A CORRELATIVE COMPARISON OF CIRCADIAN LIGHTING MODELS

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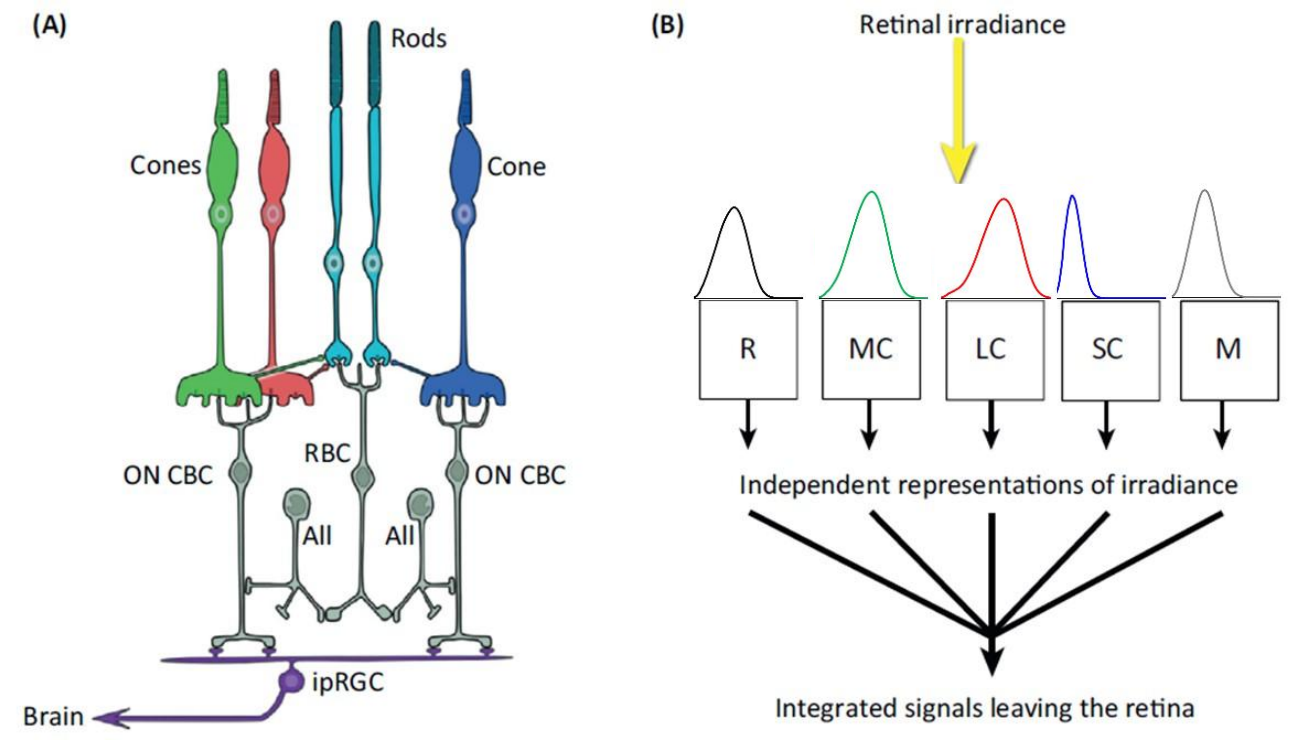
Photoreceptors and Neural Anatomy



"[A] completely successful model of human circadian phototransduction must take into account all retinal photoreceptors and their supporting neural mechanisms and must be constrained by the known anatomy and physiology of the retina and brain including neural interactions under a wide range of operating conditions." [2]

"[A] single photopigment model cannot possibly represent the dynamic operating characteristics of the neural mechanisms underlying circadian phototransduction."[2]

[1] RJ Lucas, SN Peirson, DM Berson, TM Brown, H Cooper, CA Czeisler, MG Figueiro, PD Gamlin, SW Lockley , JB O'Hagan, LL Price, I Provencio, DJ Skene, GC Brainard. "Measuring and Using Light In the Melanopsin Age." Trends Neurosci. 2013 Nov 25;37(1):1-9 doi: 10.1016/j.tins.2013.10.004

[2] Rea MS, Figueiro MG "Light as a circadian stimulus for architectural lighting." Lighting Res. Technol. 2016; 0: 1-14. doi: 10.1177/1477153516682368

Common Circadian Lighting Models

- Melanopic Equivalent Daylight Illuminance
  - CIE S 026/E:2018
- Equivalent Melanopic Lux (EML)
  - Lucas et al.[1]
  - WELL Building Standard WELL v2
- Circadian Stimulus (CL_A/CS)
  - LRC/LHRC
  - Underwriter's Laboratories DG 24480

