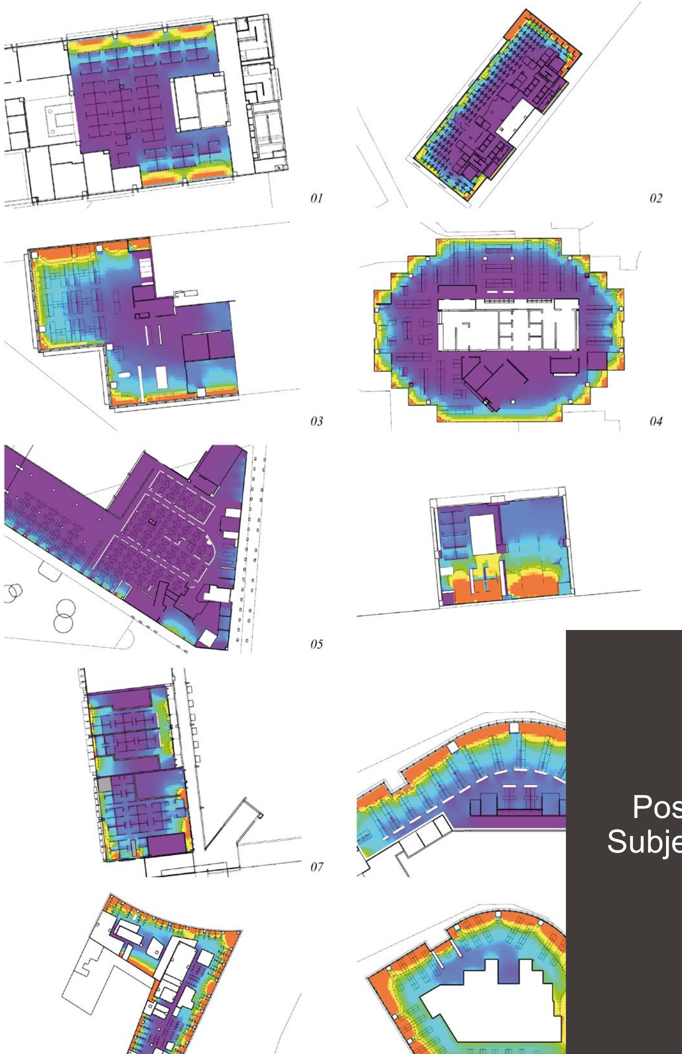

Building Climate-based Daylighting Models based on One-time Field Measurements

Post-Occupancy Study for Subjective Lighting Metrics in the Tropics

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Post-Occupancy Evaluations (POEs)

