Simulating Circadian Light and Interpreting its Results

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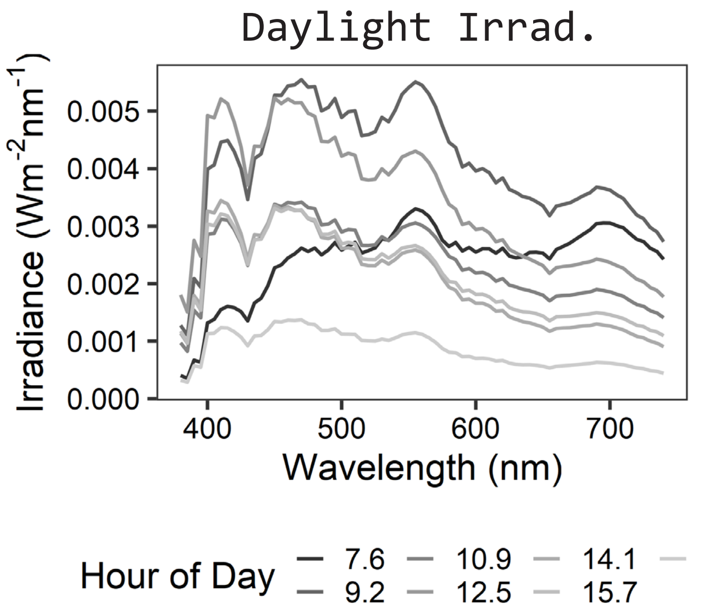
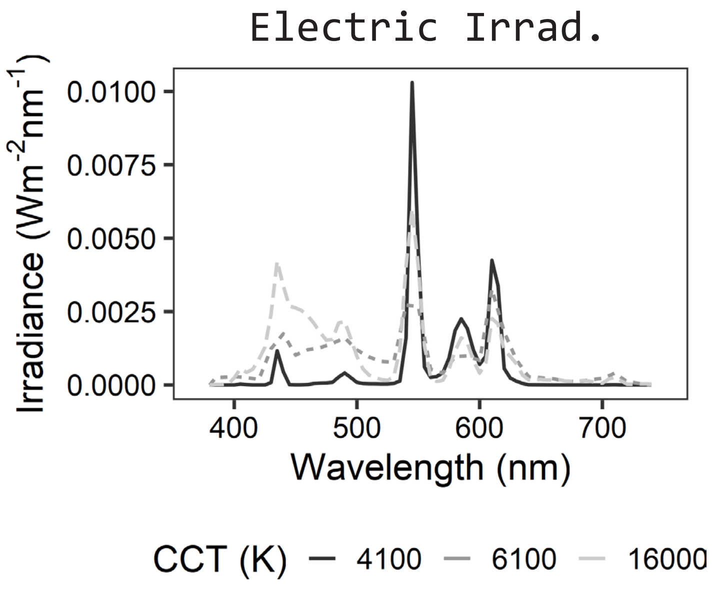
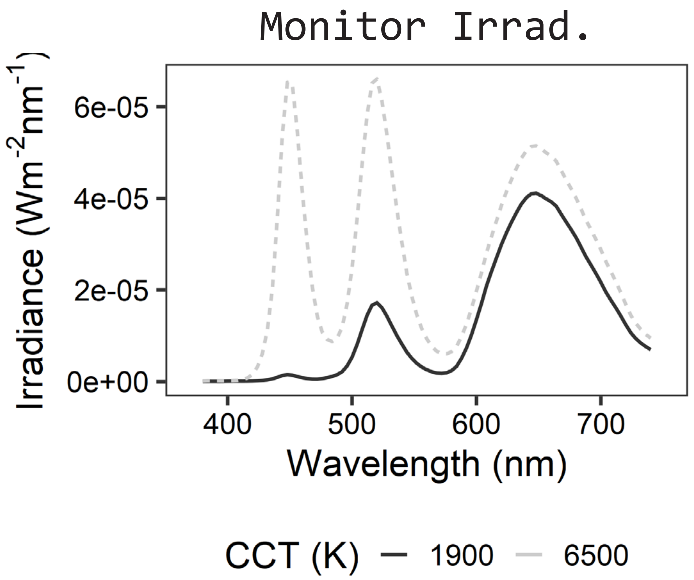
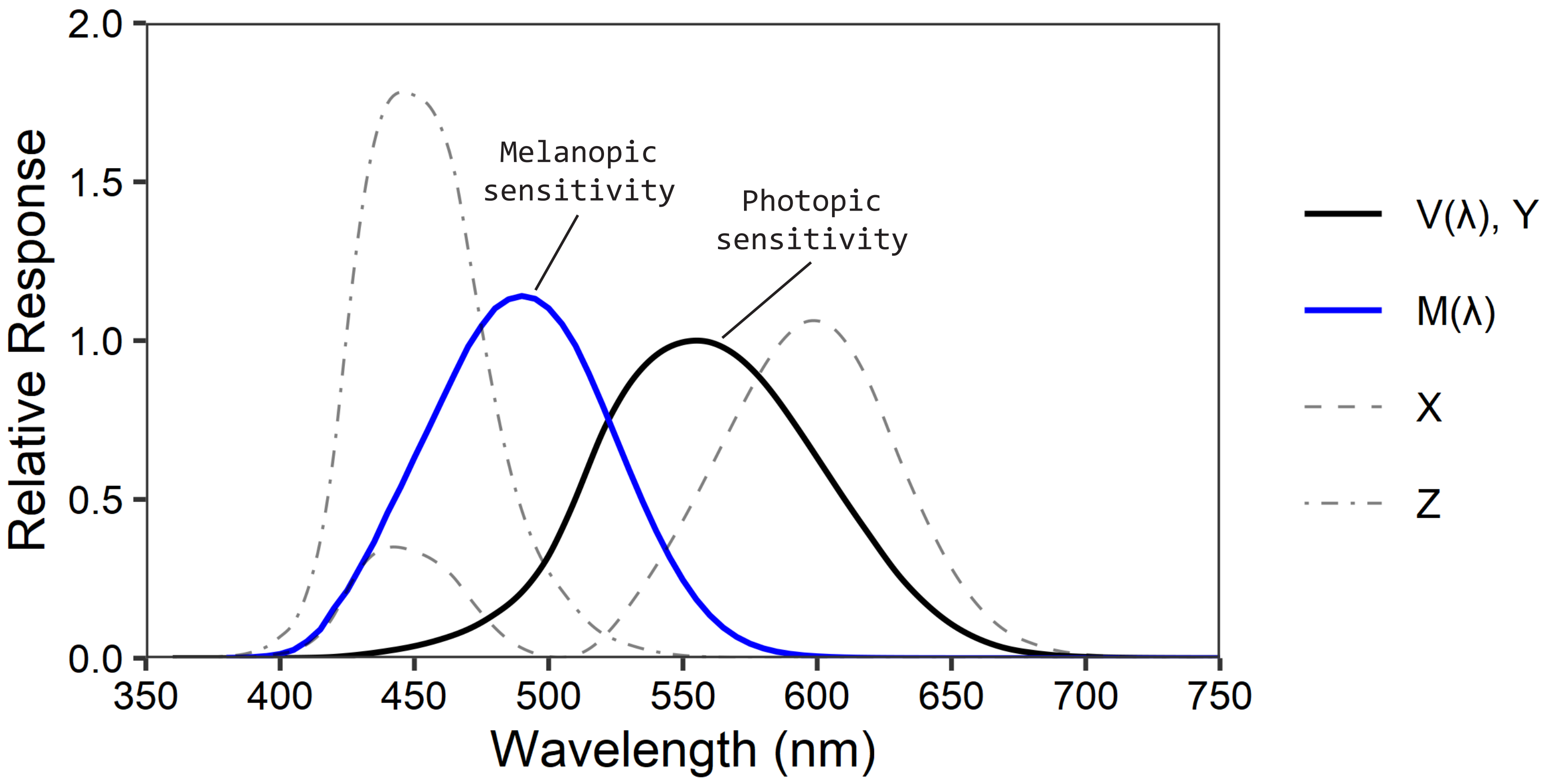
github.com/C38C/NIF_Photobiology



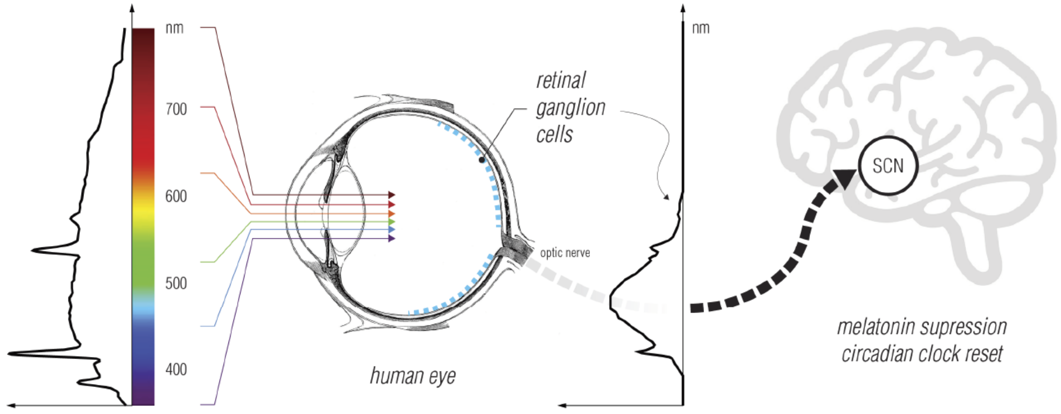




Non-image forming reception of light



- Melanopsin, a photoreceptor pigment in the eye, is more responsive to blue light than the combined photopic response of cone receptors.
- But it does not contribute to vision. Instead, it is wired directly to the suprachiasmatic nucleus (SCN) of the brain, our circadian pacemaker.



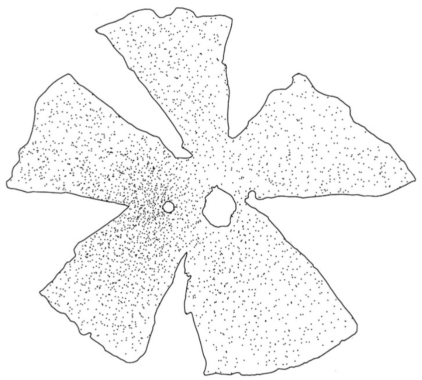
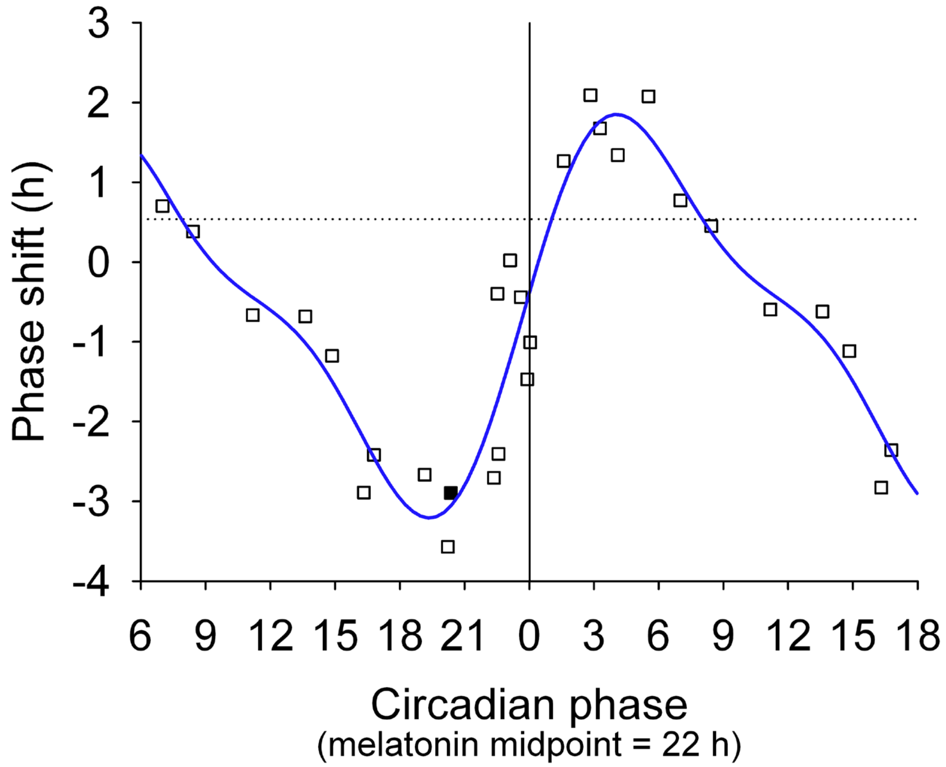


Illustration of mean cell density of melanopsin cells in a primate retina

Dacey, Dennis M., et al. “Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN.” Nature 433.7027 (2005): 749-754.

- Melanopsin-containing cells are spread throughout the retina, a wide-gamut sensor of light.

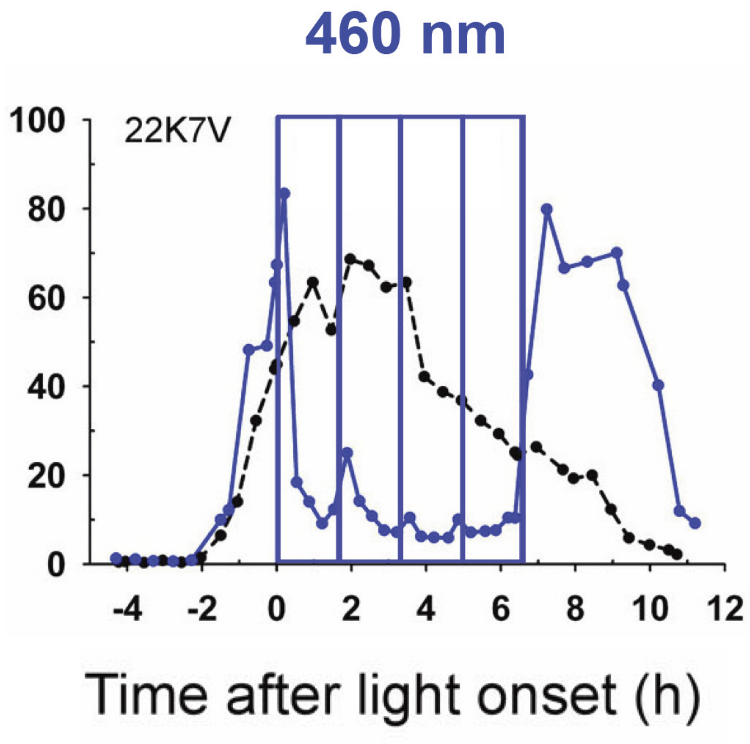
Non-image forming effects of light



Advance or delay of circadian rhythms

- Dependent on time of exposure, spectrum, intensity

(phase shift with 6.7 hours of 10,000 lx Ev)
Prayag, Abhishek S., et al. "Light modulation of human clocks, wake, and sleep." Clocks & sleep 1.1 (2019): 193-208.

