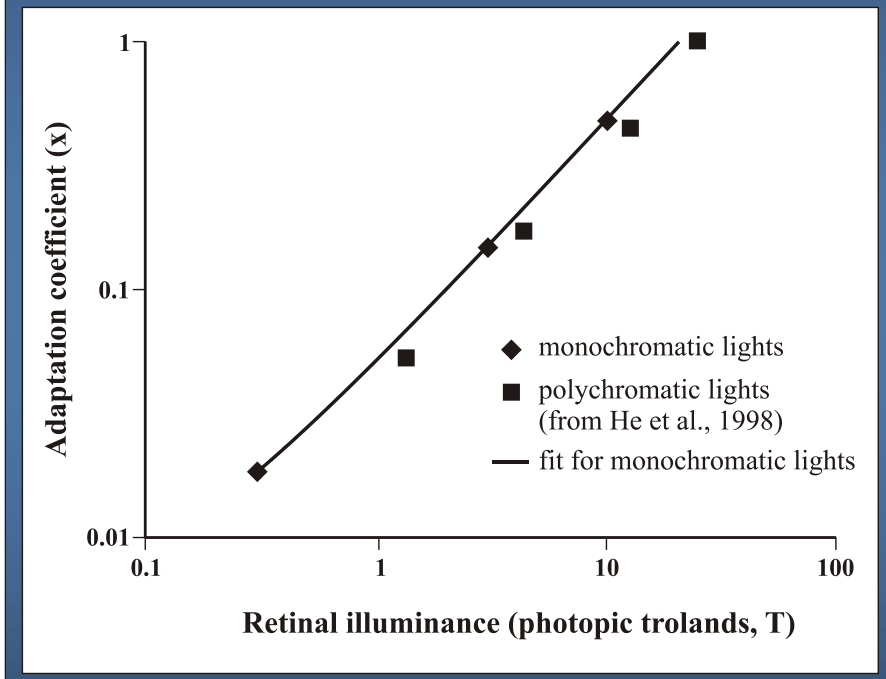
II. Preserve Abney's law of additivity





He et al., 1998

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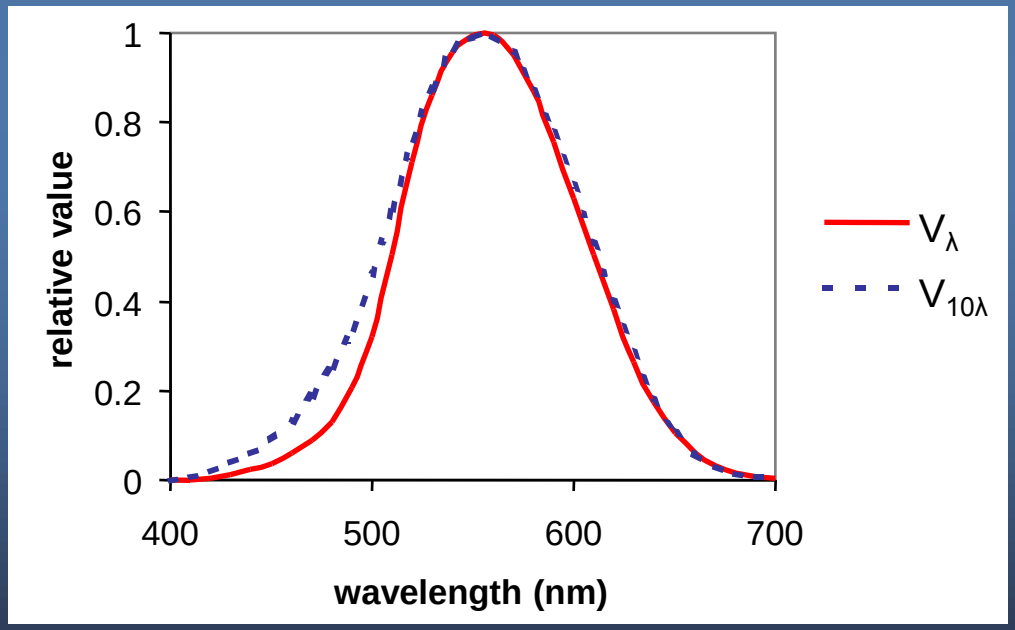
III. Preserve the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions

- Many systems of photometry for mesopic light levels incorporate $V_{10\lambda}$ (Nakano and Ikeda, 1986; Kokoschka, 1972; He et al., 1997, 1998)