Instantaneous measurements
or
Constant Monitoring

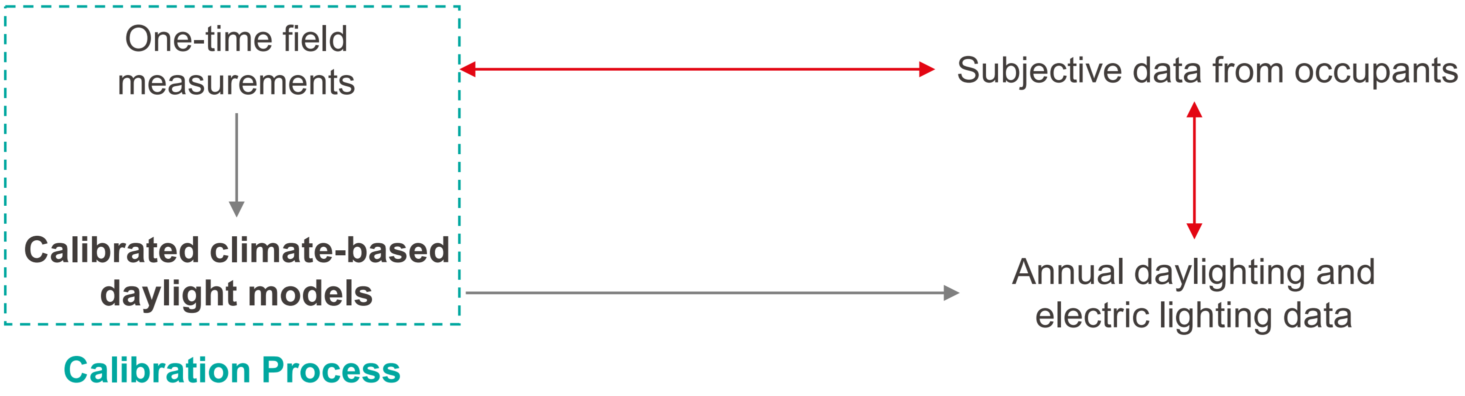
↔

Subjective data from occupants

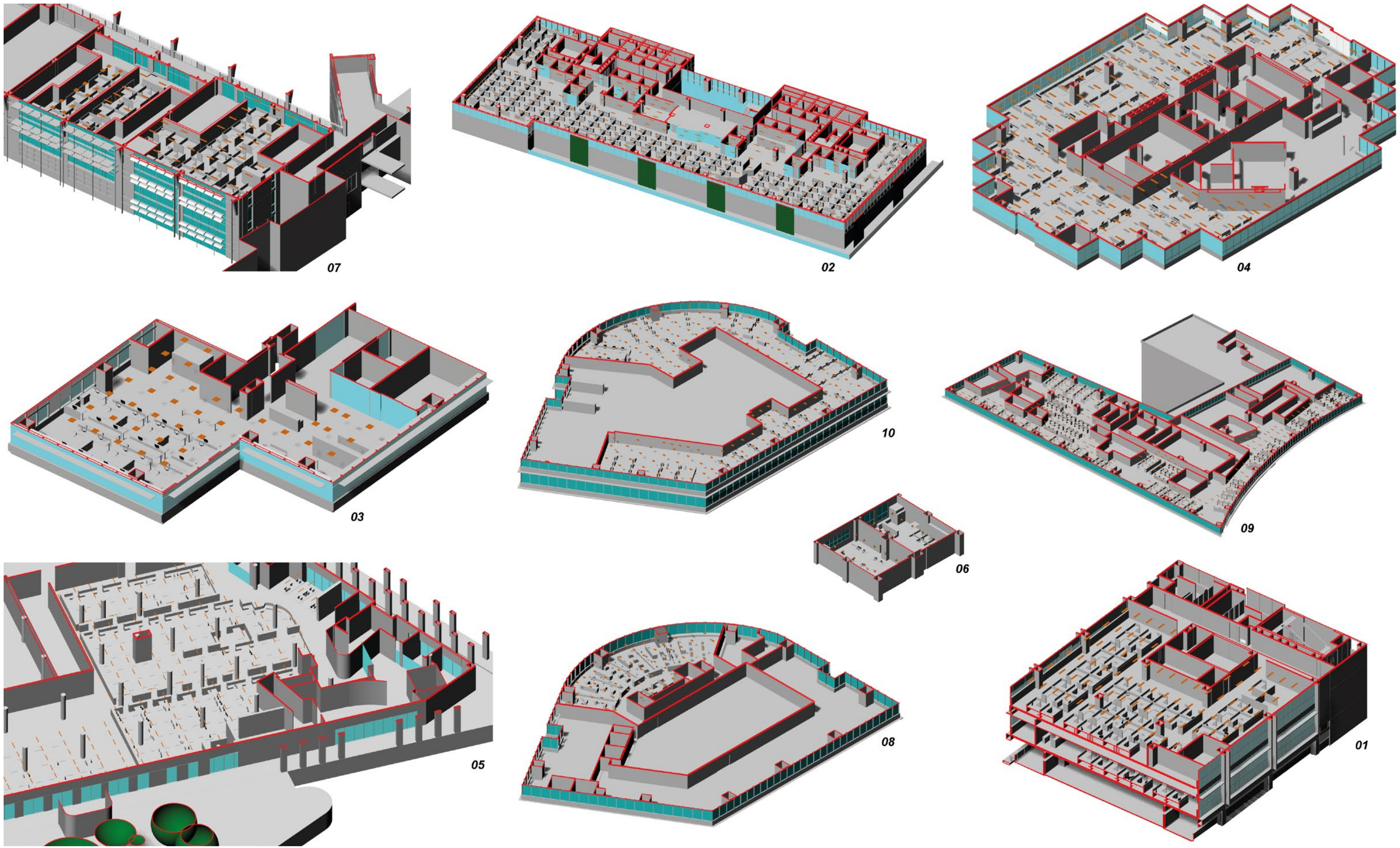
Limited to single data points

Limitations of scale (expensive sensors)

Post-Occupancy Evaluations (POEs)



It is challenging to build calibrated models based on point-in-time measurements due to the presence of **electric lighting**, **transient use of dynamic shades**, limited information on the **material specifications**, and **short durations of accessibility** to the spaces being studied.



Calibrated lighting models of 10 offices (540 workspaces)

540 individual office desks across **10 offices spaces** in Singapore

Measurements:

Instantaneous lighting measurements at each desk

HDR Photographs

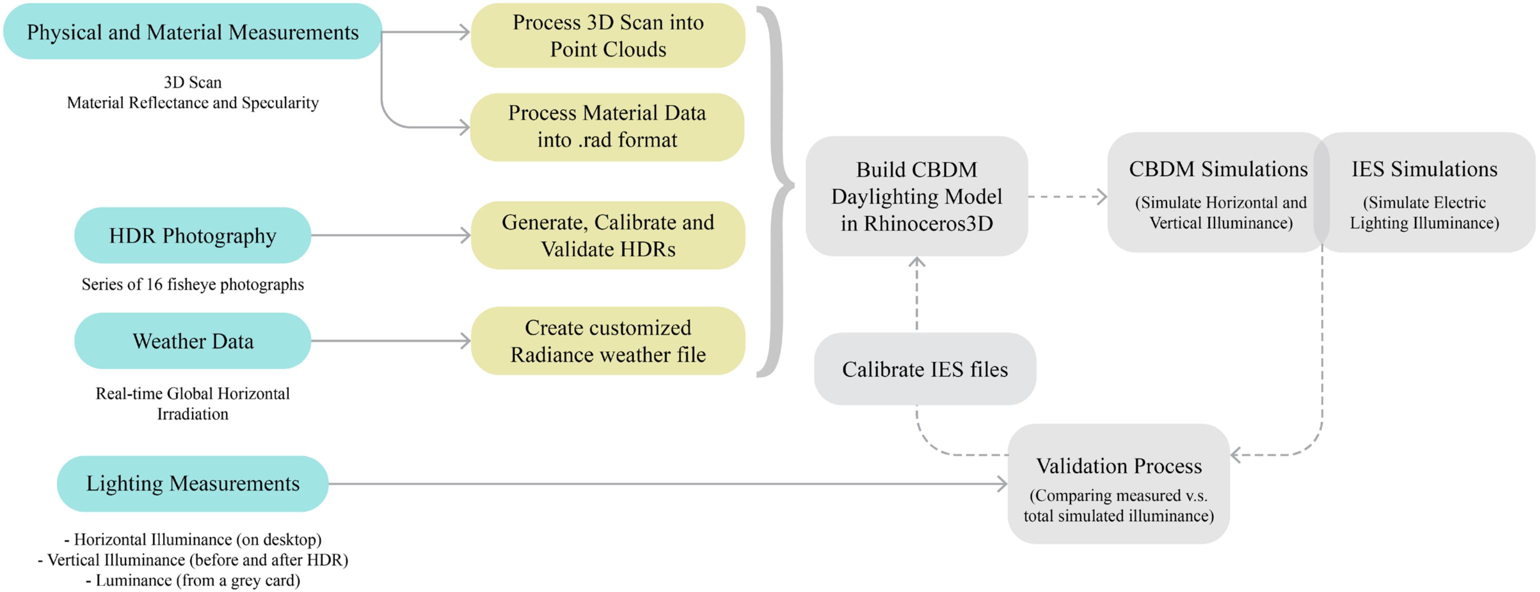
Physical Measurements (3D Scans)