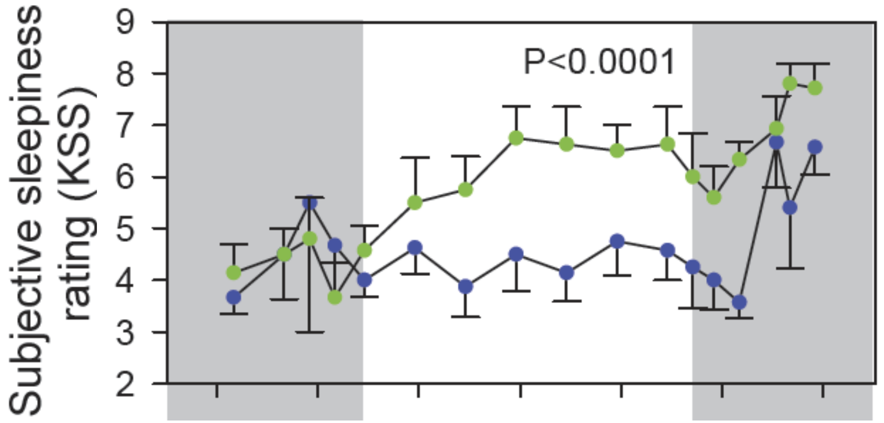


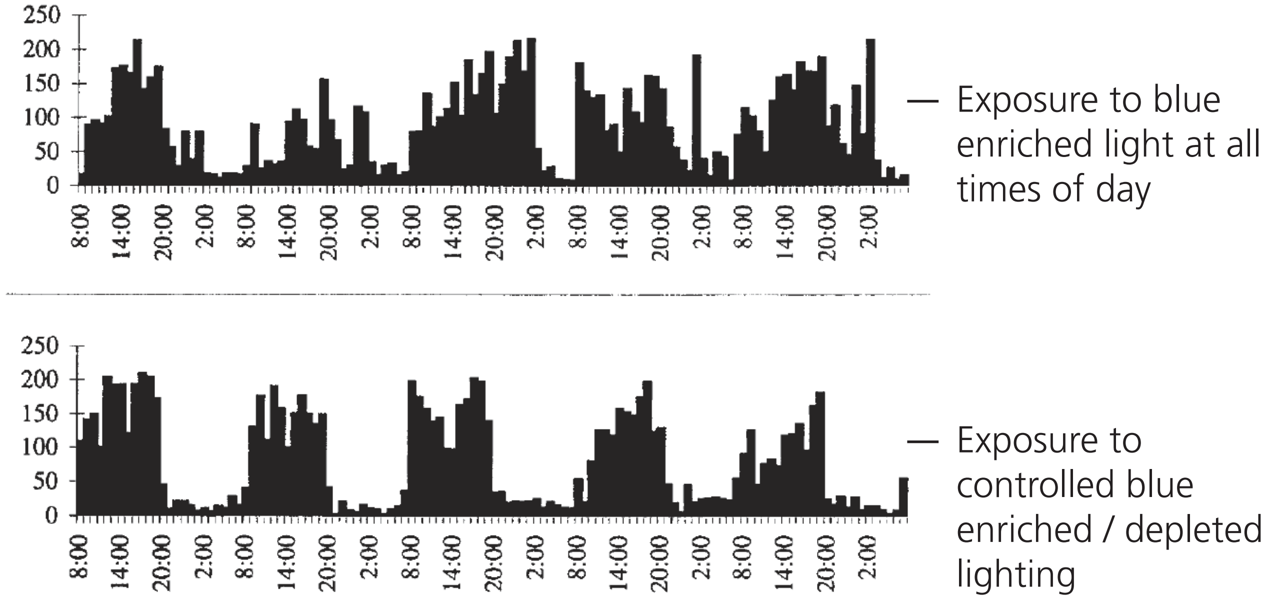
Melatonin supression

- Light exposure at night suppresses Melatonin production.
- Dependent on spectrum and intensity.

Gooley, Joshua J., et al. "Spectral responses of the human circadian system depend on the irradiance and duration of exposure to light." Science translational medicine 2.31 (2010): 31ra33-31ra33.

Non-image forming effects of light





Instantaneous alerting effects

• Light exposure decreases sleepiness, improves reaction time.

Treatment for sleep-related illnesses, dementia

• Can help regulate sleep/wake and activity patterns and improve depression symptoms.

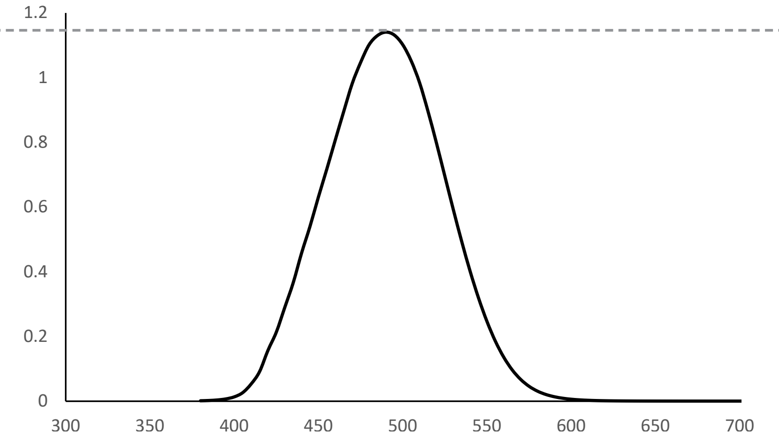
Rahman, Shadab A., et al. "Diurnal spectral sensitivity of the acute alerting effects of light." Sleep 37.2 (2014): 271-281.

Van Someren, Eus JW, et al. "Indirect bright light improves circadian rest-activity rhythm disturbances in demented patients." Biological psychiatry 41.9 (1997): 955-963.

Units of note: EML, $E_{e,mel}$

EML - Equivalent Melanopic Lux (lx)

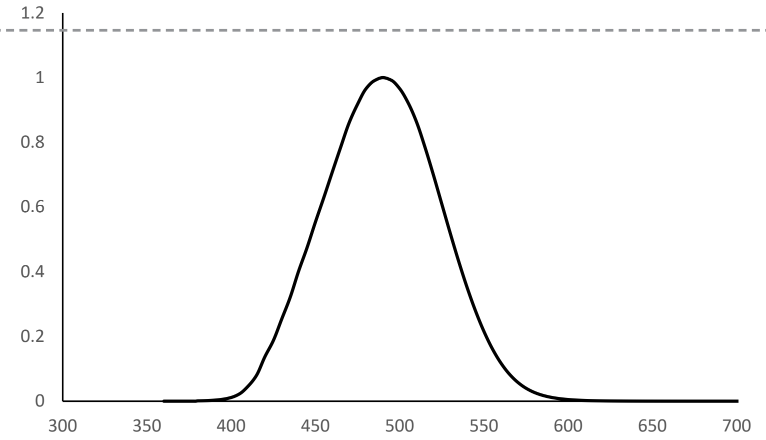
$$EML = 729.8325 \cdot \int EM(\lambda)_{lucas} d\lambda$$



- Weighted Melanopic iradiance (Lucas curve) multiplied by luminous efficacy.
- Meant to be equivalent in understanding to lux for designers.
- Used by the WELL standard, for example.

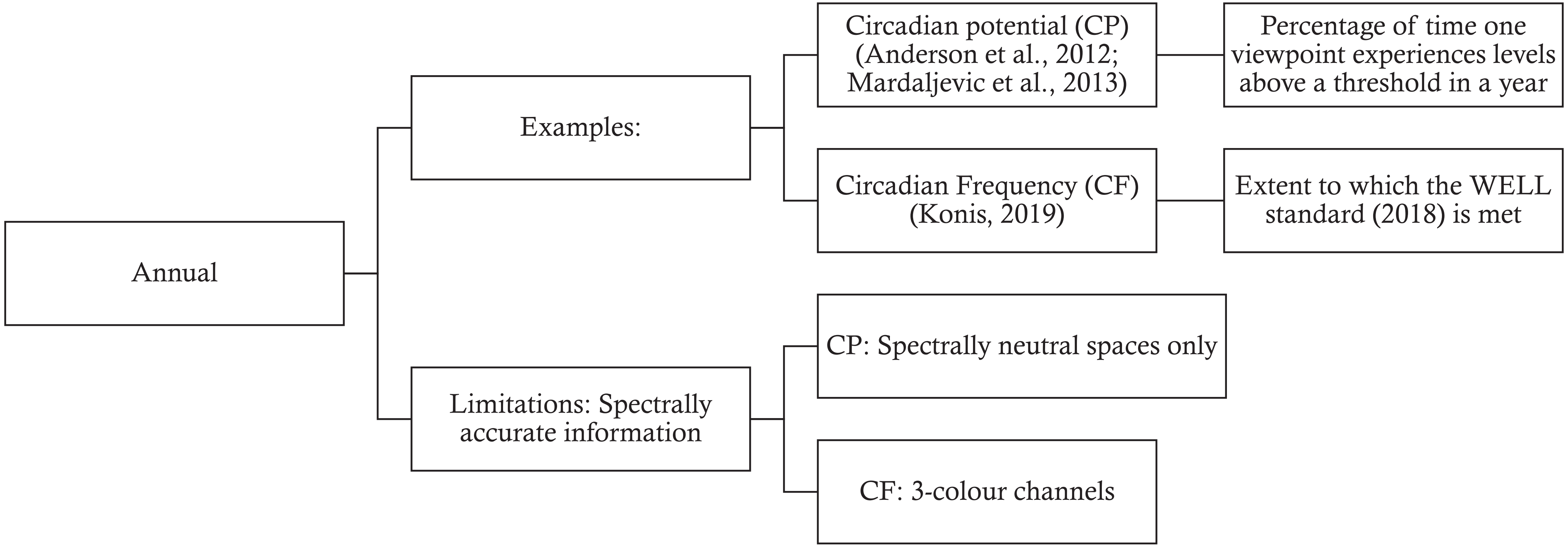
$E_{e,mel}$ - Melanopic Irradiance (W/m^2)

$$E_{e,mel} = \int EM(\lambda)\, d\lambda$$

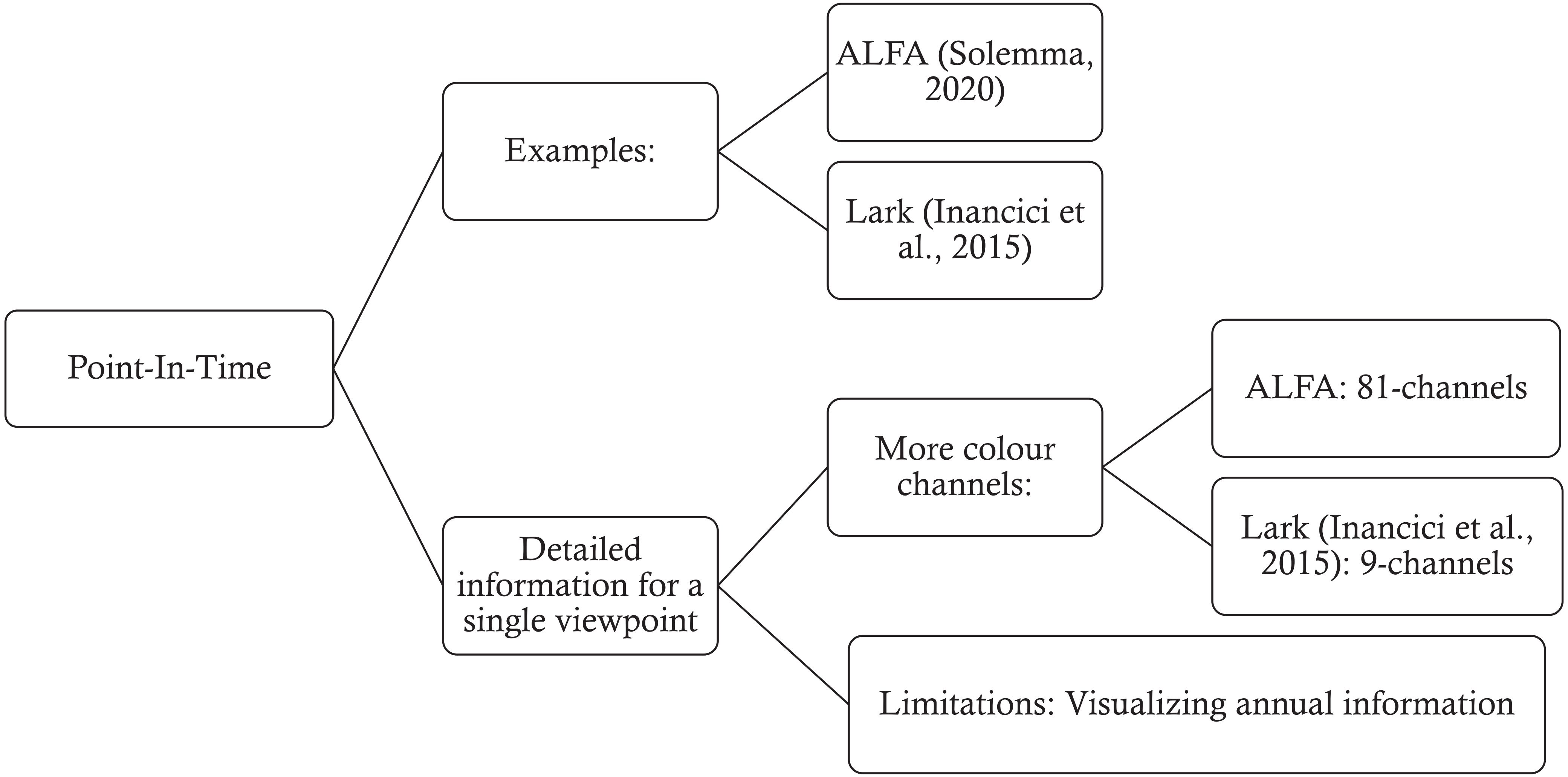


- Weighted Melanopic iradiance by a response function normalized to 1.
- Used by CIE S026, photobiological models.
- 1 W/m^2 Ee,mel ~ 834.2 lx EML