[1]Lucas et al. "Measuring and Using Light In the Melanopsin Age." Trends Neurosci. 2013 Nov 25;37(1):1-9 doi: 10.1016/j.tins.2013.10.004

MELANOPIC-EDI & EML

- Melanopic-EDI → reference: Illuminant D65
- EML → reference: Illuminant E
- Melanopic-EDI and EML are perfectly correlated ($r^2 = 1$) → equal predictive capabilities

$$EML = 1.104(melanopic\text{-}EDI)$$

- CIE is the ranking authority on matters related to vision and light
- Melanopic-EDI strongly preferred over EML

Circadian Stimulus Model

- First circadian lighting model, initially developed in 2005
- Mathematically complex
  - 5-8 explicit adjustable parameters
  - Additional adjustments via selection of photoreceptor fundamentals, macular pigment correction
  - Mathematical formulations intended to account for neural circuitry of retina
- Numerous revisions (2005, 2007, 2010, 2011, 2012, 2016, 2019, 2021)
  - Early versions (2005 – 2010) could predict a negative response
  - "CL_A" formally introduced in 2010
  - 2021 version (CL_A2.0) based on different neural circuit diagram

Circadian Stimulus Calculators

- LRC on-line CS Calculator (CL_A1.0)
  - On-line CS Calculator: https://www.lrc.rpi.edu/cscalculator/
  - Excel CS Calculator: http://www.lrc.rpi.edu/resources/CSCalculator_2017_10_03_Mac.xlsm
- LHRC on line CS Calculator (CL_A2.0)
  - https://cscalc.light-health.org/
- Luxpy.toolbox
  - https://ksmet1977.github.io/luxpy/build/html/_modules/luxpy/toolboxes/photbiochem/circadian_CS_CLa_lrc.html

Circadian Stimulus Model Today

- No clear consensus on which version should be used
- UL DG 24480[4]
  - Directs use of ***LRC*** on-line CS calculator (aka CL_A1.0) – 10 times!
  - Example calculation (Appendix C) is not found in the published literature!
  - Training videos for UL DG 24480 direct use of ***LHRC*** on-line CS calculator (aka CL_A2.0)
- Latest formulation of Circadian Stimulus model (CL_A2.0) published in 2021[5]

CL_A2.0 is almost 4 years old, but UL DG 24480 has not been updated

[4] Published 19 December 2019

[5] Submitted 8 October 2020, Accepted 8 January 2021, Published 5 February 2021

Circadian Lighting Model Comparisons

- CL_A1.0 v CL_A2.0
- CL_A1.0 v Melanopic-EDI
- CL_A2.0 v Melanopic-EDI

Mathematical Comparison of Models

$$\boldsymbol{Melanopic-EDI} = \frac{\int E_\lambda S_{mel,\lambda} d\lambda}{K_{mel,v}^{D65}} = \frac{\int E_\lambda S_{mel,\lambda} d\lambda}{1.3262\ mW\ lm^{-1}}$$

$$\boldsymbol{CL_A 1.0} = 1548\left[\int M_{C\lambda} E_\lambda d\lambda \ + \ 0.7000\left(\int S_{C\lambda} E_\lambda d\lambda \ - 0.2616 \int V_{C\lambda} E_\lambda d\lambda\right) - 3.300\left(1 - e^{-\int V'_\lambda E_\lambda d\lambda / 6.5}\right)\right] \quad \boldsymbol{BY_\lambda \geq 0}$$

$$\boldsymbol{CL_A 1.0} \ = \ 1548\left[\int M_{C\lambda} E_\lambda d\lambda\right] \quad \boldsymbol{BY_\lambda < 0}$$

$$\boldsymbol{CL_A 2.0} = 1548\left[\int M_{C\lambda} E_\lambda d\lambda \ - 2.30\left(\frac{\int V'_\lambda E_\lambda d\lambda}{\int V_{C\lambda} E_\lambda d\lambda + 1.00 \int S_{C\lambda} E_\lambda d\lambda}\right)\left(1 - e^{-\int V'_\lambda E_\lambda d\lambda / 6.5}\right) + 0.21\left(\int S_{C\lambda} E_\lambda d\lambda - 0.2616 \int V_{C\lambda} E_\lambda d\lambda\right) - 1.60\left(\frac{\int V'_\lambda E_\lambda d\lambda}{\int V_{C\lambda} E_\lambda d\lambda + 0.16 \int S_{C\lambda} E_\lambda d\lambda}\right)\left(1 - e^{-\int V'_\lambda E_\lambda d\lambda / 6.5}\right)\right] \quad \boldsymbol{BY_\lambda \geq 0}$$