Material Properties

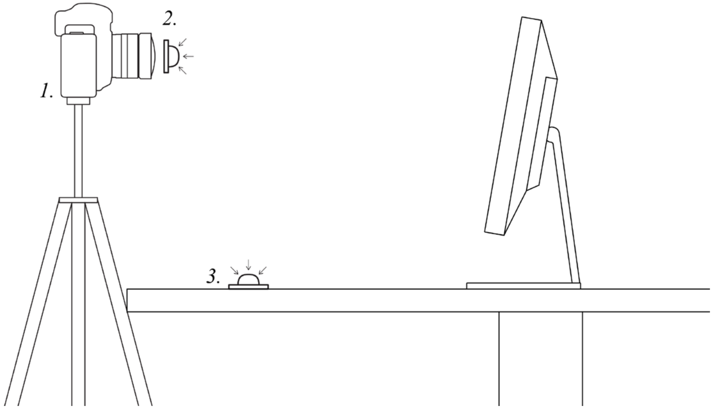
Weather Data

+

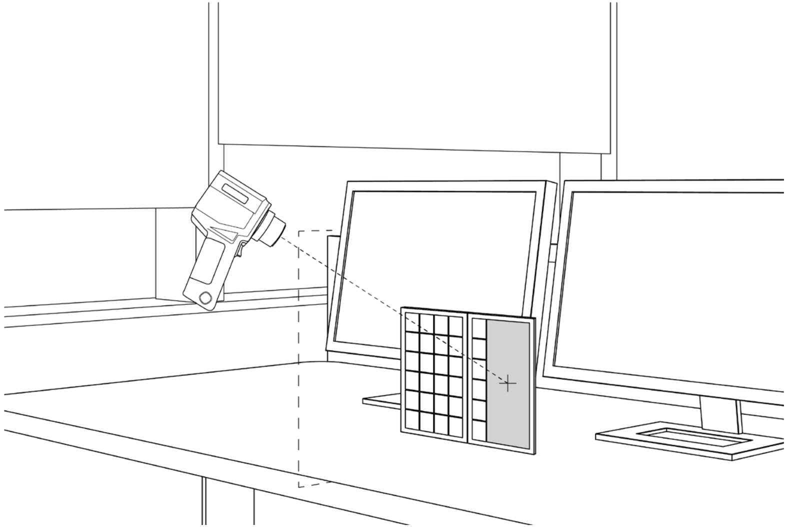
Instantaneous and long-term subjective perceptions on lighting sufficiency and quality



Overall workflow for calibrating climate-based daylighting models from single point-in-time measurements.



1. Camera setup for HDR photography
2. Vertical illuminance measurement location
3. Horizontal illuminance measurement location