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III. Preserve the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions

- Except for blue LEDs, differences between values based on V_λ and $V_{10\lambda}$ are relatively small

Light source	Luminous efficacy using different luminous efficiency functions *Percentage difference from V(λ)* $V(\lambda)$	$V_{10}(\lambda)$
1000W incandescent	14.7	15.5 *+5.5%*
T8 fluorescent (3500K)	84.9	89.3 *+5.2%*
T12 daylight fluorescent (6500K)	64.0	69.3 *+8.3%*
250W high pressure sodium	126.9	131.8 *+3.9%*
1000W metal halide	107.4	114.5 *+6.6%*
630-nm red AlGaInP LED	21.0	22.1 *+5.0%*
470-nm blue InGaN LED	6.0	11.5 *+92%*
460+555-nm white InGaN+YAG LED	15.0	16.5 *+9.8%*

Schanda et al., 2002

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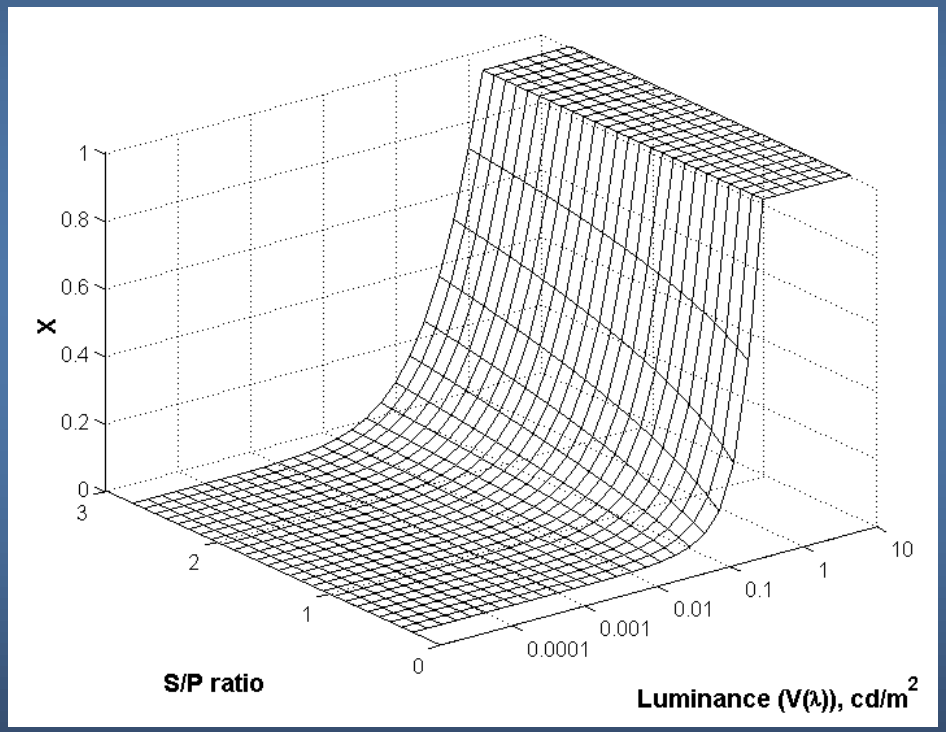
III. Preserve the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions

- 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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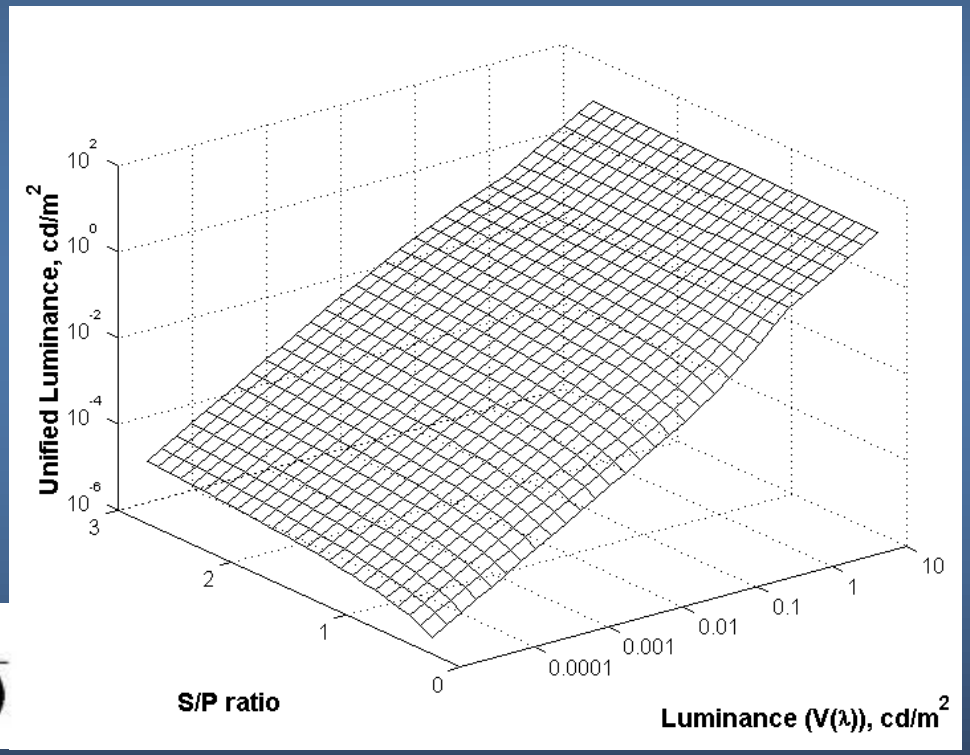
III. Preserve the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions

- Values of unified luminance (L)

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



$$L = \left[\frac{XP}{683} + \frac{(1-X)S}{1700}\right]\frac{683}{X + 0{,}402(1-X)}$$

Rea et al., 2003

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IV. A practical system

- Too much complexity guarantees it will not be used

mesopic luminance =

f(radiance, rod, S cone, M cone, L cone,

size, eccentricity, speed, ...)

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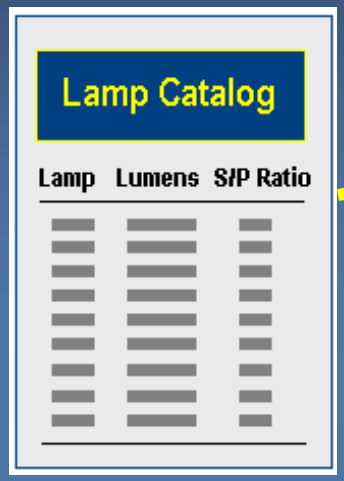
IV. A practical system



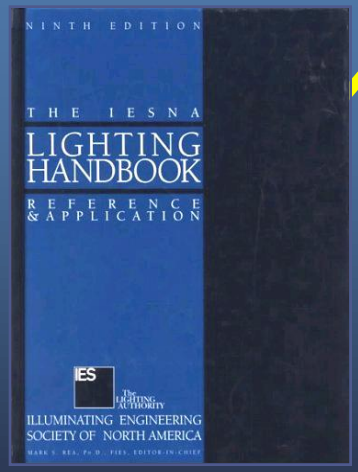
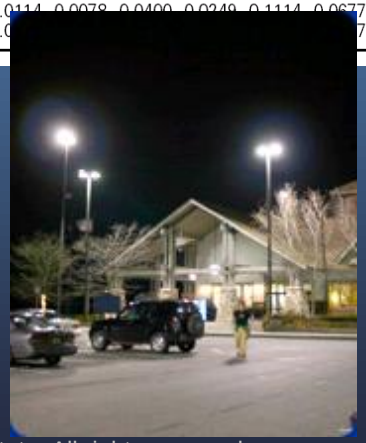