$$\boldsymbol{CL_A 2.0} \ = \ 1548\left[\int M_{C\lambda} E_\lambda d\lambda - 2.30\left(\frac{\int V'_\lambda E_\lambda d\lambda}{\int V_{C\lambda} E_\lambda d\lambda + 1.00 \int S_{C\lambda} E_\lambda d\lambda}\right)\left(1 - e^{-\int V'_\lambda E_\lambda d\lambda / 6.5}\right)\right] \quad \boldsymbol{BY_\lambda < 0}$$

$$\boldsymbol{BY_\lambda} = \int M_{C\lambda} E_\lambda d\lambda \ - \ 0.2616 \int V_{C\lambda} E_\lambda d\lambda$$

Correlative Comparisons - Challenges

- Comparison should span a sufficient range of illuminance values
- Comparison should reasonably span the gamut of light sources suitable for general illumination
  - Metameric SPDs may have very different predicted circadian effects
- Effective correlative comparisons require hundreds to ***thousands*** of different SPDs and illuminance levels

Monte Carlo Engine

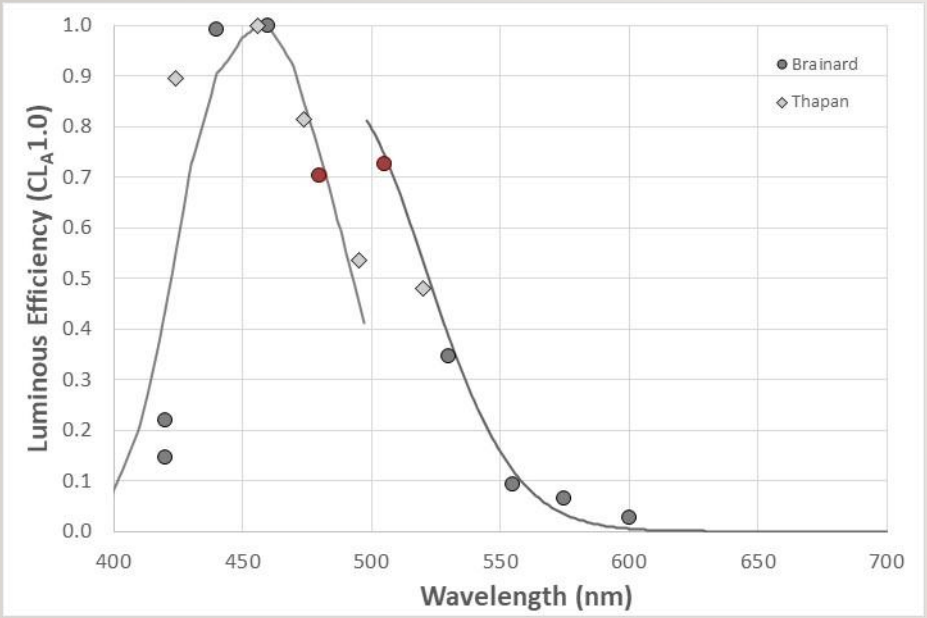
- Royer database (Royer M Real Light Source SPDs and Color Data for use in Research. Figshare. Dataset (https://doi.org/10.6084/m9.figshare.12947240.v1) n = 1,529
- EMPIR database (Jost S, Thorseth A, Poikonen T, Blattner P, Gerloff T, Kokka A EMPIR 15SIB07 PhotoLED -Database of LED product spectra. Technical University of Denmark. Dataset. https://doi.org/10.11583/DTU.12783389.v2) n = 1,495
- SPDs with $\Delta\lambda > 1$ nm interpolated to 1 nm using a cubic spline method
- Filtered SPDs for duplicates, constrained to CCT > 7500 K, CCT < 2000 K (n = 2,841)