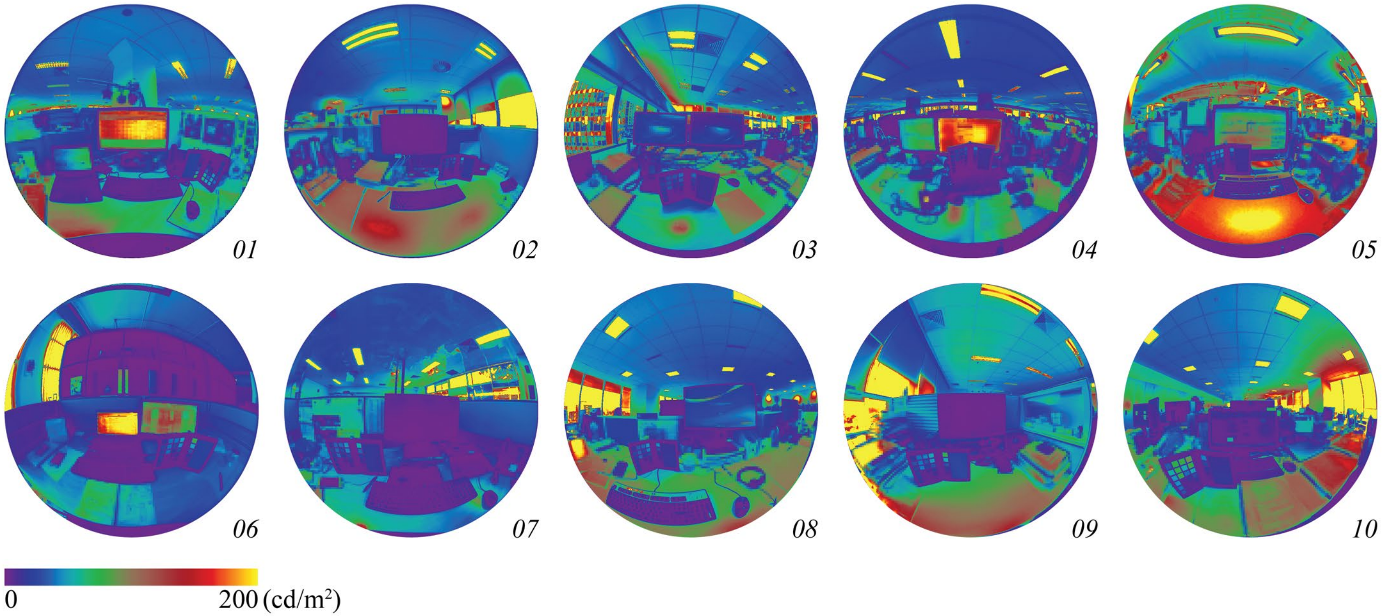


Luminance measurement setup

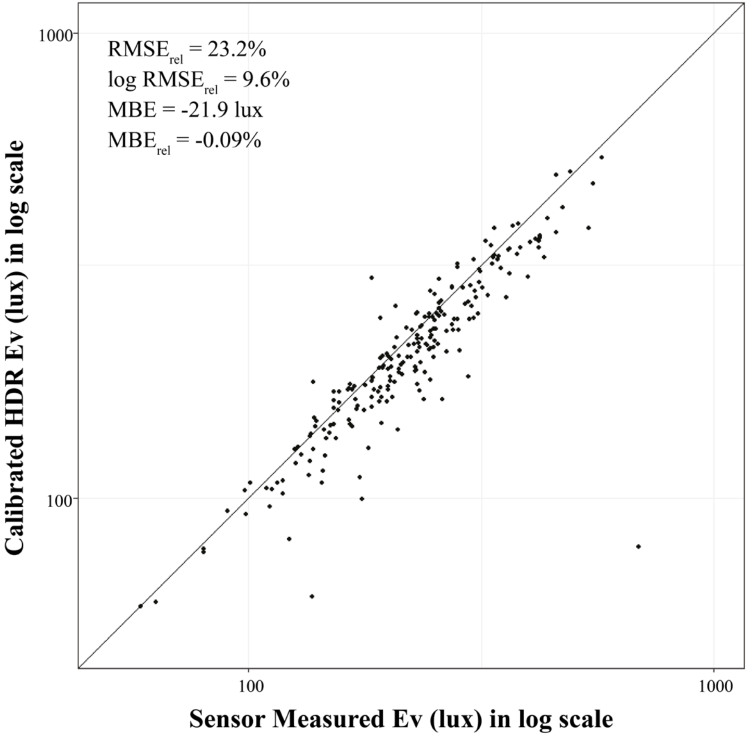
Lighting Measurements and HDR Photography

HDR Images

- **With illuminance and luminance measurements**
  - ↓ **Calibrated by luminance (Photosphere)**
  - ↓ **Validation by measured Ev and total pixel contribution**
- **With illuminance measurements only**
  - ↓ **Calibrated by vertical illuminance**