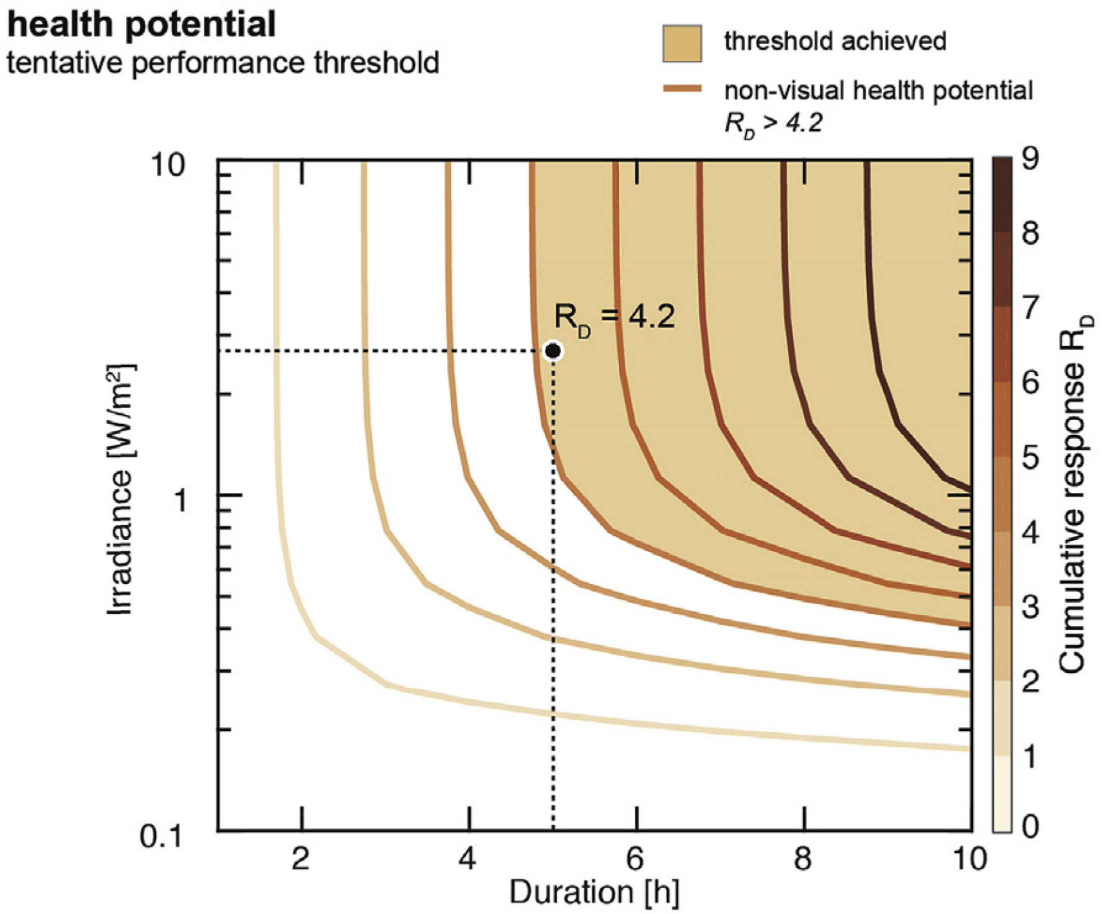
Annual Simulation Methods



Annual Simulation Methods



Existing non-image forming assessments: Amundadottir et al.'s nvR_D



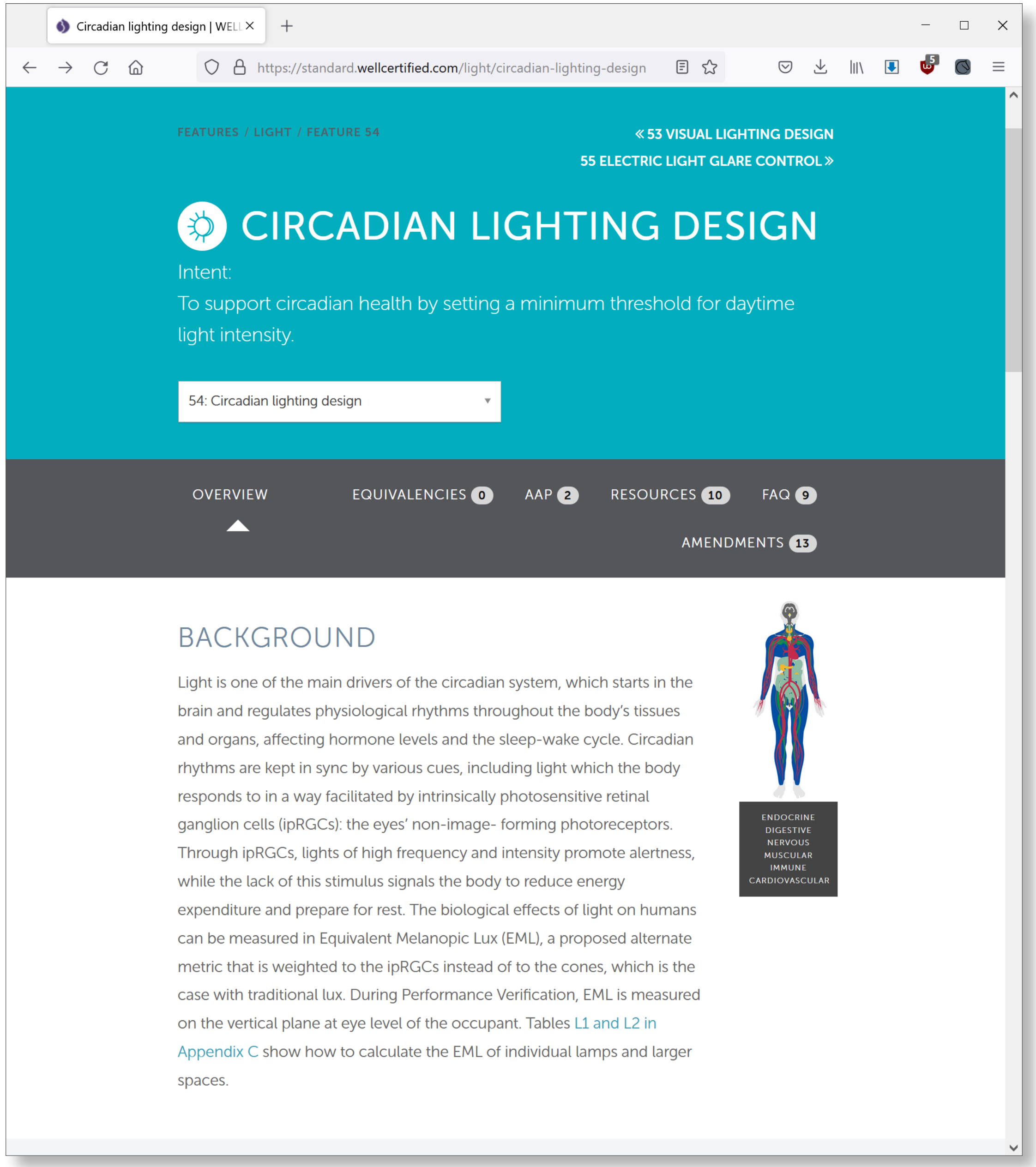
Amundadottir, Maria L., et al. "A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior." Building and Environment 113 (2017): 5-21.

- Nonvisual direct-response (nvR_D)

- Based on amount of irradiance required for nocturnal Melatonin suppression and on Phipps-Nelson et al.'s experiment that showed 2.7 W/m² of melanopic irradiance for a duration of 5 hours reduced the impact of sleep loss on sleepiness levels and performance.

- It is tentatively recommended to meet a nvR_D of 4.2 each day.

Existing non-image forming assessments: WELL Standard



https://standard.wellcertified.com/light/circadian-lighting-design

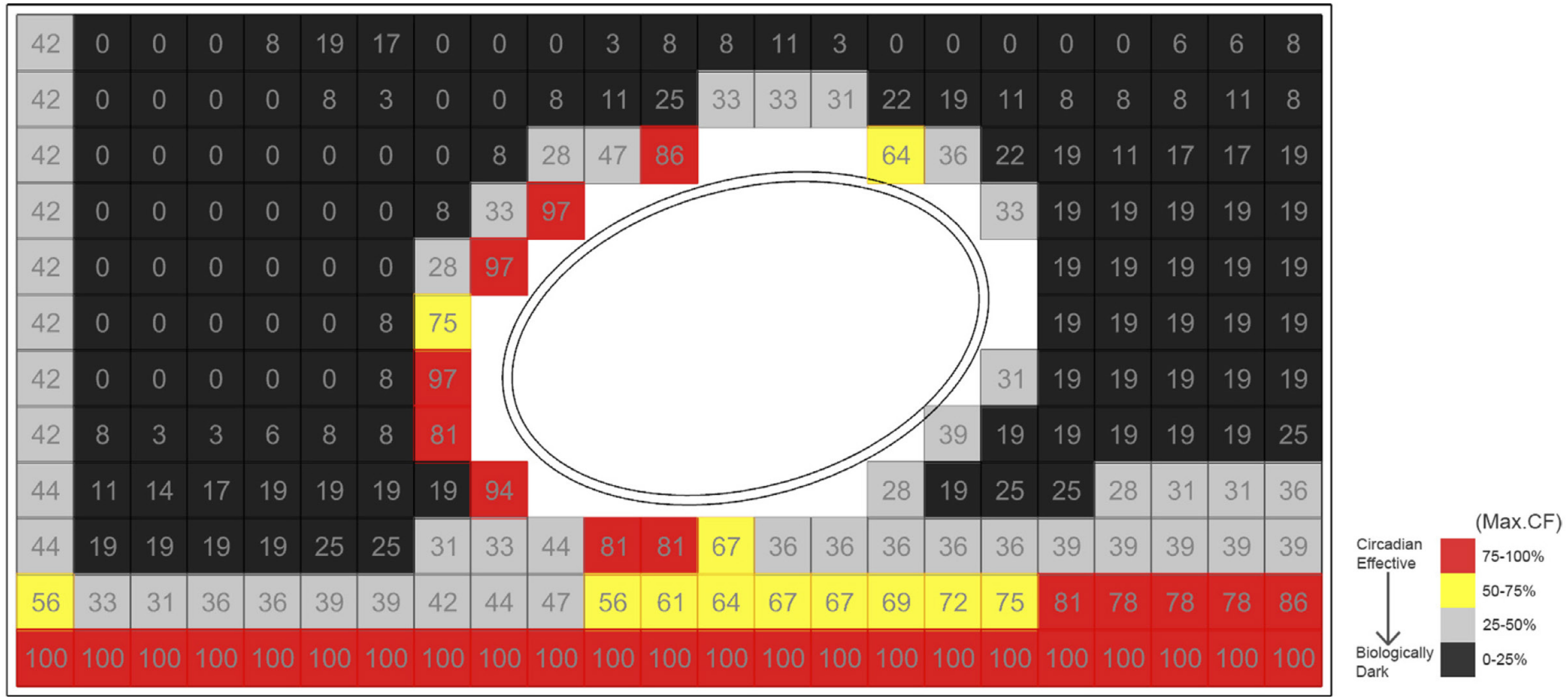
"At 75% or more of workstations, at least 200 equivalent melanopic lux is present, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the view of the occupant). This light level may incorporate daylight, and is present for at least the hours between 9:00 AM and 1:00 PM for every day of the year."

- 200 EML on eye, 4 hours per day (office standard)

"During the nighttime, lights provide not more than 50 equivalent melanopic lux (to the extent allowable by code) as measured 0.76 m [30 inches] above the finished floor."

- < 50 EML at night (residential standard)

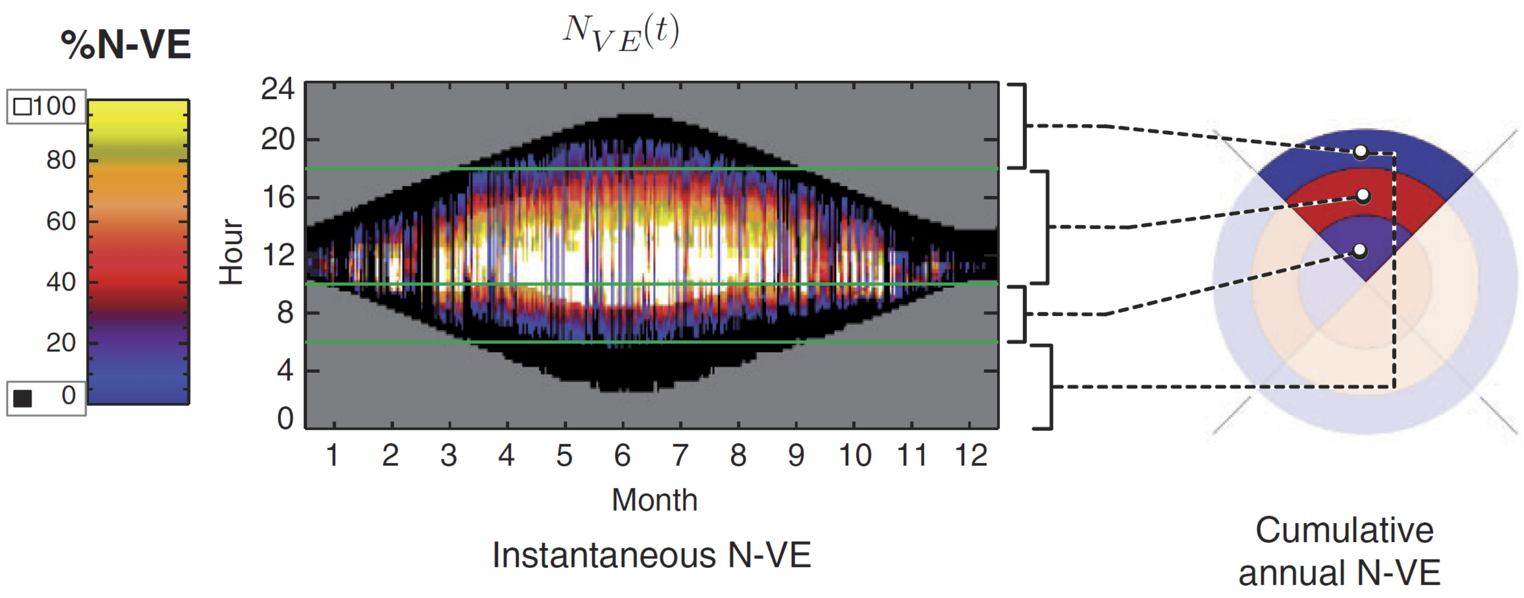
Existing non-image forming assessments: Konis's Circadian Frequency (CF)



Konis, Kyle. "A circadian design assist tool to evaluate daylight access in buildings for human biological lighting needs." Solar Energy 191 (2019): 449-458.

- Percentage of time that the WELL 200 EML standard is met during a specified hour range across the year.
- Analogous to annual daylight metrics such as Daylight Autonomy and Useful Daylight Illuminance.

Existing non-image forming assessments: Mardaljevic, et al.'s N-VE



- Non-visual effects (N-VE)
- 0% circadian efficacy at 210 lx, 100% at 960 lx.
- Percent of efficacy divided into three time bins:
  - Early morning / phase resetting
  - Midday / alertness improving
  - Evening / phase delay & Melatonin suppression

Mardaljevic, John, et al. "A framework for predicting the non-visual effects of daylight– Part II: The simulation model." Lighting Research & Technology 46.4 (2014): 388-406.