Table 3 Values of X and L for different light levels and S/P ratios

	Photopic ($V(\lambda)$) luminance (cd/m^2)													
S/P	0.001		0.003		0.01		0.03		0.1		0.3		0.55	
	X	L	X	L	X	L	X	L	X	L	X	L	X	L
0.25	0	0.0002	0	0.0007	0.0026	0.0025	0.0119	0.0082	0.0562	0.0347	0.3306	0.1990	0.8811	0.5288
0.35	0	0.0003	0.0001	0.0010	0.0043	0.0036	0.0172	0.0113	0.0749	0.0459	0.3652	0.2198	0.8876	0.5327
0.45	0	0.0004	0.0006	0.0014	0.0060	0.0046	0.0223	0.0144	0.0919	0.0560	0.3938	0.2369	0.8934	0.5362
0.55	0	0.0005	0.0011	0.0017	0.0076	0.0056	0.0273	0.0174	0.1074	0.0653	0.4183	0.2516	0.8986	0.5393
0.65	0	0.0006	0.0016	0.0020	0.0093	0.0066	0.0322	0.0203	0.1218	0.0739	0.4397	0.2644	0.9032	0.5420
0.75	0	0.0007	0.0021	0.0023	0.0110	0.0076	0.0370	0.0231	0.1352	0.0820	0.4588	0.2758	0.9075	0.5446
0.85	0	0.0008	0.0026	0.0026	0.0126	0.0085	0.0416	0.0259	0.1477	0.0895	0.4761	0.2862	0.9113	0.5469
0.95	0	0.0009	0.0031	0.0028	0.0142	0.0095	0.0462	0.0286	0.1595	0.0966	0.4917	0.2956	0.9149	0.5490
1.05	0.0001	0.0010	0.0036	0.0031	0.0158	0.0105	0.0506	0.0313	0.1707	0.1033	0.5061	0.3042	0.9181	0.5509
1.15	0.0002	0.0011	0.0041	0.0034	0.0174	0.0114	0.0549	0.0339	0.1814	0.1096	0.5194	0.3121	0.9211	0.5527
1.25	0.0004	0.0012	0.0046	0.0037	0.0190	0.0124	0.0592	0.0365	0.1915	0.1157	0.5318	0.3196	0.9239	0.5544
1.35	0.0006	0.0013	0.0051	0.0040	0.0206	0.0133	0.0634	0.0390	0.2011	0.1215	0.5433	0.3265	0.9264	0.5559
1.45	0.0007	0.0014	0.0056	0.0043	0.0221	0.0143	0.0675	0.0414	0.2104	0.1270	0.5541	0.3329	0.9288	0.5574
1.55	0.0009	0.0015	0.0060	0.0046	0.0237	0.0152	0.0715	0.0438	0.2192	0.1323	0.5643	0.3390	0.9311	0.5587
1.65	0.0011	0.0016	0.0065	0.0049	0.0252	0.0161	0.0754	0.0462	0.2278	0.1374	0.5739	0.3448	0.9332	0.5600
1.75	0.0012	0.0017	0.0070	0.0052	0.0267	0.0170	0.0793	0.0485	0.2360	0.1424	0.5830	0.3502	0.9352	0.5612
1.85	0.0014	0.0018	0.0075	0.0055	0.0282	0.0179	0.0831	0.0508	0.2439	0.1471	0.5915	0.3553	0.9370	0.5623
1.95	0.0016	0.0019	0.0080	0.0058	0.0297	0.0188	0.0868	0.0530	0.2516	0.1517	0.5997	0.3602	0.9388	0.5633
2.05	0.0017	0.0020	0.0085	0.0061	0.0312	0.0197	0.0905	0.0552	0.2590	0.1561	0.6075	0.3649	0.9404	0.5643
2.15	0.0019	0.0021	0.0090	0.0064	0.0327	0.0206	0.0941	0.0574	0.2661	0.1604	0.6149	0.3693	0.9420	0.5653
2.25	0.0021	0.0022	0.0094	0.0067	0.0342	0.0215	0.0977	0.0595	0.2730	0.1646	0.6220	0.3736	0.9435	0.5662
2.35	0.0022	0.0023	0.0099	0.0069	0.0356	0.0224	0.1012	0.0616	0.2798	0.1686	0.6287	0.3776	0.9449	0.5670
2.45	0.0024	0.0024	0.0104	0.0072	0.0371	0.0232	0.1046	0.0637	0.2863	0.1725	0.6352	0.3815	0.9462	0.5678
2.55	0.0026	0.0025	0.0109	0.0075	0.0385	0.0241	0.1080	0.0657	0.2927	0.1763	0.6415	0.3852	0.9475	0.5686
2.65	0.0027	0.0026	0.0114	0.0078	0.0400	0.0249	0.1114	0.0677	0.2989	0.1800	0.6474	0.3888	0.9487	0.5693
2.75	0.0029	0.0027	0.0					7	0.3049	0.1836	0.6532	0.3923	0.9499	0.5700



Rea et al. (2004)

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Table 3 Values of X and L for different light levels and S/P ratios