Examples of calibrated HDR photographs from each of the 10 office spaces

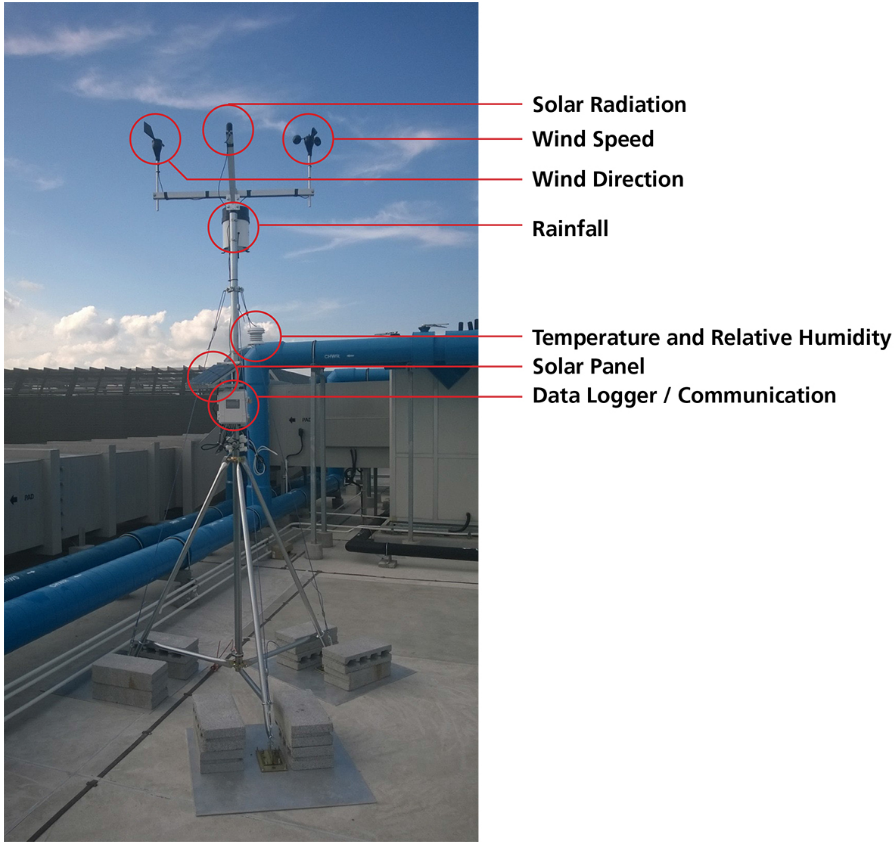


Validation of luminance-calibrated HDR Images: Total pixel illuminance contribution v.s. Measured Vertical Illuminance

	Material	Radiance Definition
Interior	Wood Laminate Table Top	void plastic TableTop 0 0 5 0.6112 0.4779 0.3081 0.0141 0.15
	Beige Partition Fabric	void plastic PartitionFabric 0 0 5 0.6249 0.5803 0.4762 0.0097 0.10
	Grey Carpet	void plastic GreyCarpet 5 0.0731 0.0708 0.0654 0.0000 0.40
	Grey Mullions	void plastic GreyMullions 5 0.4618 0.4716 0.4765 0.0374 0.05
	White Wall	void plastic WhiteWall 5 0.8911 0.8933 0.8495 0.0107 0.30
	White Column	void plastic WhiteColumn 5 0.8884 0.8896 0.8423 0.0113 0.30
	Acoustic Ceiling Panels	void plastic AcousticCeilingPanels 5 0.8752 0.8717 0.8471 0.0079 0.40
	Light Shelf (Bottom)	void plastic LightShelfBottom 5 0.4851 0.4963 0.4958 0.0552 0.05
	Light Shelf (Top)	void plastic LightShelfTop 5 0.4929 0.5007 0.4951 0.0515 0.05
	Opaque Roller Shade	void plastic OpaqueShade 5 0.5812 0.5560 0.4676 0.0059 0.20
	Glazing	void glass Glazing 3 0.3815 0.3815 0.3815
	Roller Blinds	void BRTDfunc RollerBlinds 10 0 0 0 tspec tspec tspec 0 0 0 mechoshade.cal 0 9 0.37 0.37 0.37 0.56 0.56 0.56 0.2 0.2 0.2
Exterior	White Painted Wall	void plastic WhiteExteriorWall 0 0 5 0.4067 0.4968 0.5054 0.0050 0.3
	External Mullions	void plastic ExternalMullions 0 0 5 0.4732 0.5545 0.5009 0.0252 0.15
	Decorative Floor Tiles	void plastic DecorativeExternalFloorTiles 0 0 5 0.1545 0.1628 0.1390 0.0089 0.2
	Specular Steel Handrail	void plastic SpecularSteelHandrail 0 0 5 0.2247 0.2896 0.2991 0.3287 0.05
	Asphalt	void plastic Asphalt 0 0 5 0.1086 0.0998 0.0850 0.0004 0.4
	Wood Plank Walkway	void plastic WoodPlankWalkway 0 0 5 0.1162 0.0958 0.0841 0.0011 0.4
Monitor	Screen	void trans MonitorScreen 0 0 7 0.575 0.575 0.575 0.033 0.01 0.88 1
	High-State Pixel	void glow MonitorHigh 0 0 4 1.396 1.396 1.396 0
	Low-State Pixel	void glow MonitorLow 0 0 4 0.3352 0.3352 0.3352 0
	Dark Plastic	void plastic MonitorPlasticBlack 0 0 5 0.054 0.054 0.062 0.013 0.1
	Light Plastic	void plastic MonitorPlasticSilver 5 0.464 0.470 0.452 0.078 0.1

An example list of Radiance material definitions from Office 5

Material Measurements (161 surface materials measured from 10 offices)



Global horizontal solar irradiation (every 5 min)

↓

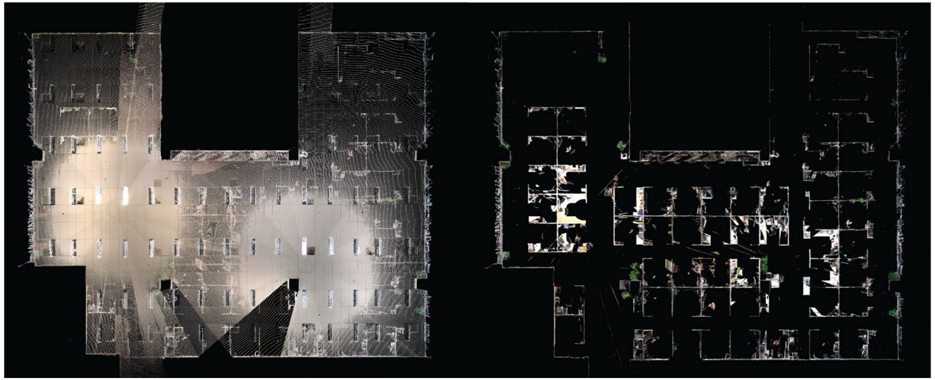
Direct-horizontal and diffuse-horizontal irradiance *(gen_reindl)*