Research goals

1. Framework for simulation:
    - Spectral qualities of a space / materiality
    - Demonstrates variability over the day and year based on climate and behaviour
    - Integrate electric lighting and screen devices

2. Compare simulation workflows

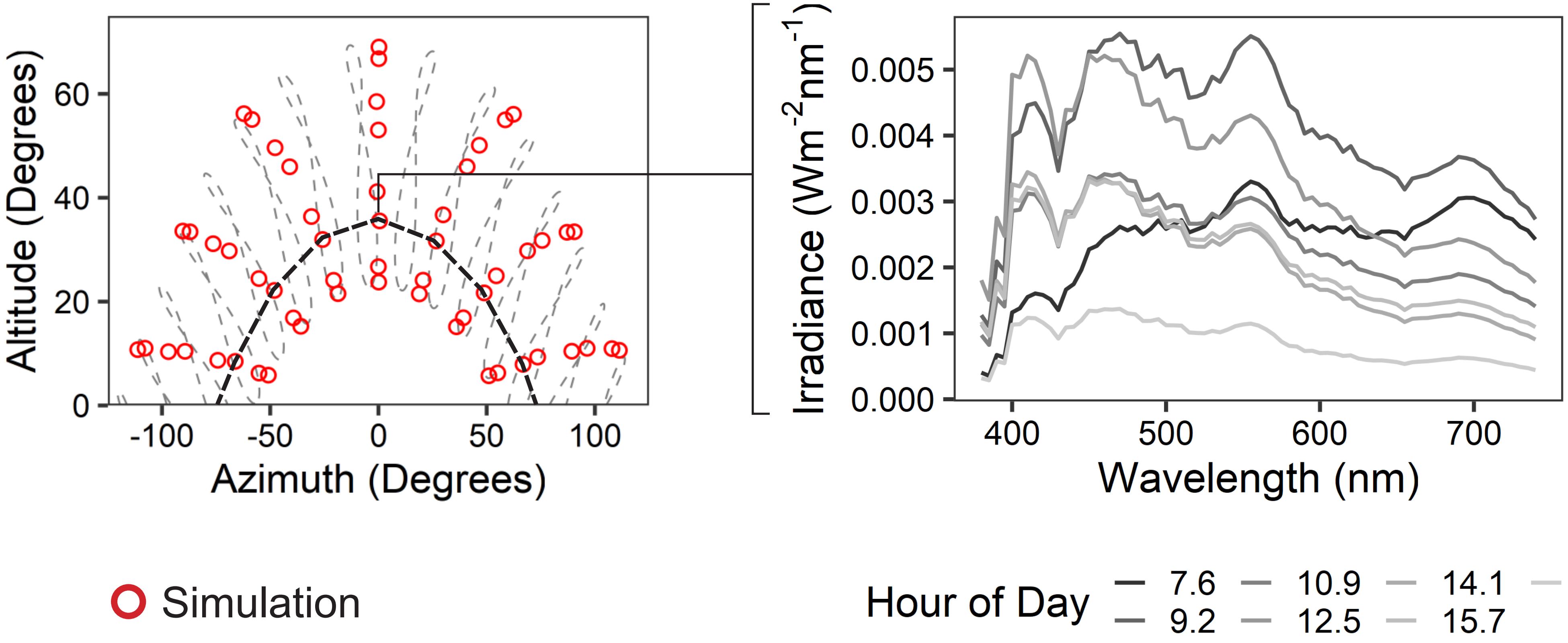
3. Develop a human photobiological effects model based on the best current research

4. Evaluate photobiological effects of realistic lighting scenarios

5. Compare circadian health metrics

Methodology

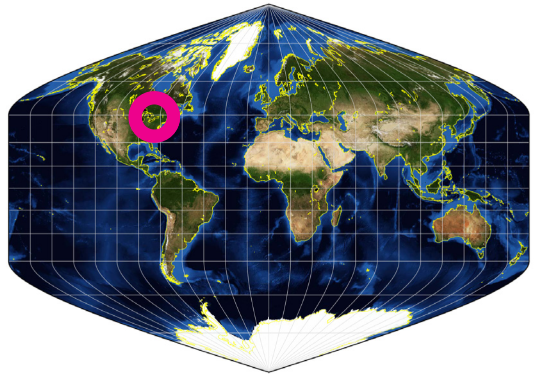
Calculating spectral irradiance timeseries: Daylight



ALFA

- We employ the Lightsolve approach (Kleindienst et al. 2008) in conjunction with an 81 spectral channel Radiance-based raytrace tool ALFA, interpolating across the year based on 56 solar positions evenly spaced throughout the year.

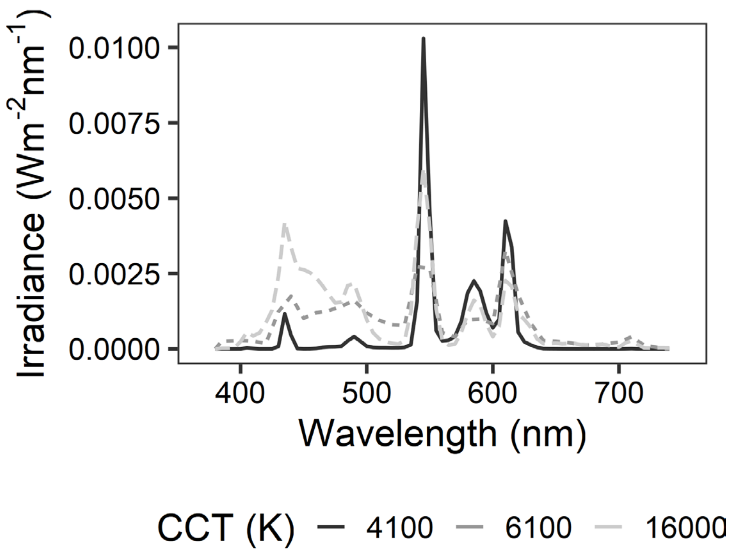
- ALFA uses physics-based skies based on the atmospheric radiant transfer solver libRadtran and prototypical atmospheric profiles.

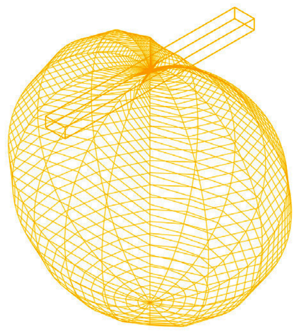


Location: Toronto, ON

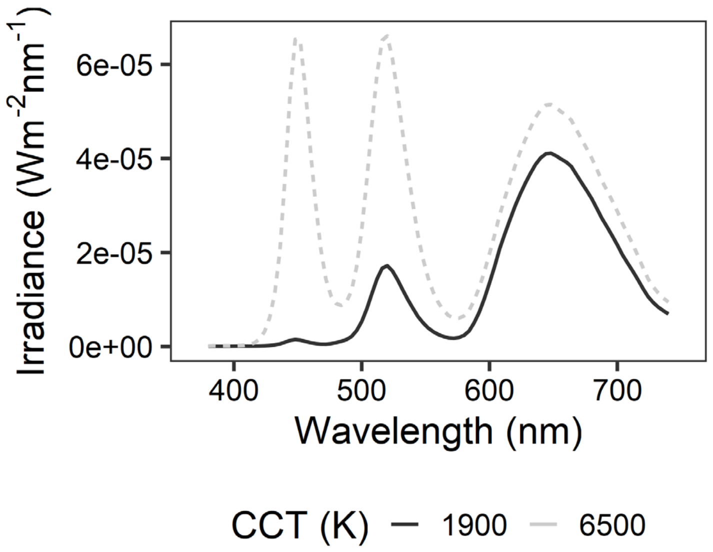
Kleindienst, Siân, Magali Bodart, and Marilyne Andersen. "Graphical representation of climate-based daylight performance to support architectural design." Leukos 5.1 (2008): 39-61.

Calculating spectral irradiance timeseries: Electric lighting



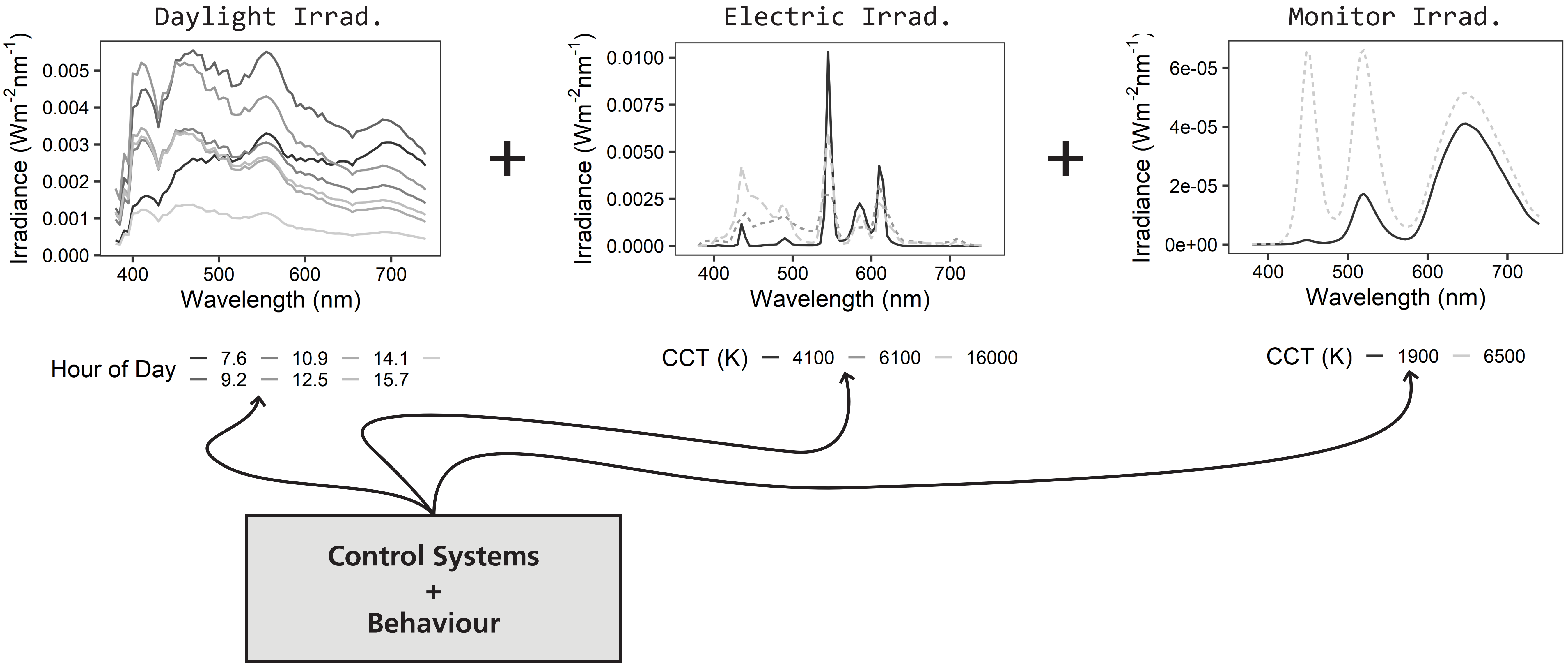


- ALFA is used to calculate melanopic irradiance due to electric luminaires (IES luminous intensity data) and specific lamp spectral power distributions.
- Here we have simulated warm (4100 K), neutral/cool (6100 K), and very high CCT (16000 K) fluorescent options.

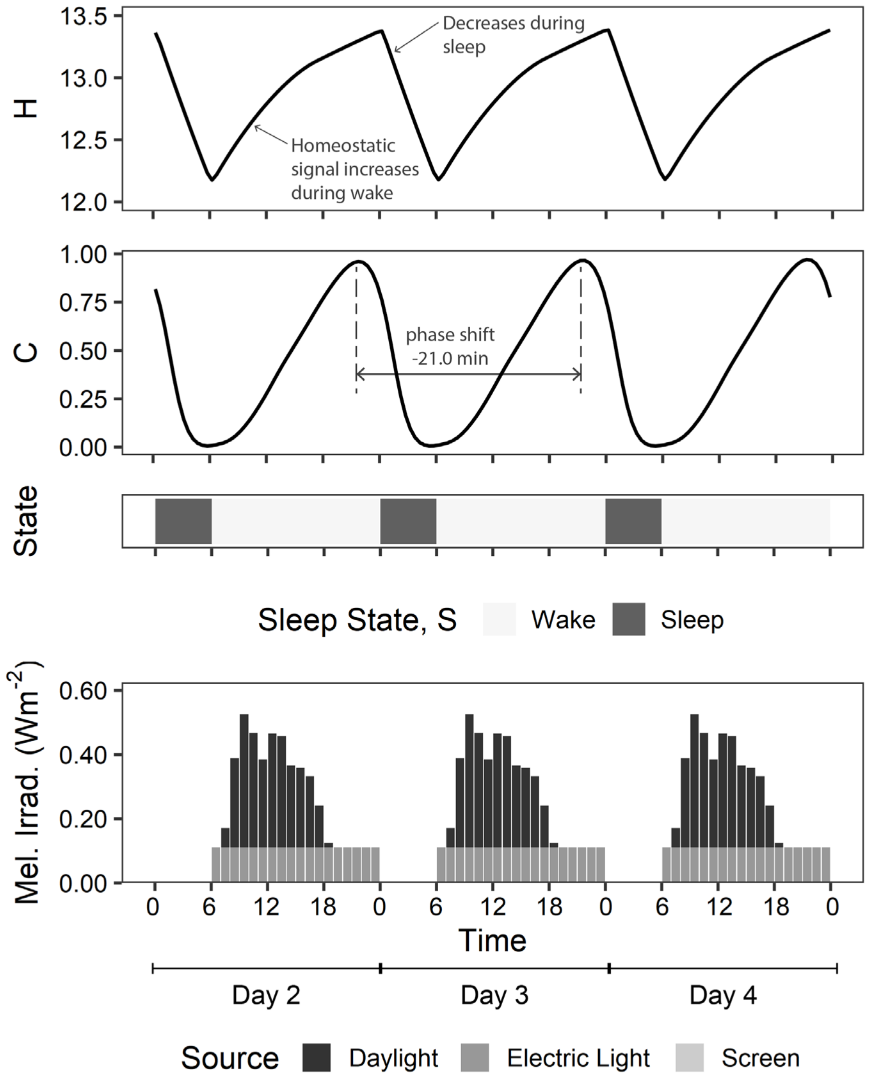


- Monitor irradiance values are supplied from fluxometer.com, here illustrating an evening warm color temperature shift and a regular color palette.

Calculating spectral irradiance timeseries: Combined Melanopic Irradiance



Photobiological effects model



⟵ Homeostatic system
Controlled by sleep/wake

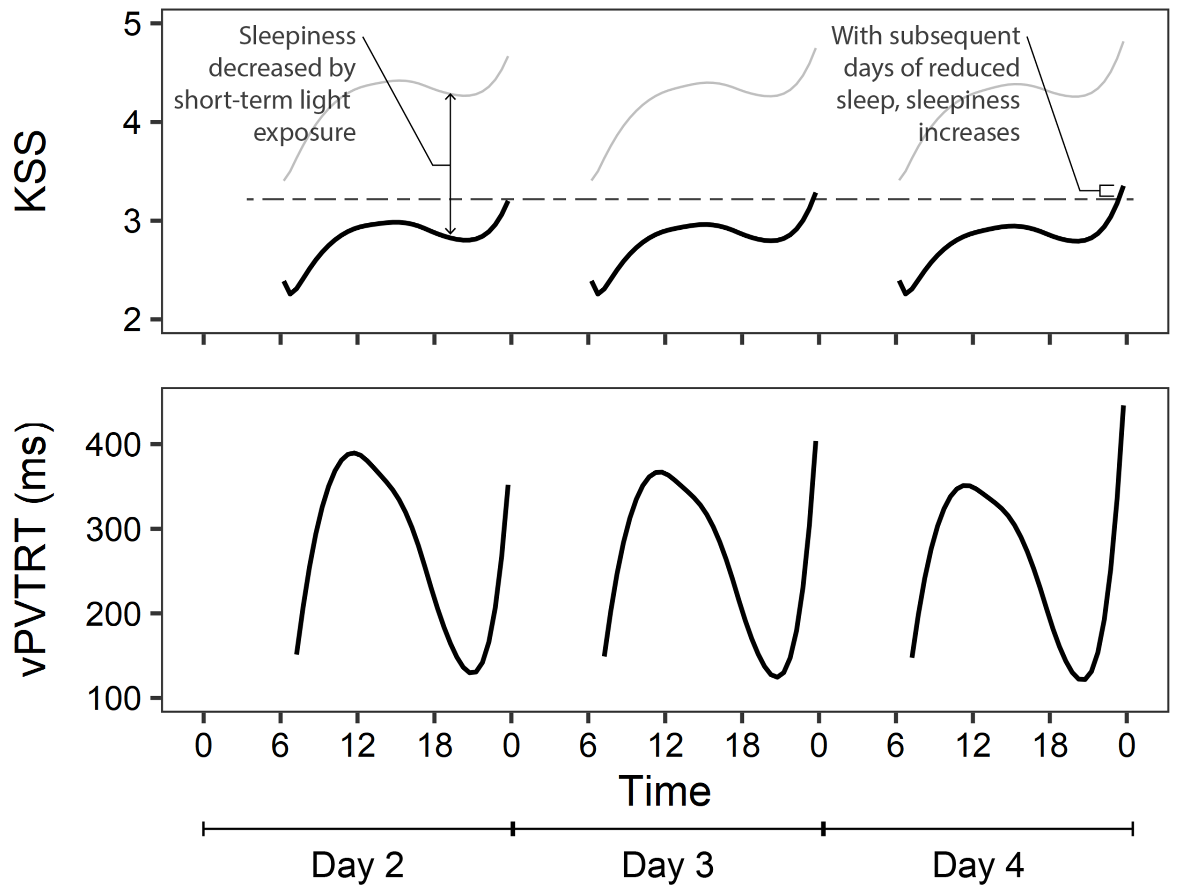
⟵ Circadian system
Controlled by light and
Non-photic factors (sleep/wake)

⟵ Sleep
Scheduled
Wake: 6 - 24
Sleep: 0 - 6

⟵ Melanopic Irradiance
Calculated from daylight, electric light, monitor screen use, and control schedules

- We implement the photobiological effects model by Postnova et al. (2018), Abeysuriya et al. (2018) and Tekieh et al. (2020).
- The model predicts homeostatic and circadian effects on alertness and productivity.