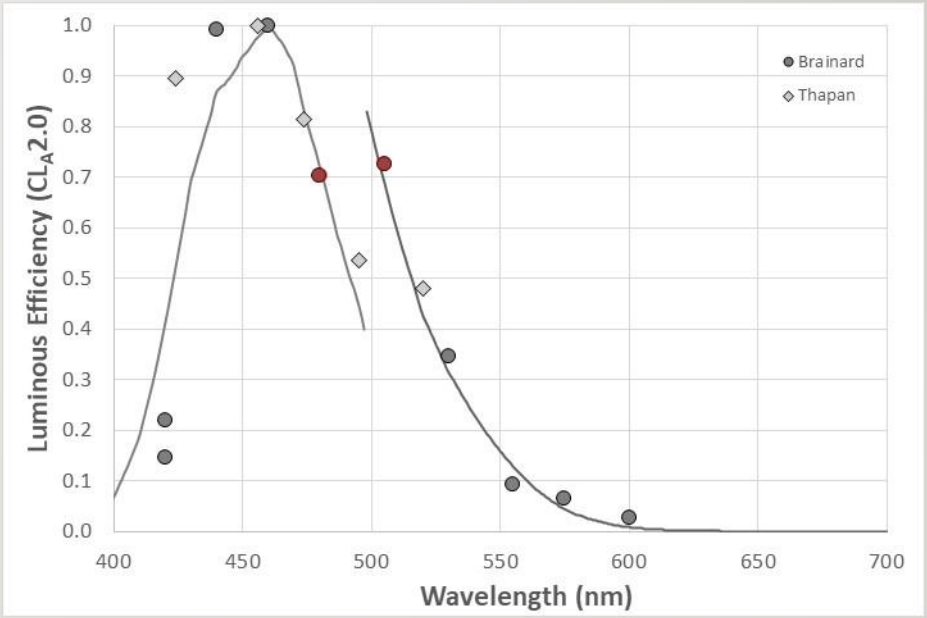
Monte Carlo Engine

Core engine calculations:

- Binary combination data (50-800 lux net illuminance)
- Chromaticity coordinates
- Melanopic-EDI
- CL_A/CS/BY_λ for ***all versions*** of the CS model
- Correlations here based on n = 32,000

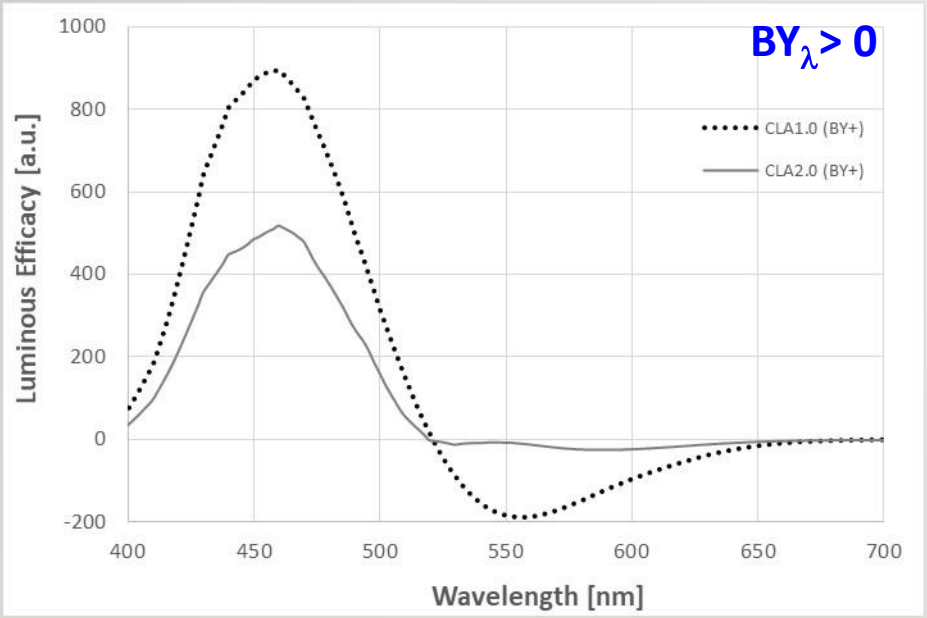
CL_A1.0 vs CL_A2.0 – Normalized Monochromatic Action Spectra