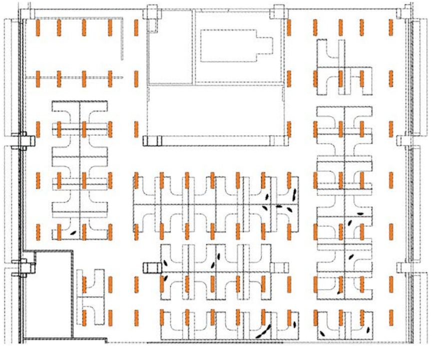
↓

Customized Radiance .wea weather file

Weather Data (SUTD Rooftop 36m above ground)

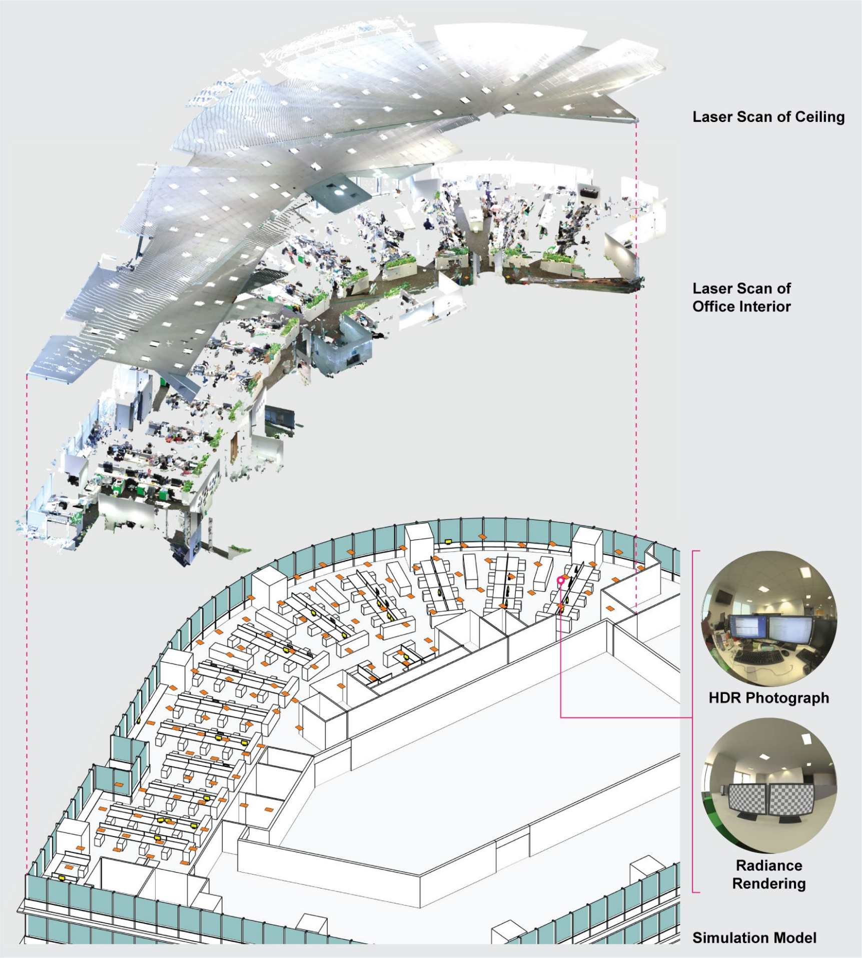
Geraldine Quek

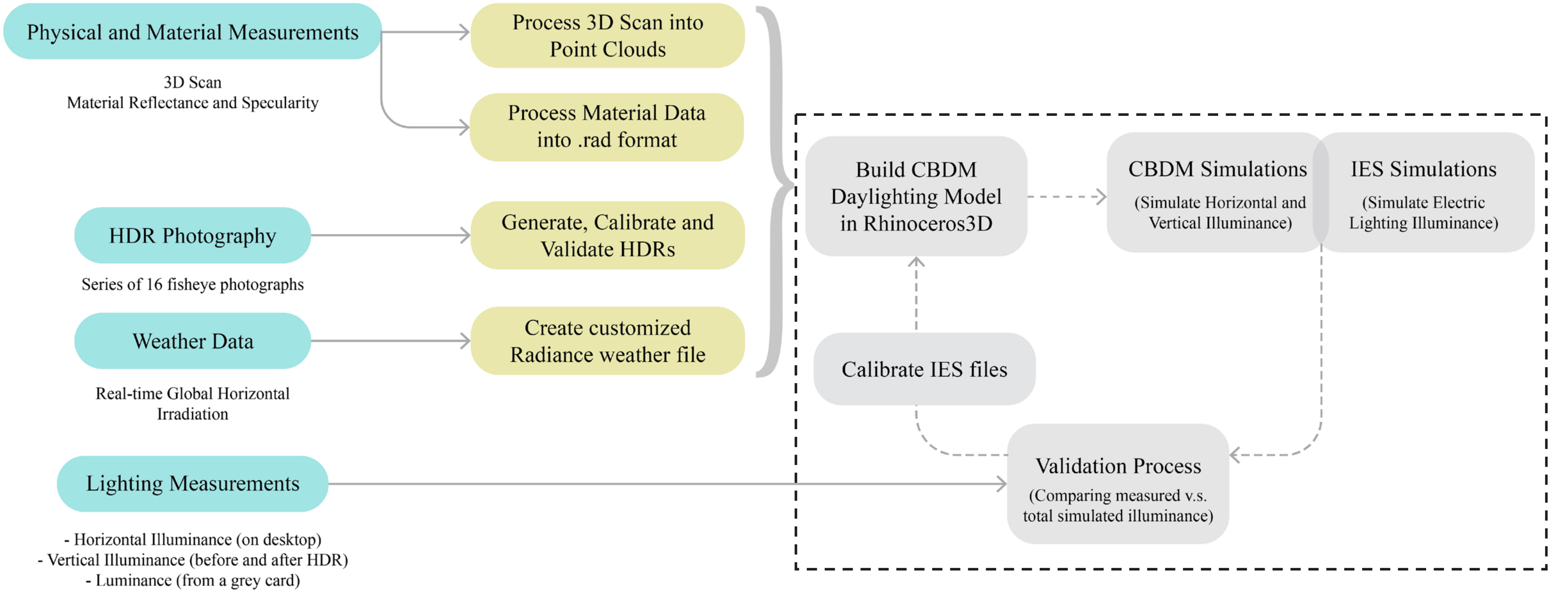




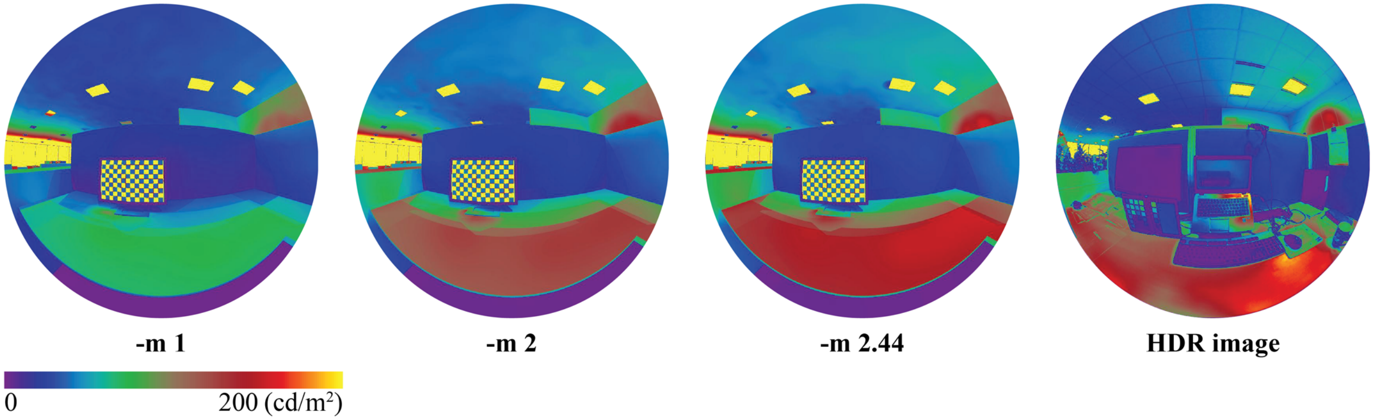