Photobiological performance metrics: Alertness



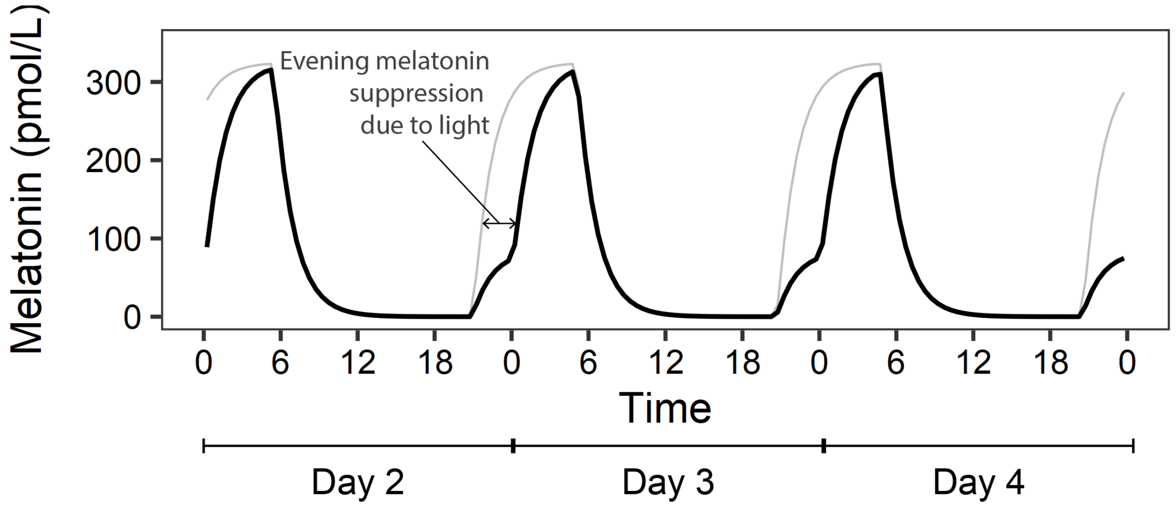
- KSS - Karolinska Sleepiness Scale

  1 - Extremely alert
  5 - Neither alert nor sleepy
  9 - Very sleepy, fighting sleep

- Average reaction time on a visual Performance Vigilance Test (vPVTRT)

  Lower is better / more alert

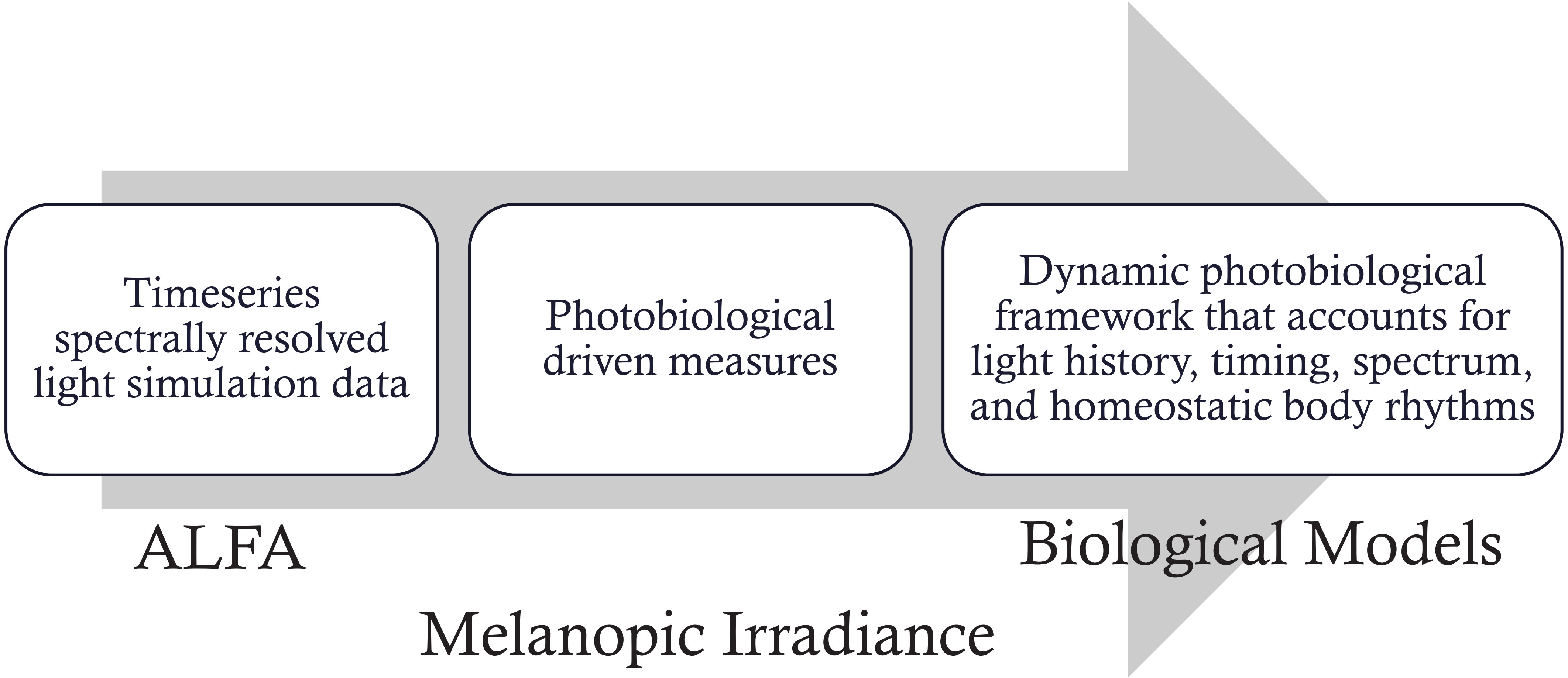
Photobiological performance metrics: Melatonin suppression



- Melatonin suppression

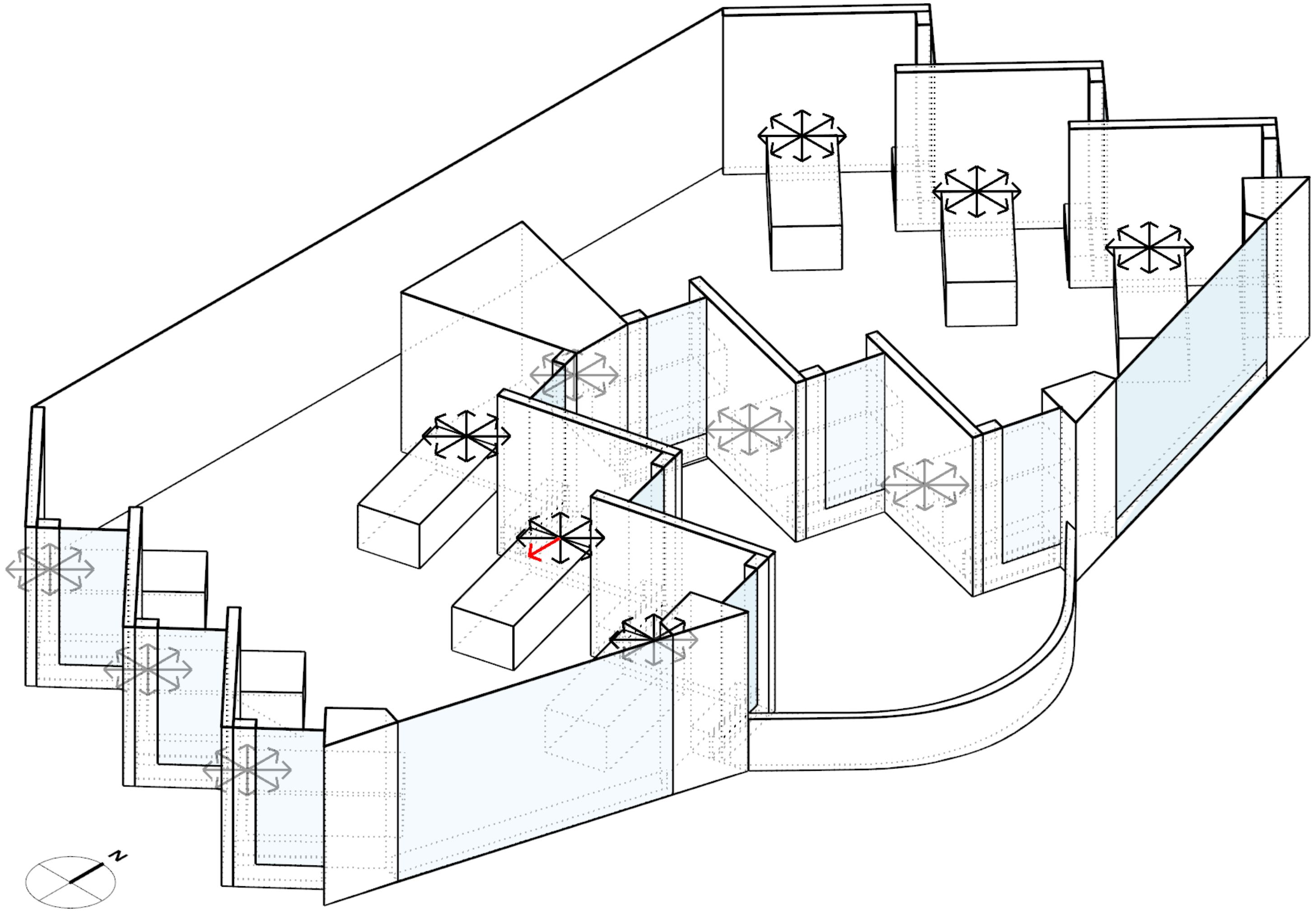
  Expressed as the percentage of melatonin suppressed compared to no light exposure.

Framework Summary



Results

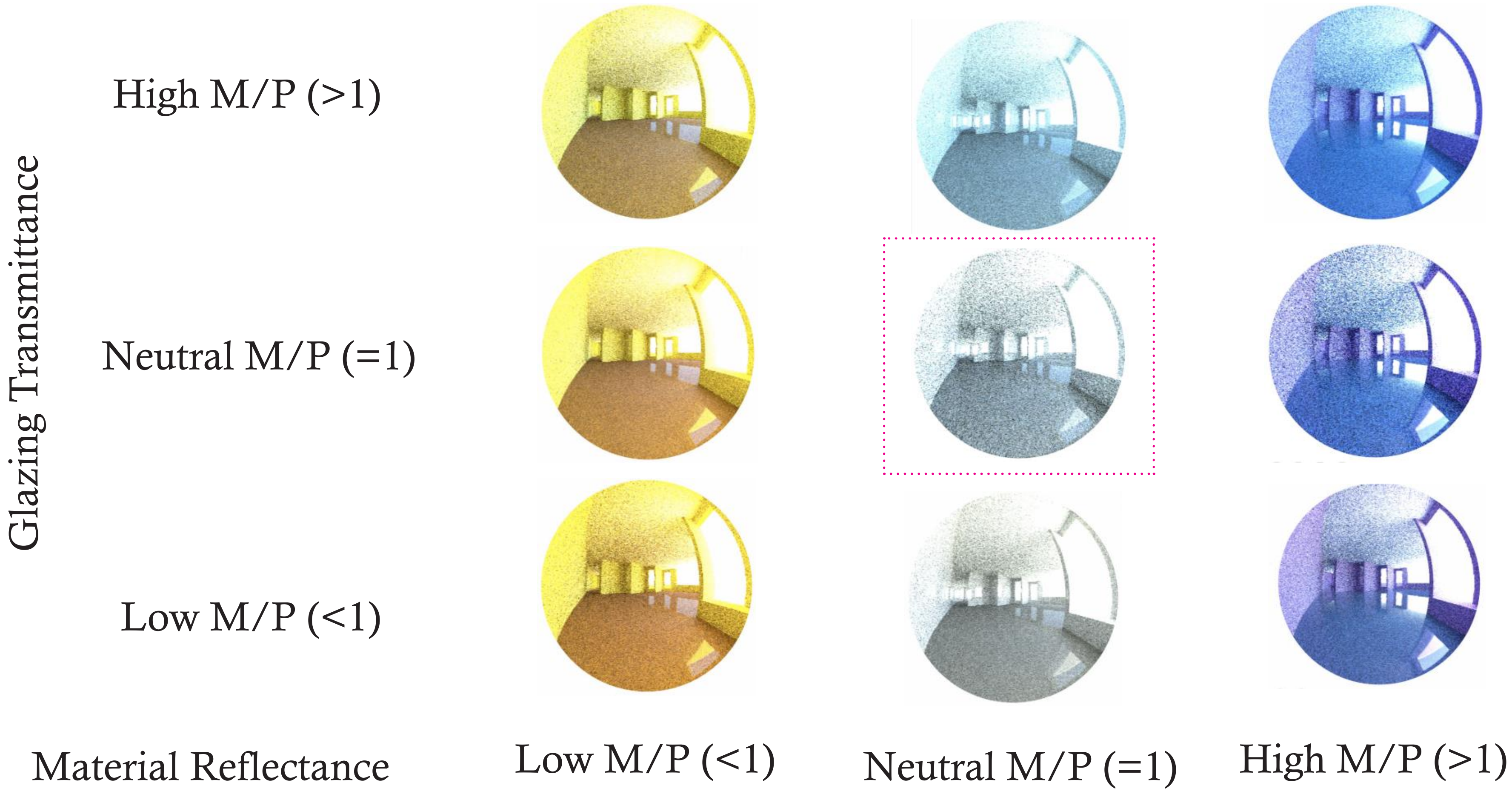
Prototypical space



- A hospital model based on HOK's Ng Teng Fong east-facing daylit hospital wards was constructed and simulated with neutral spectral materials.
- 96 views (12 locations x 8 directions) were calculated.
- Climate of Toronto, Canada

Surface and Glazing Properties

- Similar visible reflectance/transmittance + different melanopic reflectance/transmittance



Simulation Methods / Comparative Measures

Methods in Comparison:

- ALFA (Solemma, 2019)
- Lark (Inanici et al., 2015; Inanici, 2015)
- CDAT (Konis, 2019)
- Mardaljevic et al., (2013)

* All methods use spectral sensitivity curve by Lucas et al., 2014

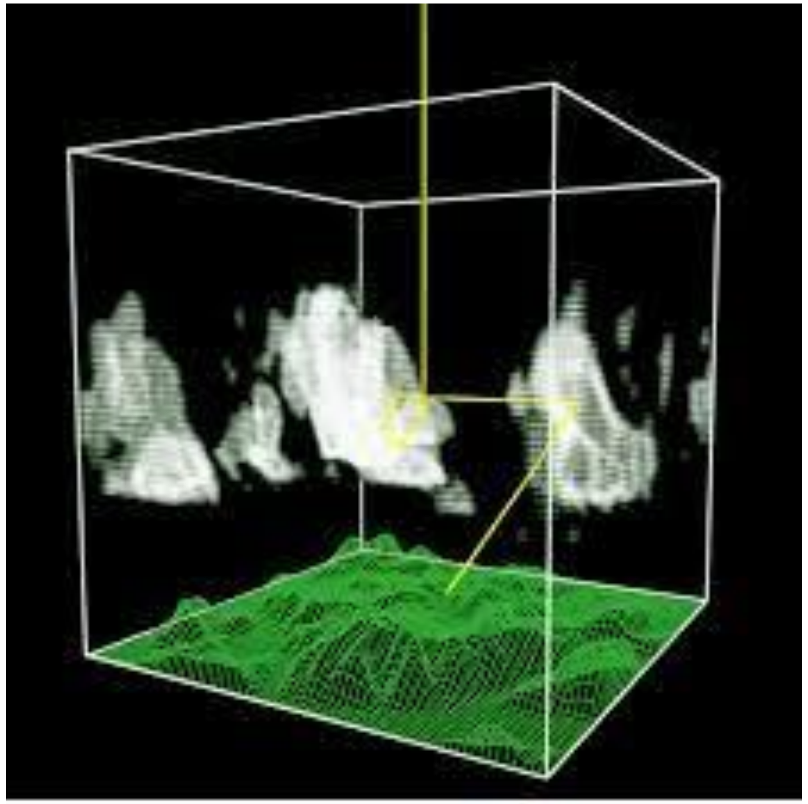
Equivalent Melanopic Lux, EML, is used as a standard comparative unit between the four methods.