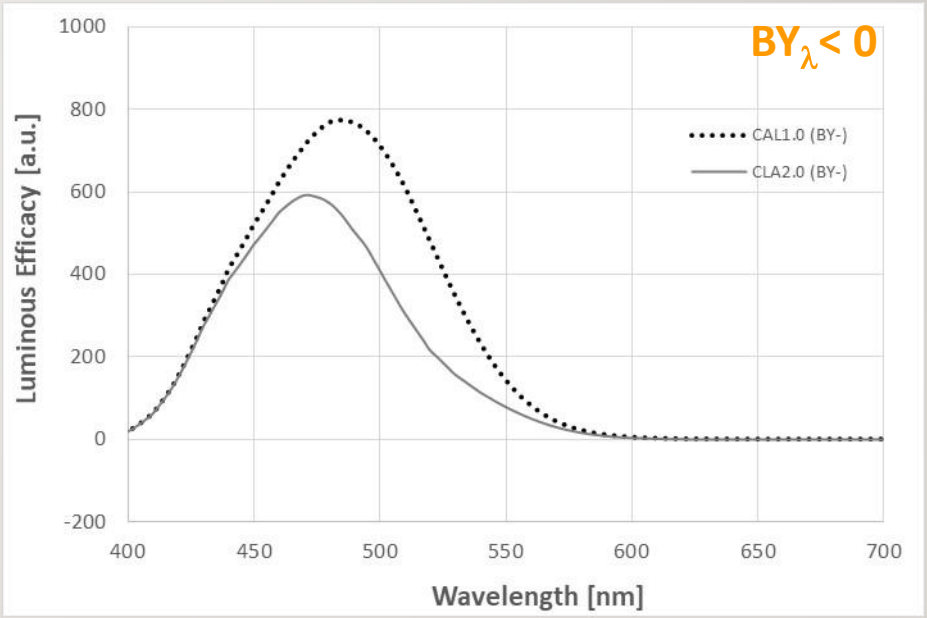




Using Circadian Stimulus Model's definition of action spectrum – CL_A1.0 and CL_A2.0 appear highly similar

$CL_A1.0$ vs $CL_A2.0$
Monochromatic Stimulus, Constant Irradiance





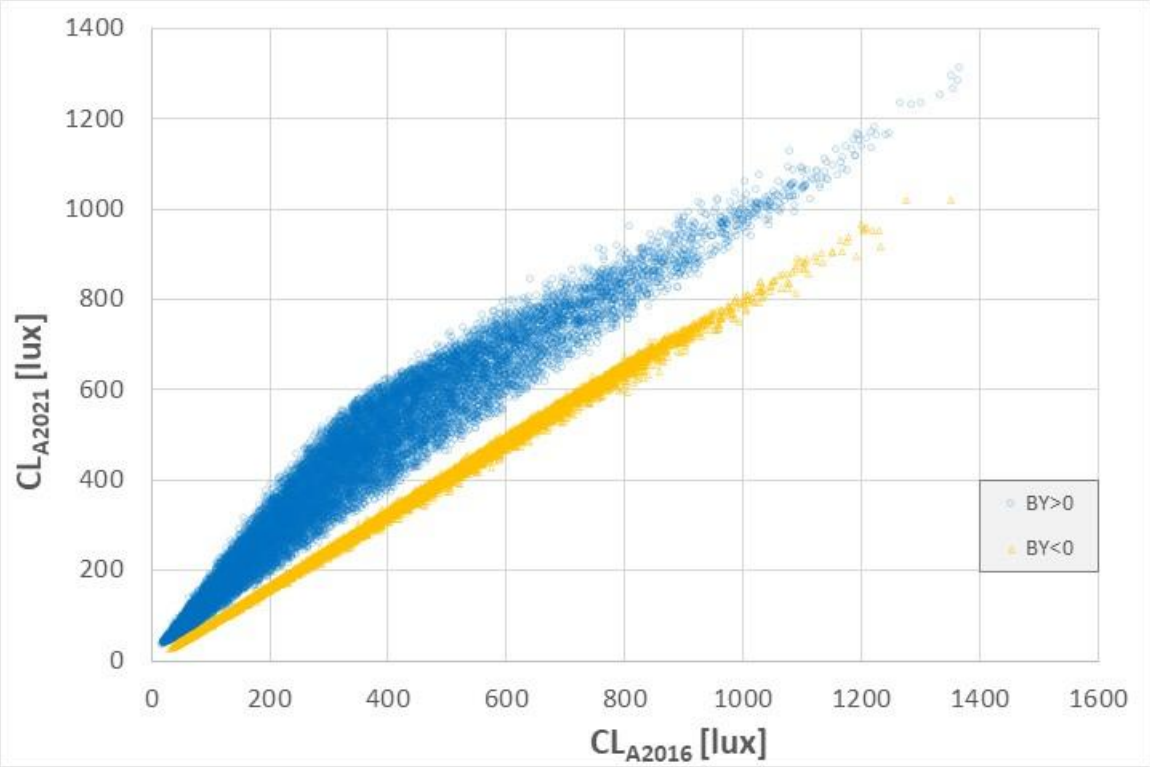
$CL_A2.0$ "blue-dominated" opponency

- effect shifted to longer wavelengths
- magnitude reduced by ~90%

$CL_A2.0$ "yellow-dominated"

- peak response shifted to shorter wavelengths
- magnitude reduced by ~25%

Circadian Stimulus Model v2016 (CL_A1.0)