	Photopic ($V(\lambda)$) luminance (cd/m^2)													
S/P	0.001		0.003		0.01		0.03		0.1		0.3		0.55	
	X	L	X	L	X	L	X	L	X	L	X	L	X	L
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0.35	0	0.0003	0.0001	0.0010	0.0043	0.0036	0.0172	0.0113	0.0749	0.0459	0.3652	0.2198	0.8876	0.5327
0.45	0	0.0004	0.0006	0.0014	0.0060	0.0046	0.0223	0.0144	0.0919	0.0560	0.3938	0.2369	0.8934	0.5362
0.55	0	0.0005	0.0011	0.0017	0.0076	0.0056	0.0273	0.0174	0.1074	0.0653	0.4183	0.2516	0.8986	0.5393
0.65	0	0.0006	0.0016	0.0020	0.0093	0.0066	0.0322	0.0203	0.1218	0.0739	0.4397	0.2644	0.9032	0.5420
0.75	0	0.0007	0.0021	0.0023	0.0110	0.0076	0.0370	0.0231	0.1352	0.0820	0.4588	0.2758	0.9075	0.5446
0.85	0	0.0008	0.0026	0.0026	0.0126	0.0085	0.0416	0.0259	0.1477	0.0895	0.4761	0.2862	0.9113	0.5469
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1.05	0.0001	0.0010	0.0036	0.0031	0.0158	0.0105	0.0506	0.0313	0.1707	0.1033	0.5061	0.3042	0.9181	0.5509
1.15	0.0002	0.0011	0.0041	0.0034	0.0174	0.0114	0.0549	0.0339	0.1814	0.1096	0.5194	0.3121	0.9211	0.5527
1.25	0.0004	0.0012	0.0046	0.0037	0.0190	0.0124	0.0592	0.0365	0.1915	0.1157	0.5318	0.3196	0.9239	0.5544
1.35	0.0006	0.0013	0.0051	0.0040	0.0206	0.0133	0.0634	0.0390	0.2011	0.1215	0.5433	0.3265	0.9264	0.5559
1.45	0.0007	0.0014	0.0056	0.0043	0.0221	0.0143	0.0675	0.0414	0.2104	0.1270	0.5541	0.3329	0.9288	0.5574
1.55	0.0009	0.0015	0.0060	0.0046	0.0237	0.0152	0.0715	0.0438	0.2192	0.1323	0.5643	0.3390	0.9311	0.5587
1.65	0.0011	0.0016	0.0065	0.0049	0.0252	0.0161	0.0754	0.0462	0.2278	0.1374	0.5739	0.3448	0.9332	0.5600
1.75	0.0012	0.0017	0.0070	0.0052	0.0267	0.0170	0.0793	0.0485	0.2360	0.1424	0.5830	0.3502	0.9352	0.5612
1.85	0.0014	0.0018	0.0075	0.0055	0.0282	0.0179	0.0831	0.0508	0.2439	0.1471	0.5915	0.3553	0.9370	0.5623
1.95	0.0016	0.0019	0.0080	0.0058	0.0297	0.0188	0.0868	0.0530	0.2516	0.1517	0.5997	0.3602	0.9388	0.5633
2.05	0.0017	0.0020	0.0085	0.0061	0.0312	0.0197	0.0905	0.0552	0.2590	0.1561	0.6075	0.3649	0.9404	0.5643
2.15	0.0019	0.0021	0.0090	0.0064	0.0327	0.0206	0.0941	0.0574	0.2661	0.1604	0.6149	0.3693	0.9420	0.5653
2.25	0.0021	0.0022	0.0094	0.0067	0.0342	0.0215	0.0977	0.0595	0.2730	0.1646	0.6220	0.3736	0.9435	0.5662
2.35	0.0022	0.0023	0.0099	0.0069	0.0356	0.0224	0.1012	0.0616	0.2798	0.1686	0.6287	0.3776	0.9449	0.5670
2.45	0.0024	0.0024	0.0104	0.0072	0.0371	0.0232	0.1046	0.0637	0.2863	0.1725	0.6352	0.3815	0.9462	0.5678
2.55	0.0026	0.0025	0.0109	0.0075	0.0385	0.0241	0.1080	0.0657	0.2927	0.1763	0.6415	0.3852	0.9475	0.5686
2.65	0.0027	0.0026	0.0114	0.0078	0.0400	0.0249	0.1114	0.0677	0.2989	0.1800	0.6474	0.3888	0.9487	0.5693
2.75	0.0029	0.0027	0.0118	0.0081	0.0414	0.0258	0.1147	0.0697	0.3049	0.1836	0.6532	0.3923	0.9499	0.5700