3D Point-cloud Scans → Rhino 3D Model → Radiance .rad format

Physical Measurements

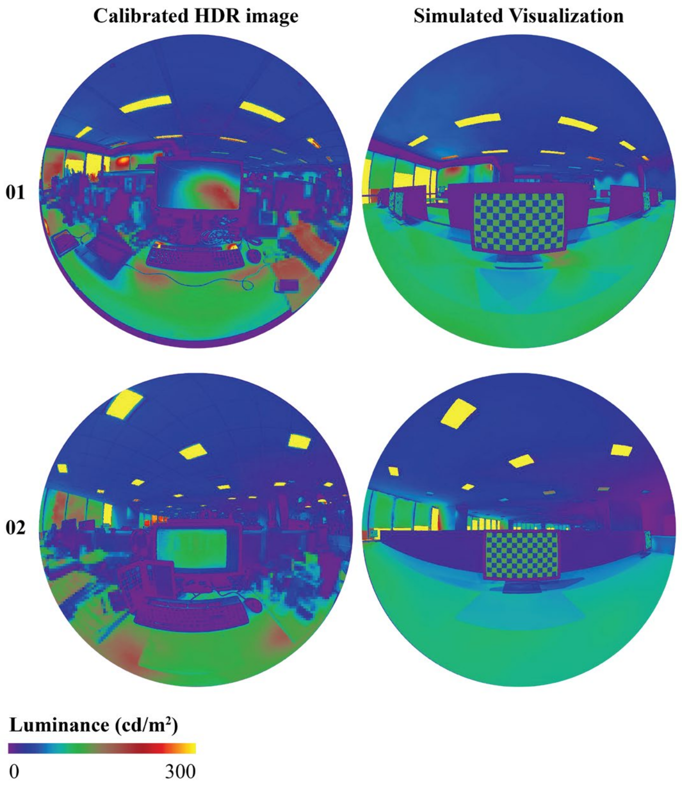

Laser Scan of Ceiling
Laser Scan of Office Interior
HDR Photograph
Radiance Rendering
Simulation Model