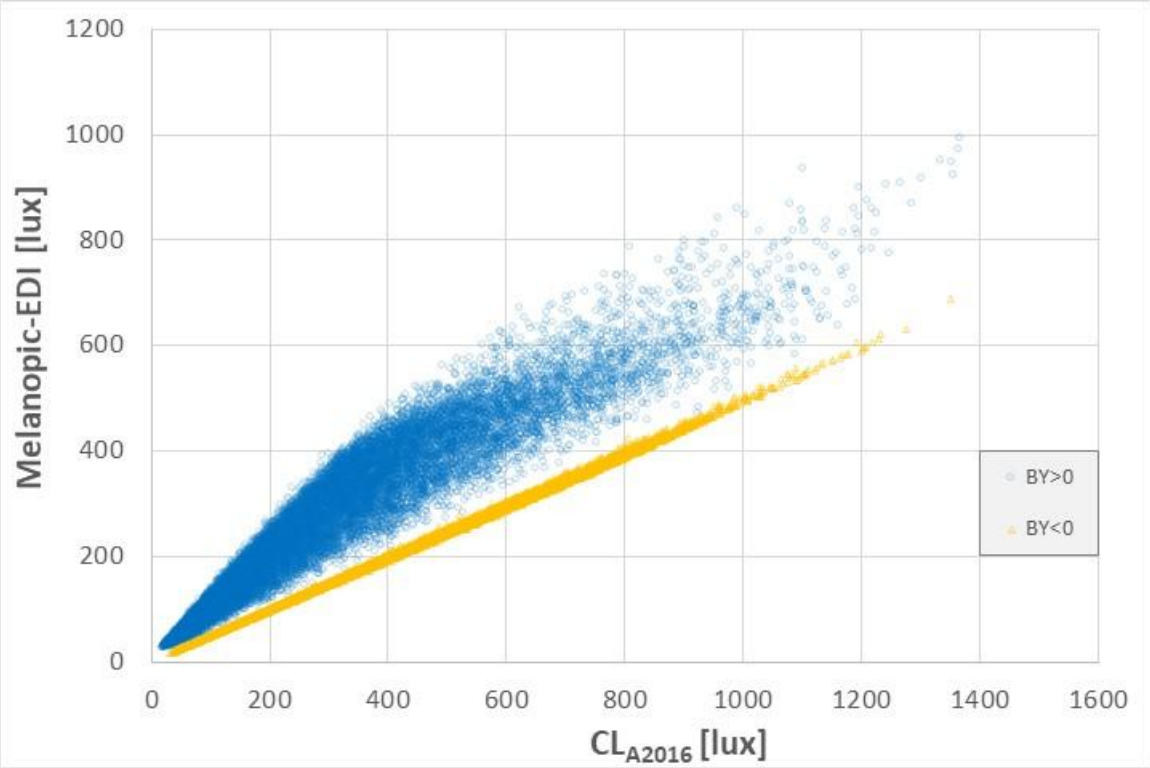
Comparison to CL_A2.0

- Overall Correlation $r^2 = 0.834$
  - $BY_\lambda > 0$ correlation $r^2 = 0.936$
  - $BY_\lambda < 0$ correlation $r^2 = 0.999$

~~"Any test of a model must be able to predict circadian system response to both narrowband and broadband (polychromatic) light sources."~~[6]

[6] Rea MS, Nagare R, Figueiro MG Modeling Circadian Phototransduction: Quantitative Predictions of Psychophysical Data. Front. Neurosci. 2021; 15:615322. doi: 10.3389/fnins2021.615322