IV. A practical system

- 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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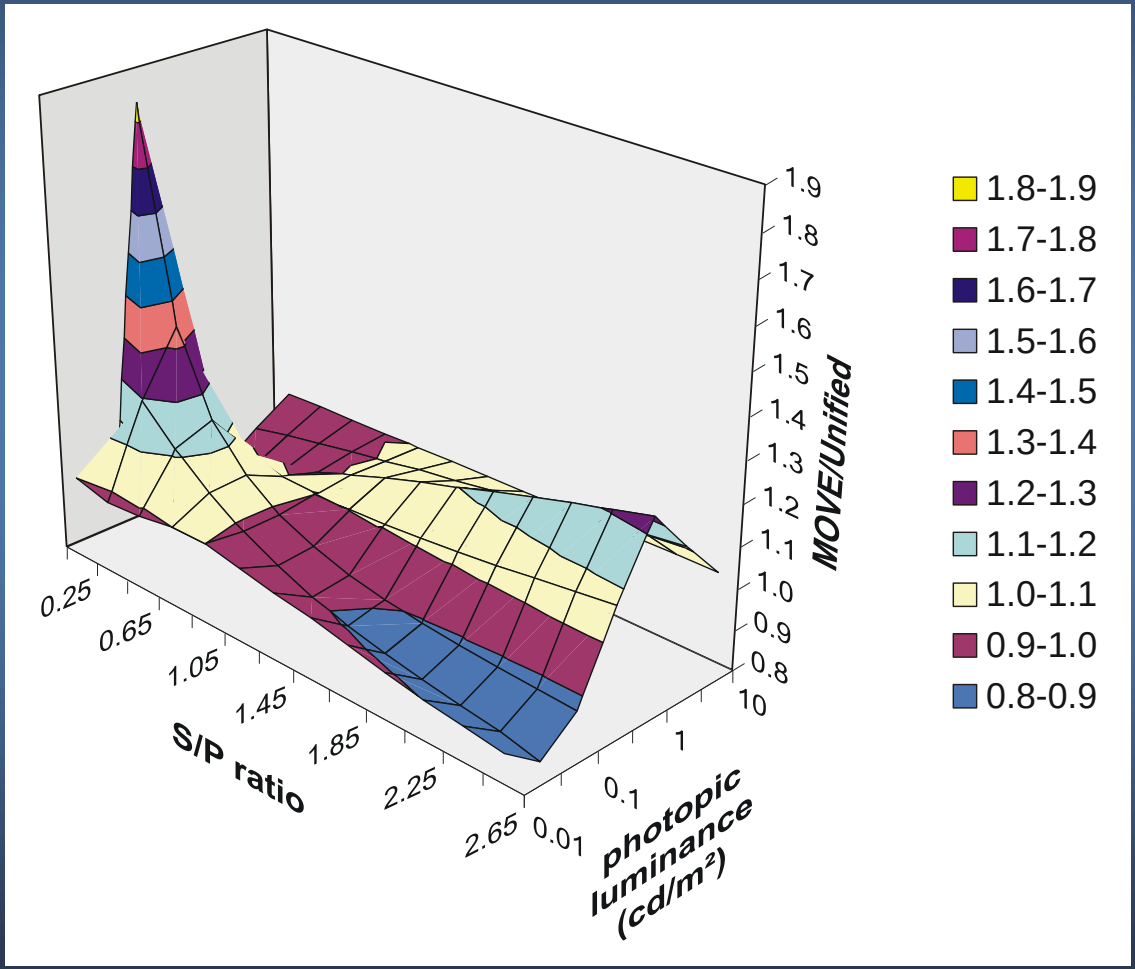
Unified/MOVE luminance ratio



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Summary

- Photometry needs to follow four tenets
  I. Based upon studies of human vision
     - Consistently demonstrated effects in multiple laboratories
  II. Preserve Abney's law of additivity
     - Demonstrated with monochromatic and polychromatic sources
  III. Preserve both the photopic (V_λ) and scotopic (V'_λ) luminous efficiency functions
     - Simplified system utilized by North America and Europe
  IV. Practical to use
     - Nothing new for lamp manufacturers and sanctioning bodies (IES, CIE)
     - Simple look-up table for specifiers

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Thank you.

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