<u>Daylight only</u> because Lark / CDAT / Mardaljevic et al. do not support luminaires.

Sky Spectra

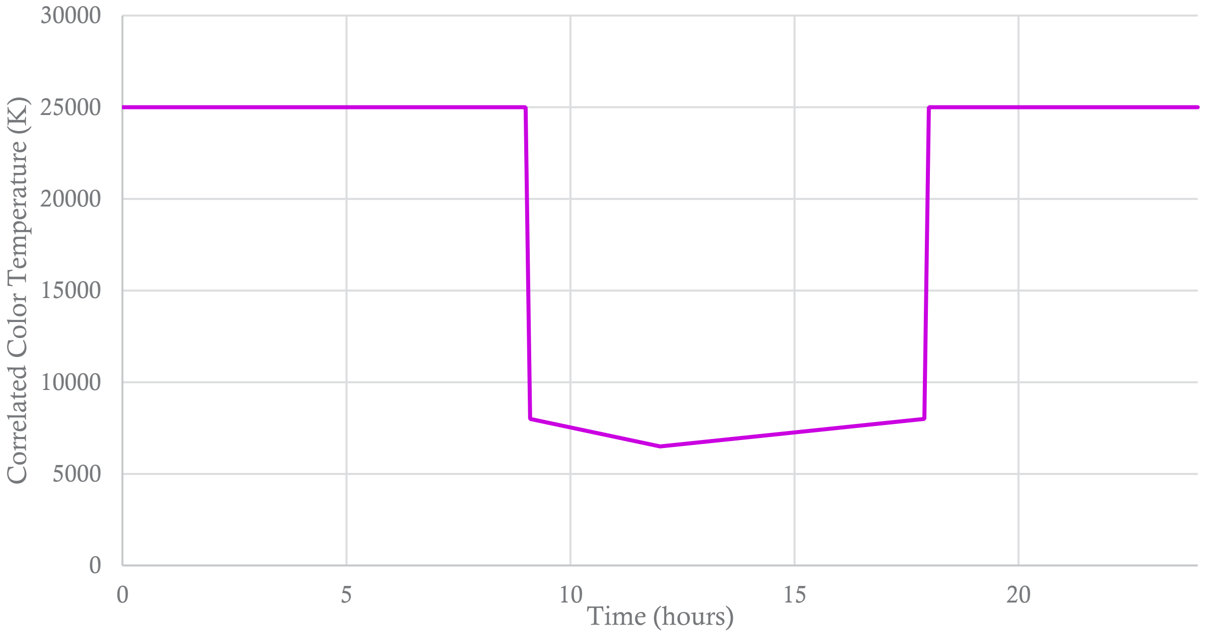
ALFA: Physics Based

- Calculated using libRadtran (Mayer and Kylling, 2005)



Lark: User Input

- Based on Inanici et al., 2015.
- Daylight spectra from Excel Daylight Series Calculator (Munsell Color Science Laboratory, 2002)



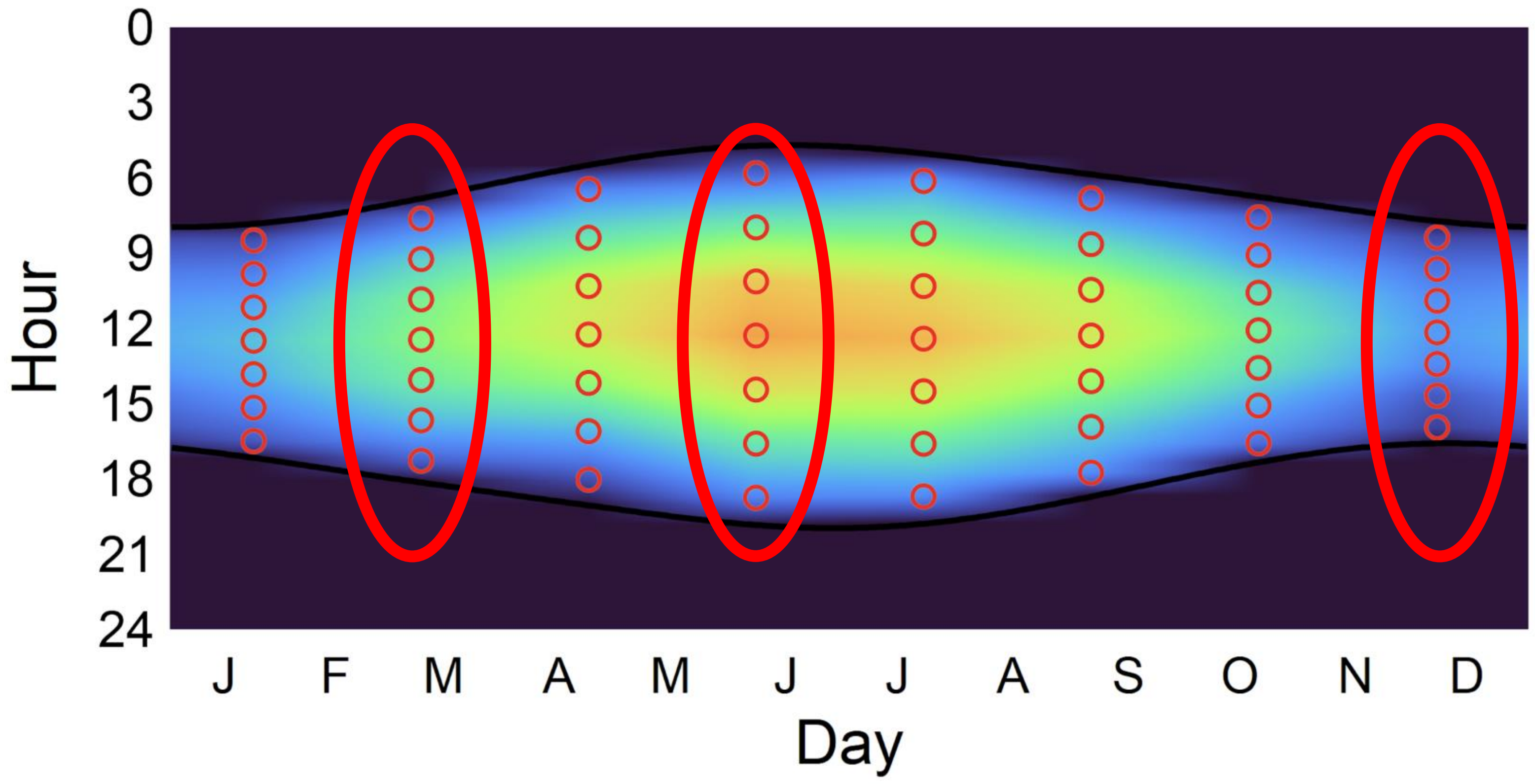
Mayer et al., 2020

MARDELJEVIC ET AL., 2013 AND CDAT: SKY CLASSIFICATION

Mardeljevic et al., 2013	CDAT cloud cover:
• Clear: D75 • Cloudy: D65	• 0%: 25000K • 10-50%: 7000K • 60-100% 5000 K

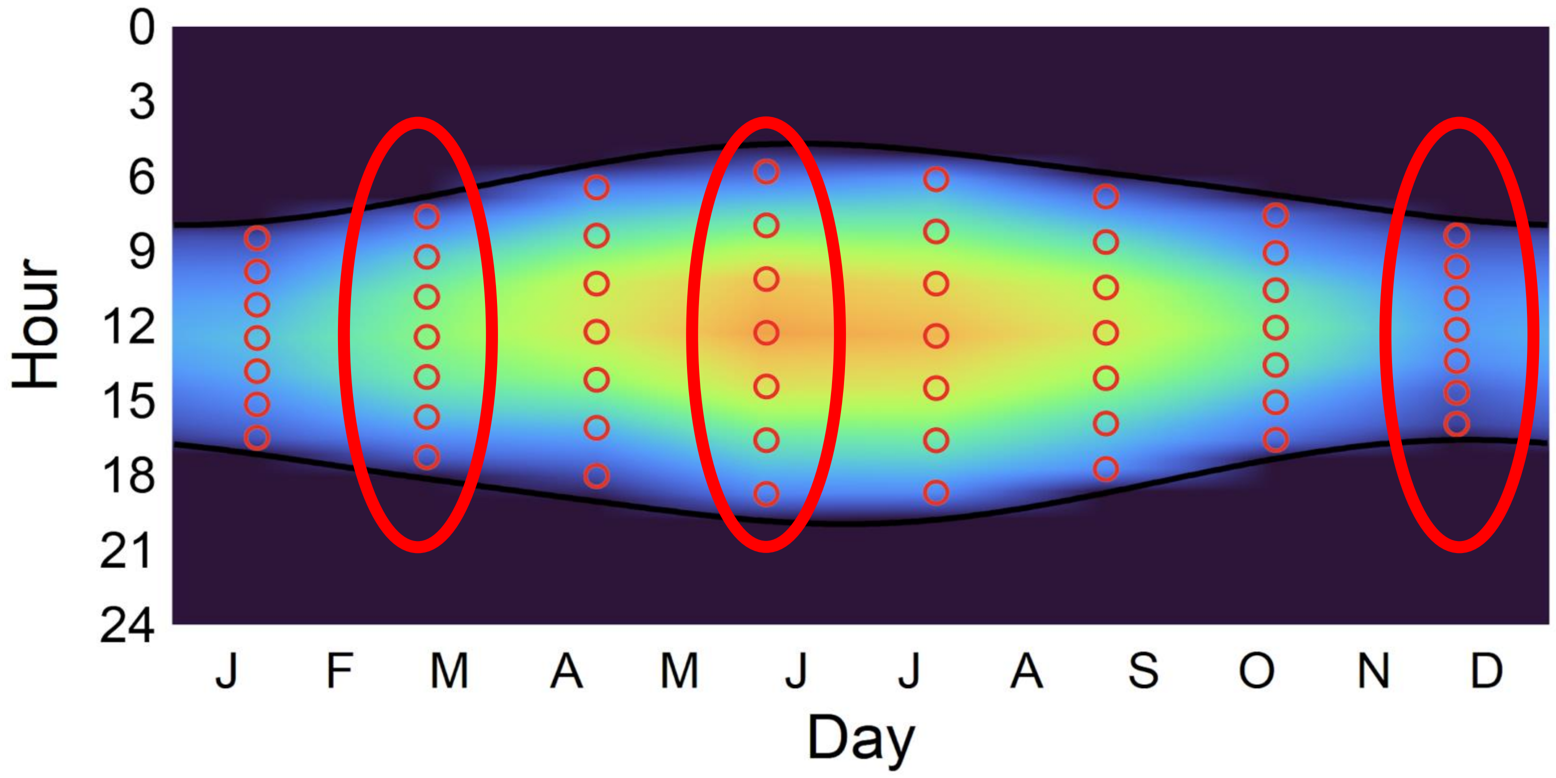
ALFA and Lark

- Derived from Lightsolve framework (Anderson et al., 2008; Kliendienst et al., 2008)
- Solar positions for Toronto
- Clear Sky

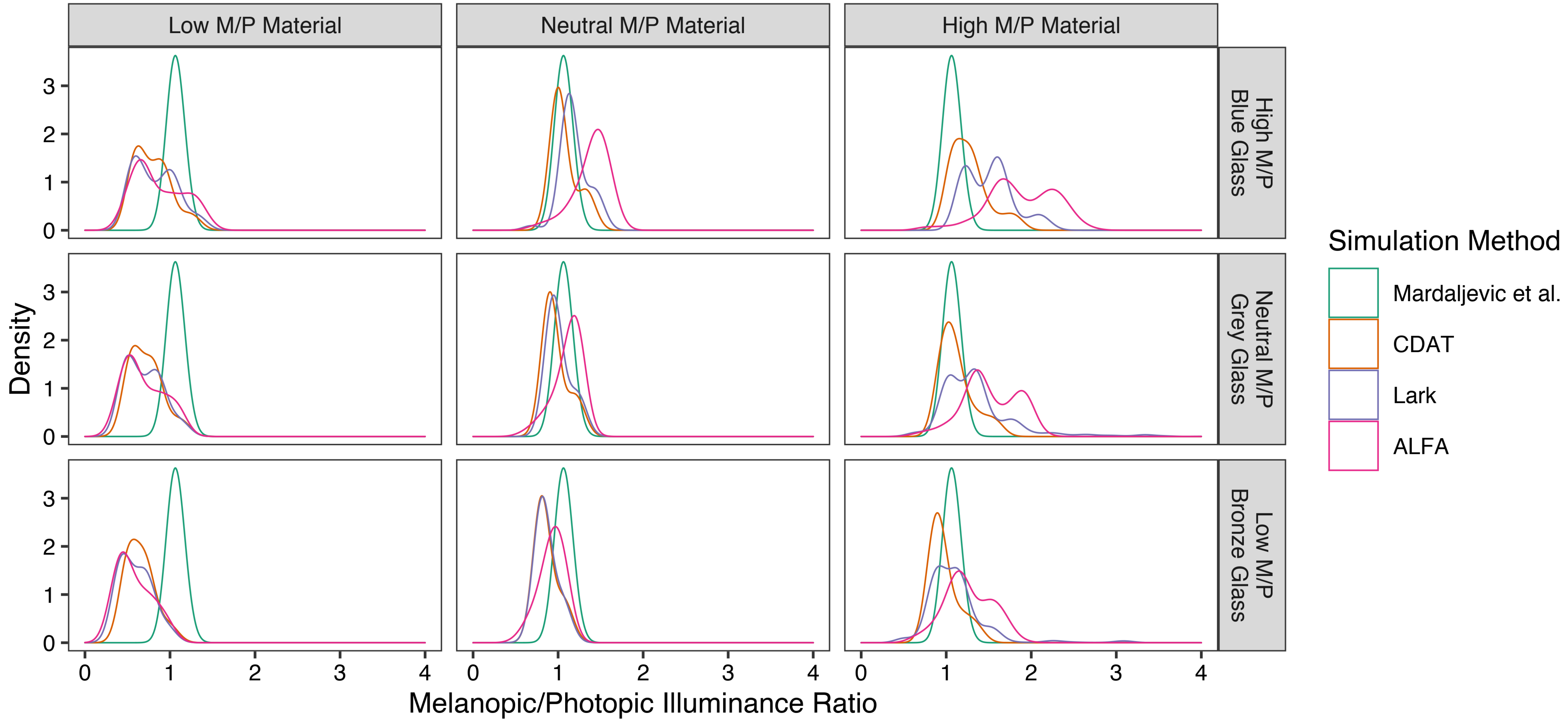


Mardaljevic et al., 2013 and CDAT

- Uses standard climate files
- Clearest day with 7 days of Lightsolve day



Results


Low M/P Material
Neutral M/P Material
High M/P Material
High M/P Blue Glass
Neutral M/P Grey Glass
Low M/P Bronze Glass
Density
0
1
2
3
4
Melanopic/Photopic Illuminance Ratio
Simulation Method
Mardaljevic et al.
CDAT
Lark
ALFA