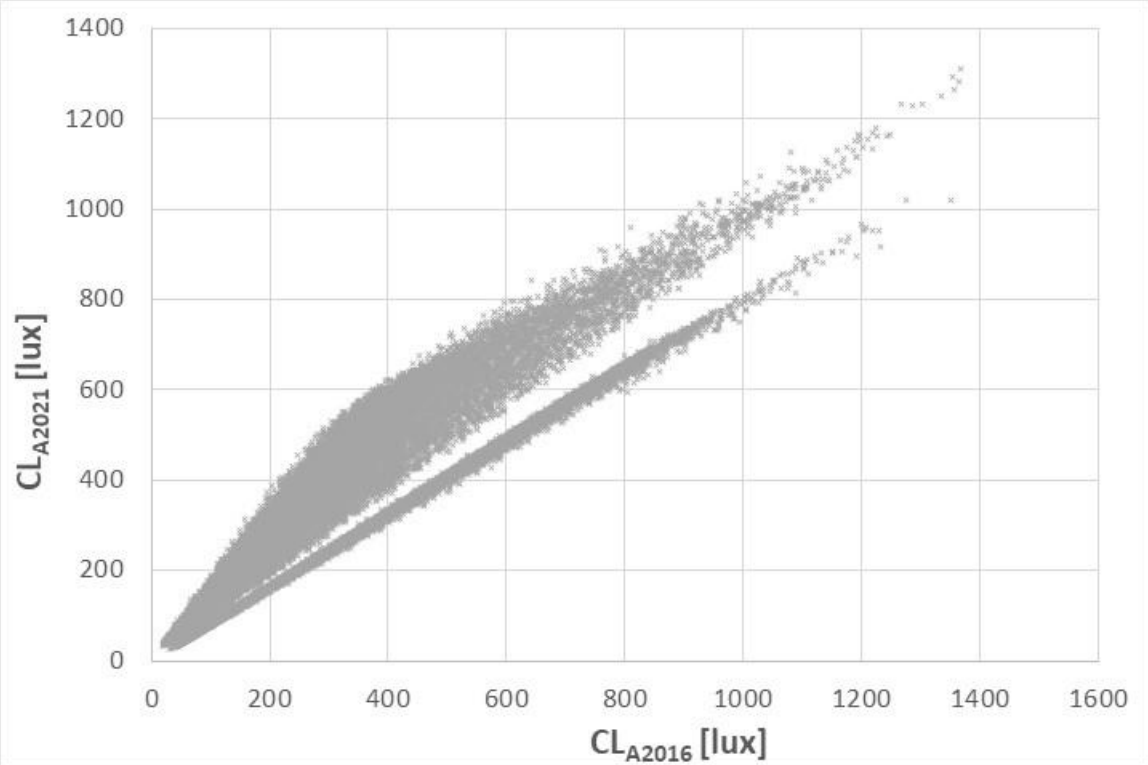
Circadian Stimulus Model v2016 (CL_A1.0)

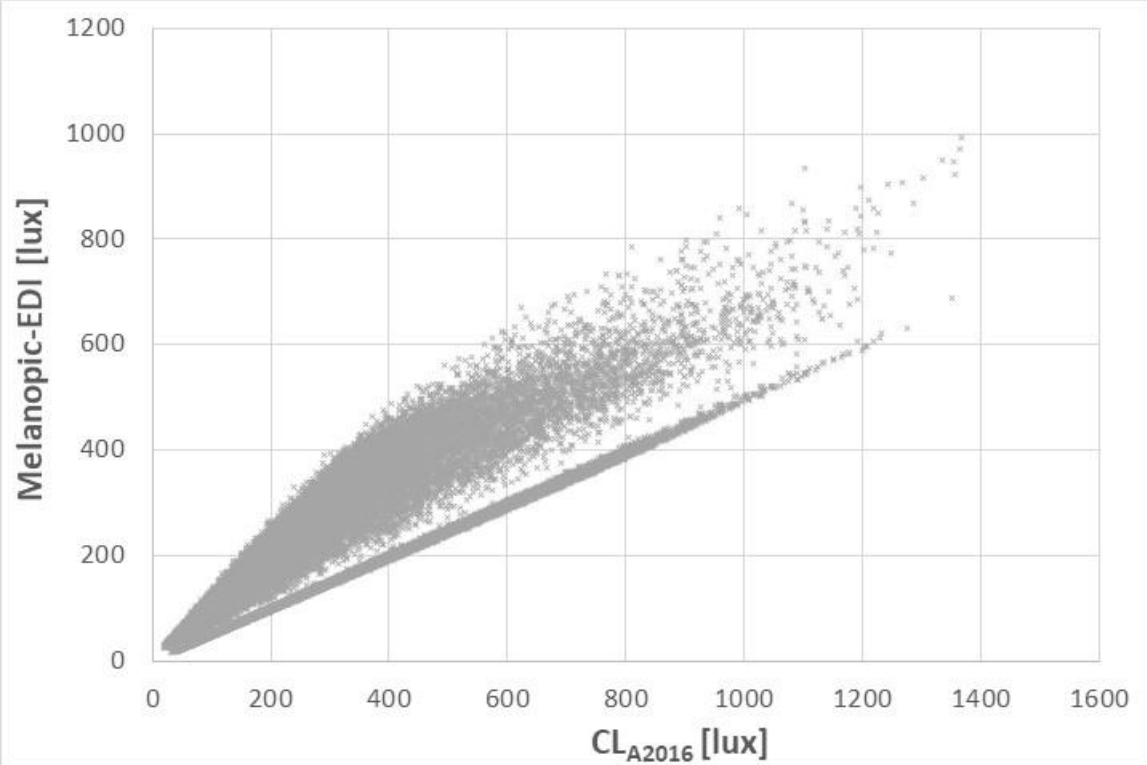


Comparison to Melanopic-EDI

- Overall Correlation $r^2 = 0.708$
  - $BY_\lambda > 0$ correlation $r^2 = 0.896$
  - $BY_\lambda < 0$ correlation $r^2 = 0.999$