MARDALJEVIC ET AL. (2013)

- Accounts for spectrum of light source
- Missing spectral qualities of materials, which this study design highlights

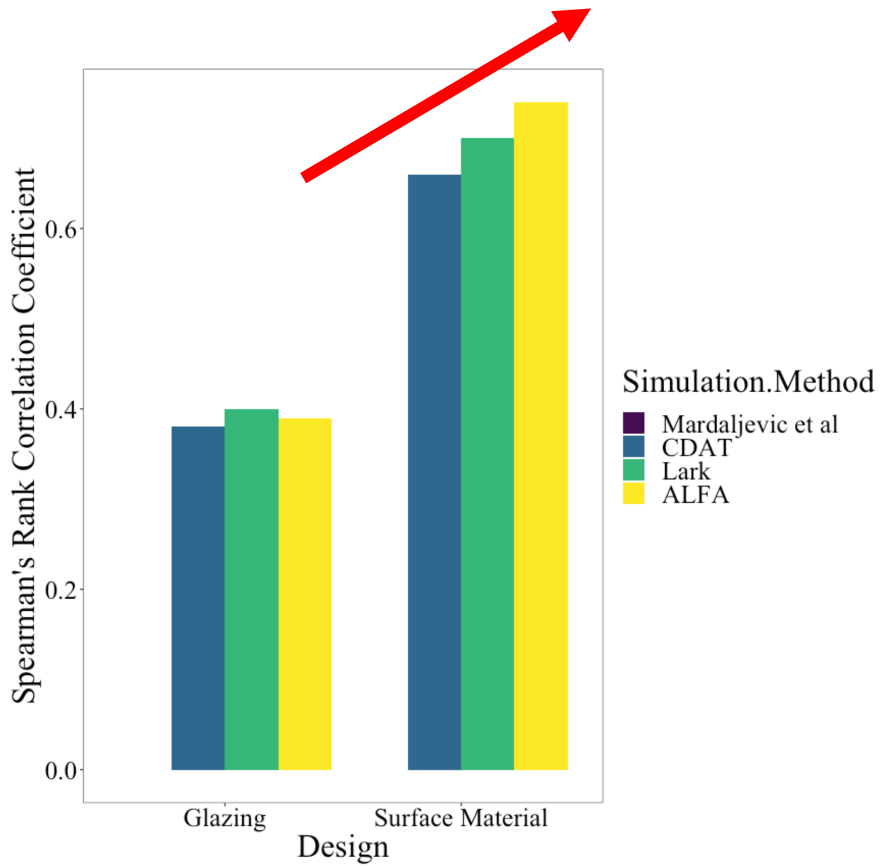
Table 3: Spearman's rank correlation coefficients of simulated M/P and design variables.

	Simulation Method			
	Mardaljevic et al. (2013)	Lark	CDAT	ALFA
Material M/P Reflectance	≈ 0	.70**	.66**	.74**
Glazing M/P Transmittance	≈ 0	.40**	.38**	.39**

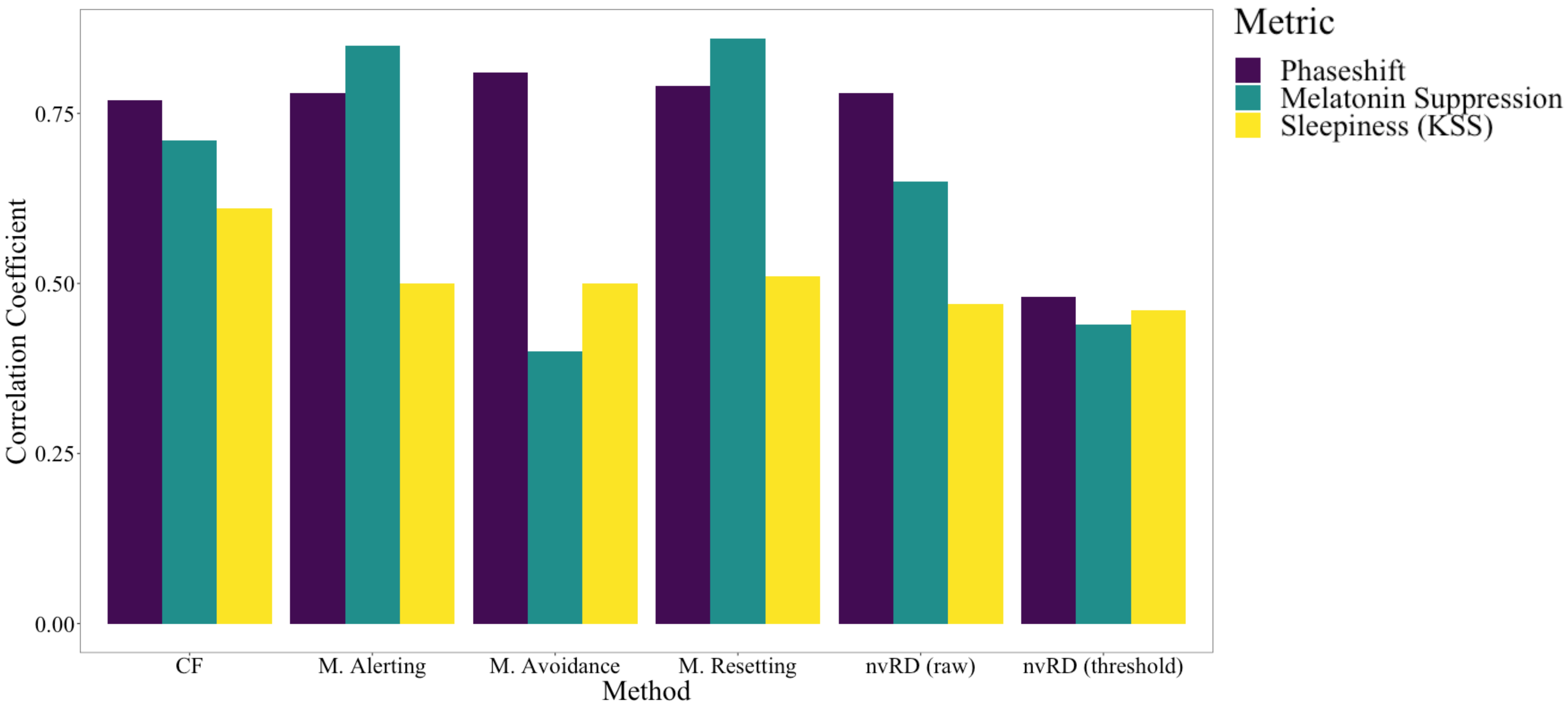
** is significant at 0.01 level
* is significant at 0.05 level

ALFA, LARK AND CDAT

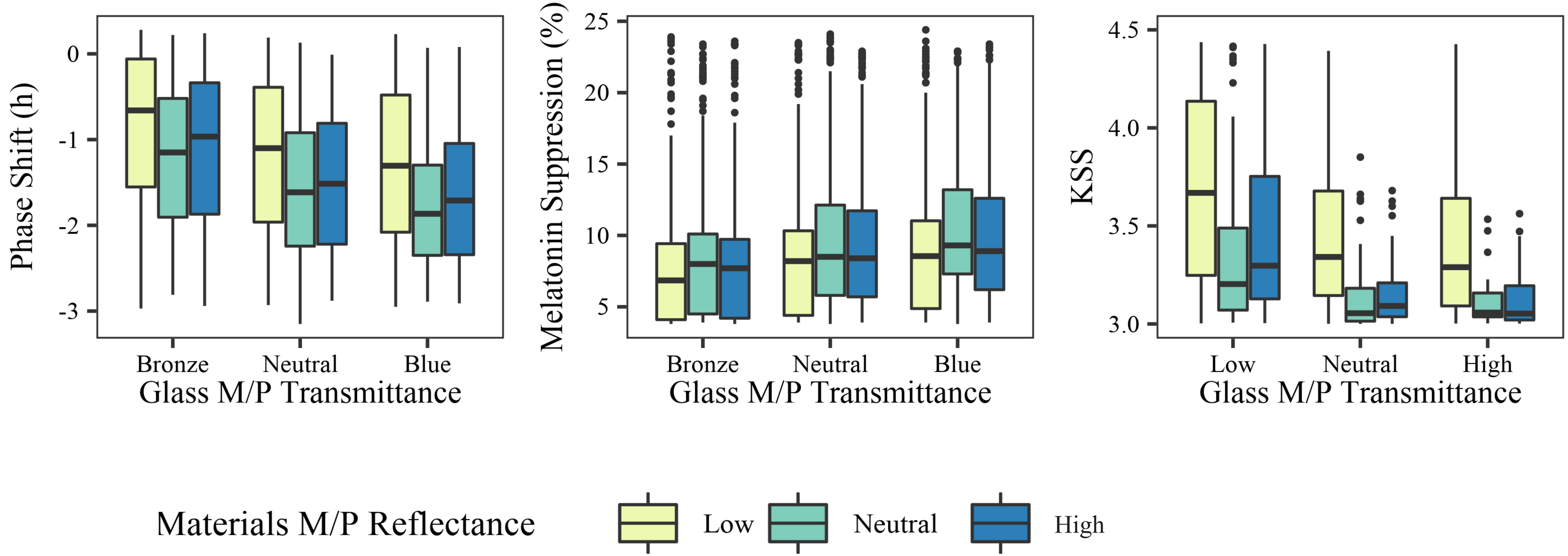
- Impact/sensitivity of material spectra on results of each methods
- Follows number of colour channels
  - ALFA: 81
  - Lark: 9
  - CDAT: 3



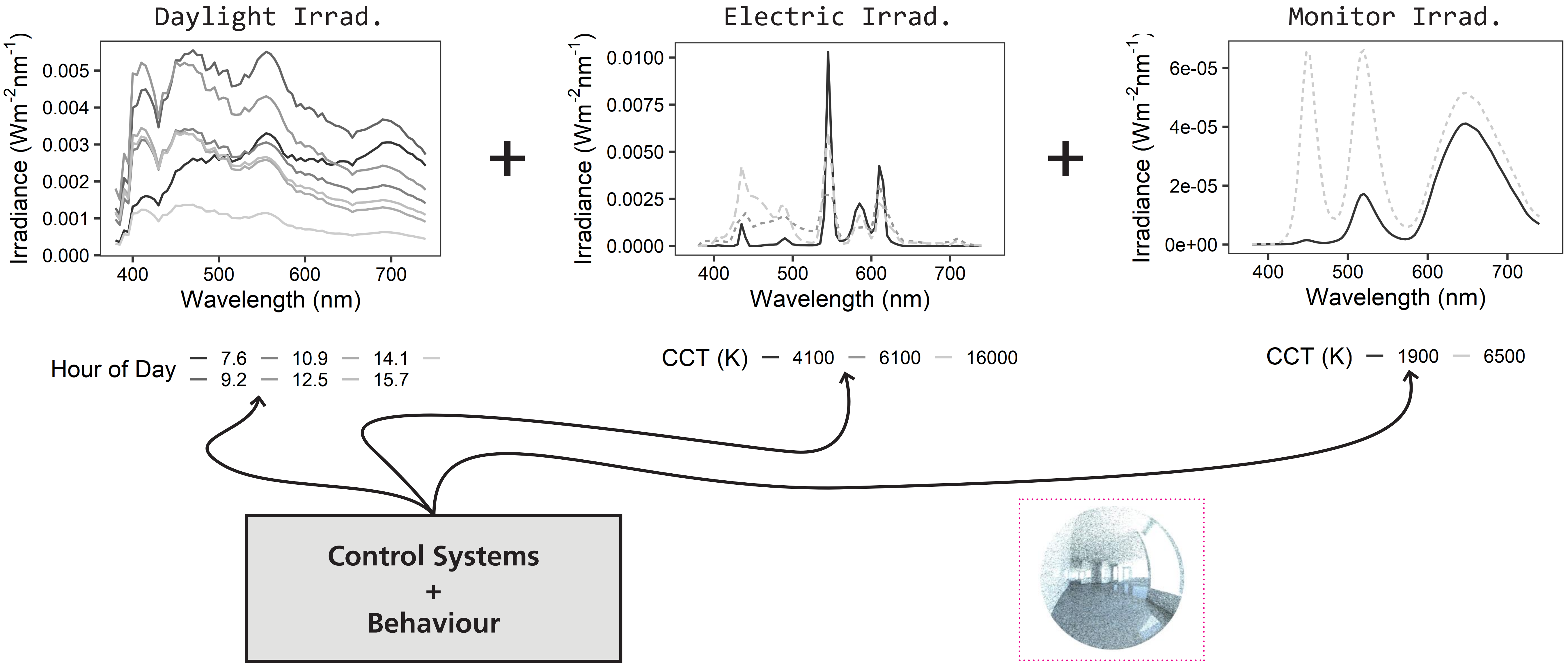
Daylight only photobiological effects correlations



Influence of glazing and materials on daylight-only circadian effects

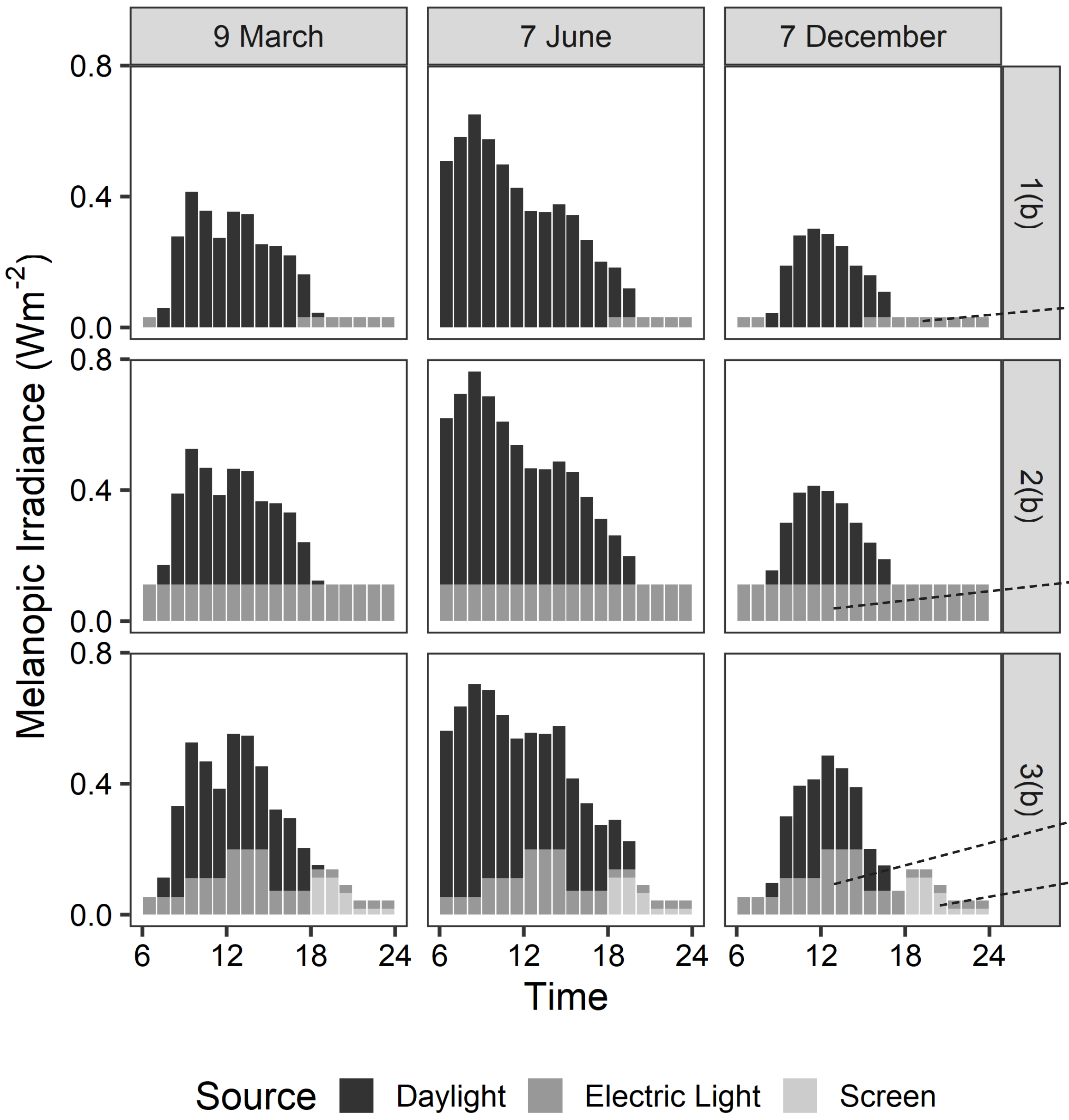


Realistic lighting scenario generation for circadian effects



1 M/P material properties

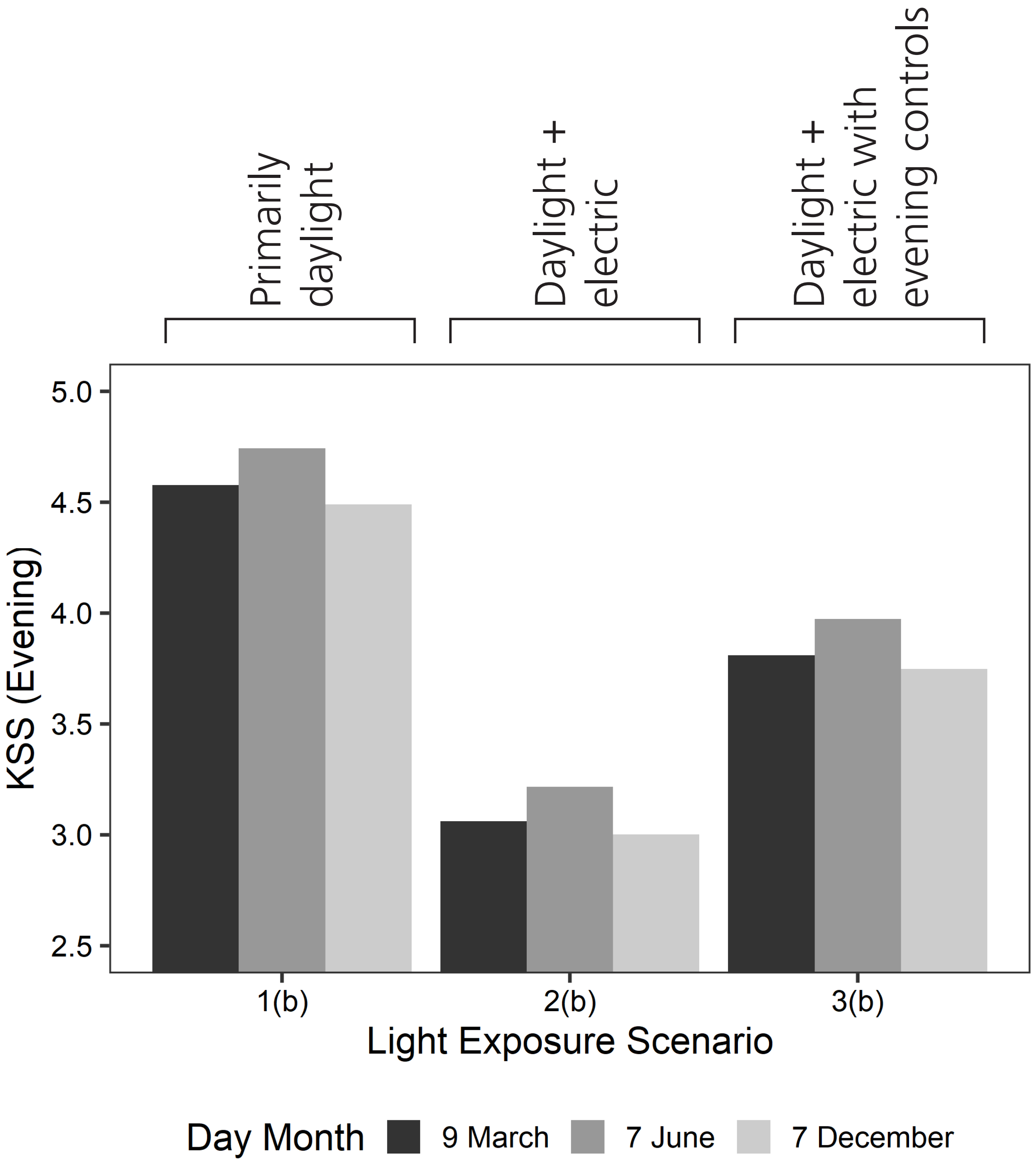
Lighting scenarios: 9 lighting design profiles and 3 seasonal daylight profiles



3 Scenarios

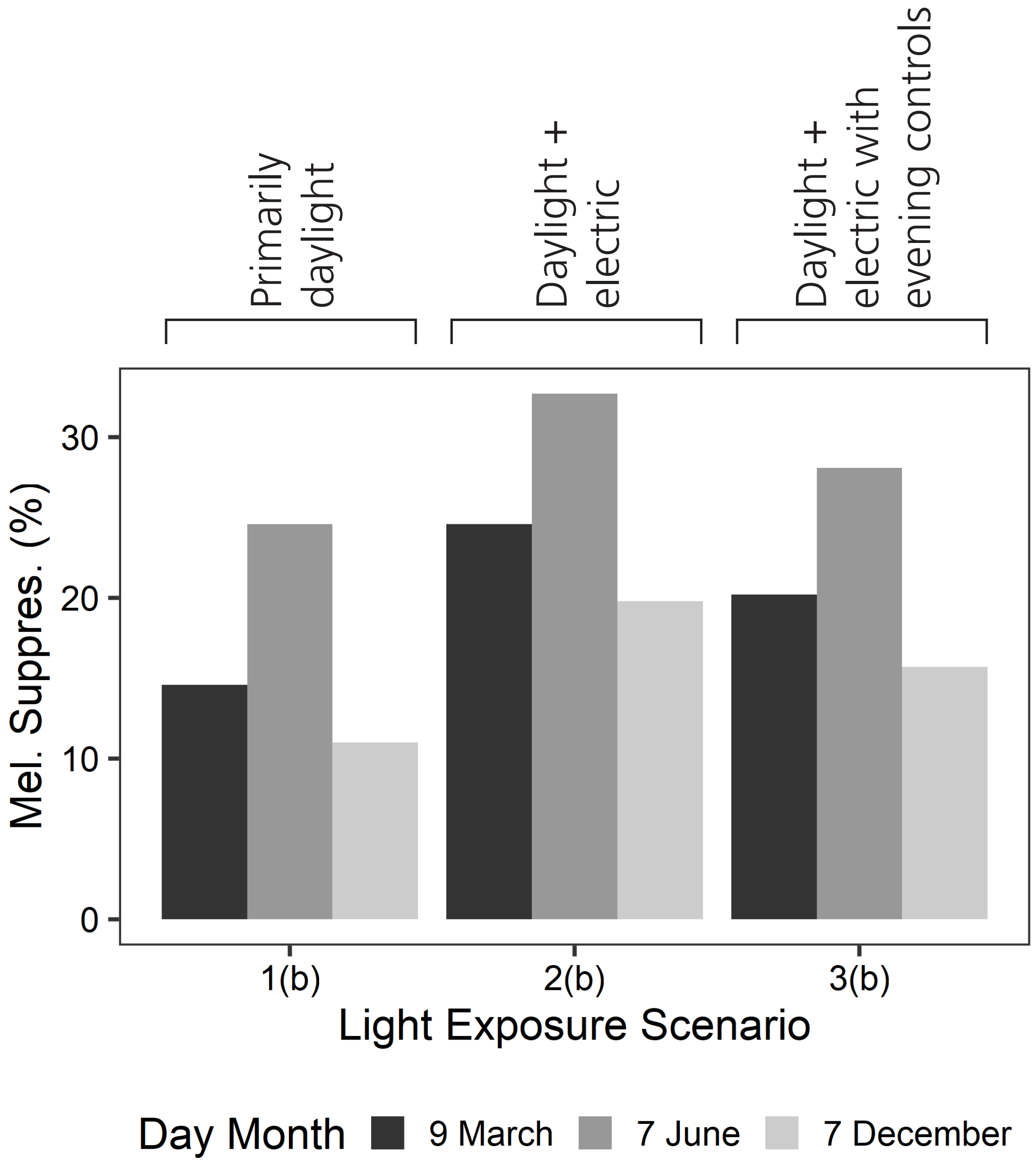
- Scenario 1(b) Daylight only
  - Minimal supplemental electric light during dark
  - neutral glazing and neutral materials
- Scenario 2(b) Daylight and
  - constant electric lighting at 6500 K CCT
- Scenario 3(b) Daylight and
  - electric lighting controlled to reduce early morning and late evening irradiance
  - monitor light that shifts to a warm CCT in the evening
- Calculated for daylight levels in March, June, and December.

Results: Mean alertness (pre-sleep hours)



- Mean KSS during evening hours: 9pm - midnight
- The impact of full-strength electric light is 1.5 units on the KSS scale. The difference between 'fairly alert' and 'some signs of sleepiness.'
- Lighting controls (color, intensity change) have a meaningful impact on evening sleepiness!

Results: Mean Melatonin suppression



- As expected, Melatonin suppression follows the evening KSS results: there is less suppression with daylight as the only source of illumination.

- Melatonin suppression varies significantly by season and the length of a day.

Discussion / conclusion

• Sky models result in significant discrepancies between spectral lighting simulation methods

(see Diakite-Kortlever & Knoop 2022; Maskarenj et al. 2022)

• Compared to daylight-only analysis, realistic combined models of melanopic irradiance are needed to fully assess non-visual photobiological effects.

• Calculating direct photobiological effects gives lighting designers more nuanced and actionable information for circadian wellbeing.

Limitations

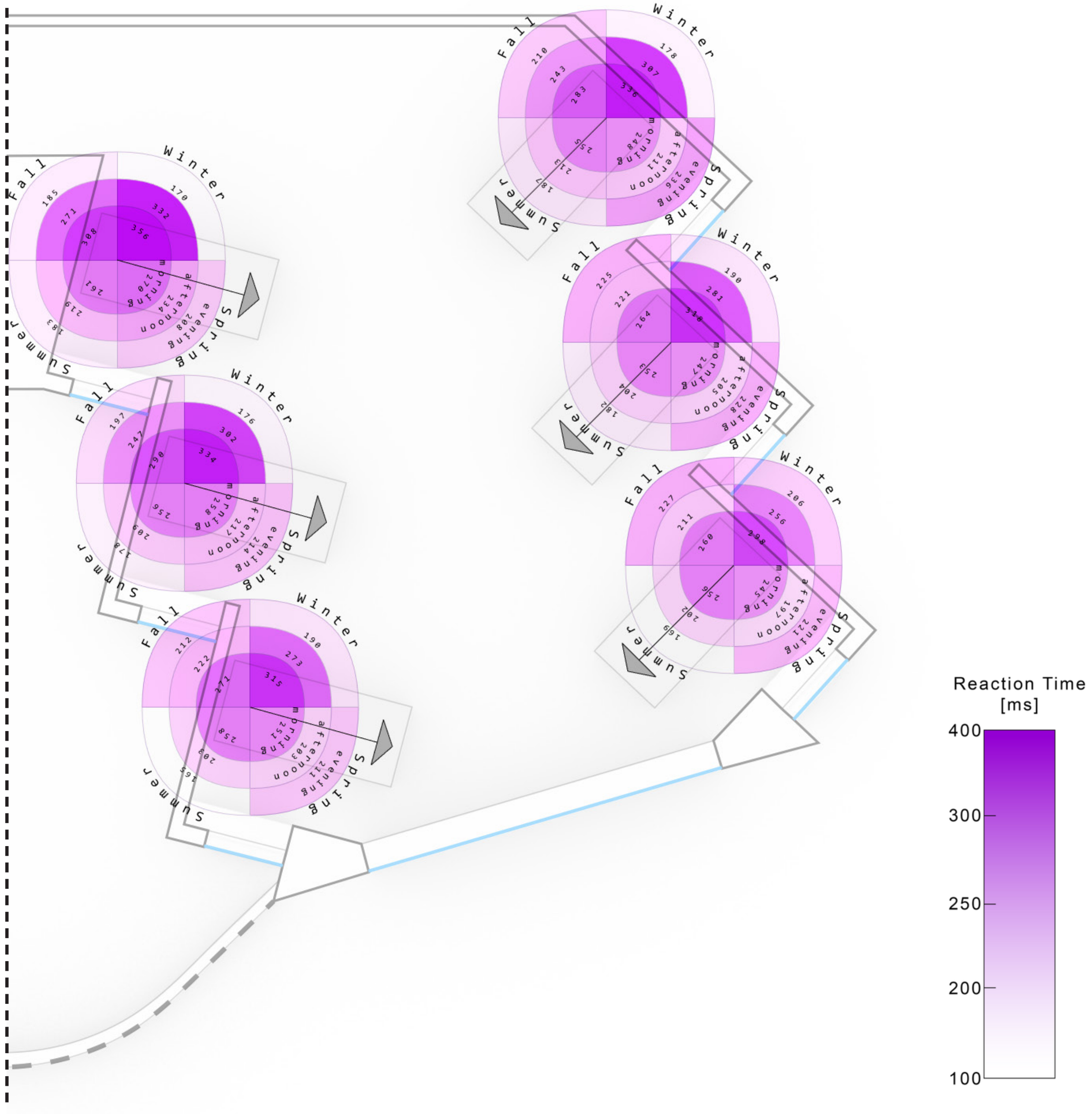
- Many simulation methods cannot simulate electric light.

- More validation against real-world measurements are necessary
  (see Pierson et al. 2021; Safranek et al. 2022 in press)

- New models require complex inputs:
  - Occupant behavior and movement (see Danell, Amundadottir & Rockcastle 2020)
  - Electric lighting controls
  - Daylight controls (blinds / shades)
  - Light exposure profiles outside of a single building (home & office)
  - Sleep schedules

- Photobiological results do not provide a threshold of good / bad.

Ongoing work



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J. Alstan Jakubiec

Thank you!

The code used in this presentation is available at,
`github.com/C38C/NIF_Photobiology`

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- Dr. Svetlana Postnova, and
- Dr. Tahereh Tekieh

1. University of Toronto, Daniels Faculty of Architecture, Landscape and Design