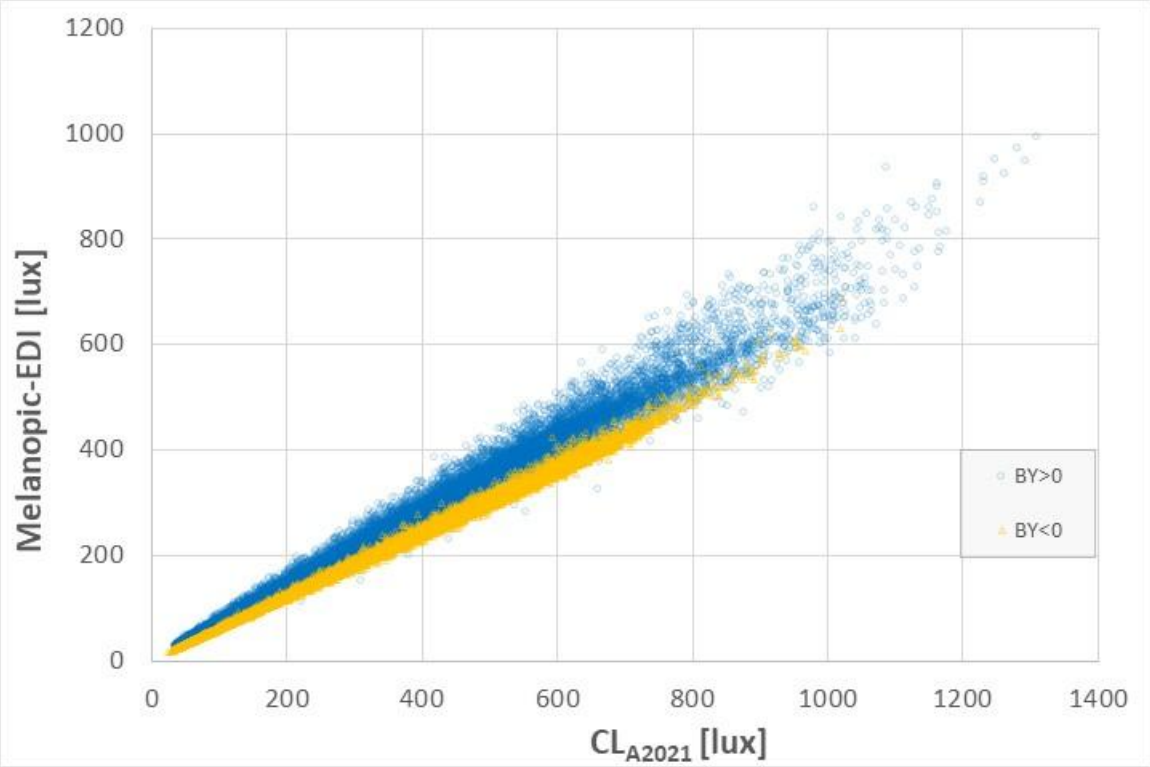
Circadian Stimulus Model v2021 (CL_A2.0)





Observation: Correlations between CL_A1.0/ CL_A2.0 and CL_A1.0/Melanopic-EDI appear very similar . . .

Circadian Stimulus Model v2021 (CL_A2.0)



Comparison to Melanopic-EDI

- Overall Correlation $r^2 = 0.968$
  - $BY_\lambda > 0$ correlation $r^2 = 0.982$
  - $BY_\lambda < 0$ correlation $r^2 = 0.997$

Circadian Model Complexity

"If a simple, additive function can properly rank order practical light sources in terms of their impact on the human circadian system (e.g. nocturnal melatonin suppression), a more complicated, albeit physiologically more correct, non-linear system of circadian photometry may not be necessary."[7]

- CL_A2.0
  - 8 explicit adjustable parameters
  - 1 implicit adjustable parameter (macular pigment correction)
  - Non-standard crystalline lens correction and opsin template
- Melanopic-EDI
  - No adjustable parameters
  - Model capability greatly exceeds threshold of rank order prediction

[7] MS Rea, MG Figueiro, A Bierman, R Hamner "Modeling the spectral sensitivity of the human circadian system." Lighting Res. Technol. 2012; 44. 386-396. doi:: 10.1177/1477153511430474

CONCLUSIONS

- Developers of the Circadian Stimulus model agree that a complex model is not justified if simpler model makes similar predictions
- Melanopic-EDI and $CL_A2.0$ are exceptionally well correlated ($r^2 = 0.968$), no significant difference in predictive capabilities
- Given the extreme mathematical complexity of CS model and its tight correlation with melanopic-EDI, use of the CS model in industry cannot be rationally supported