Iterative calibration / validation process

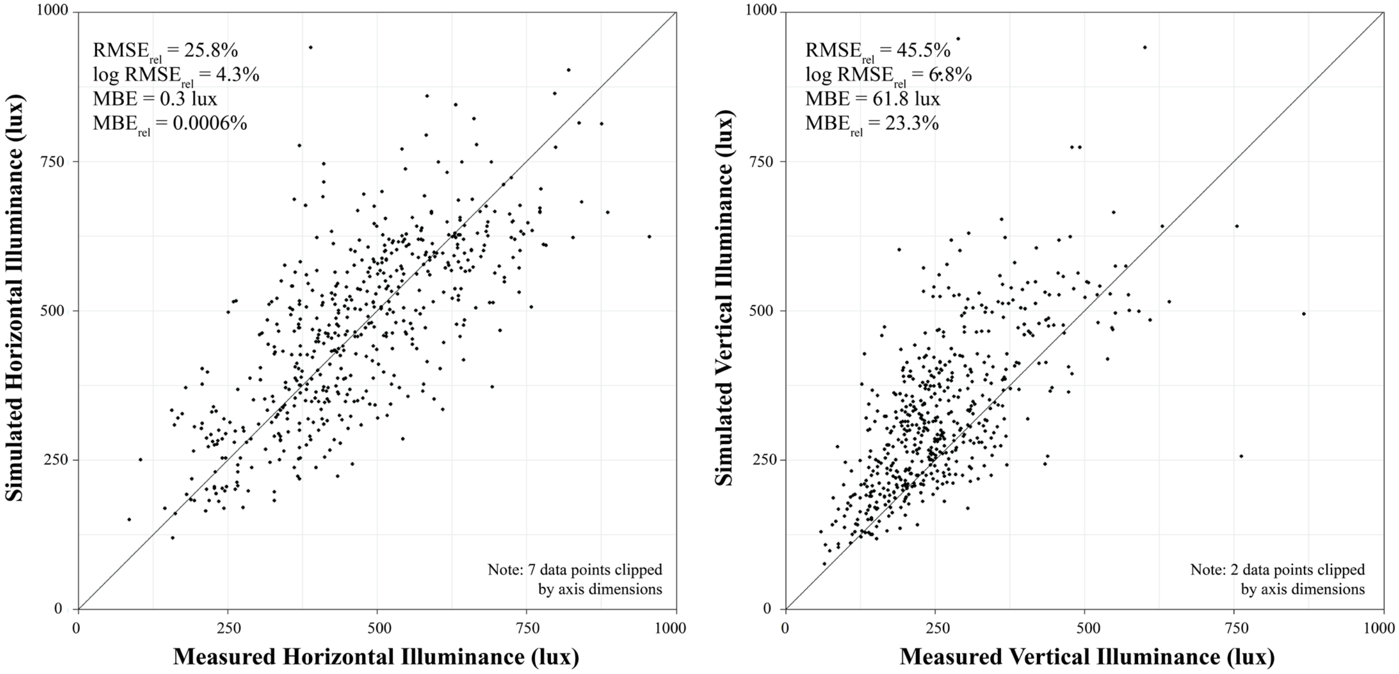


Scaling IES files for electric lighting in the simulation models *(-ies2rad)*



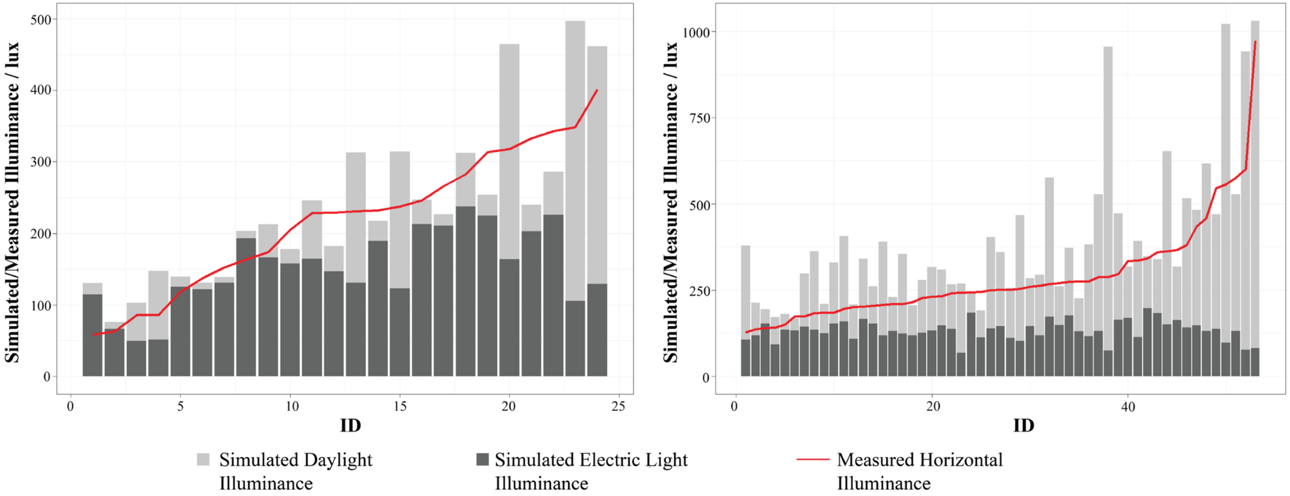
Resolving (most) modelling issues by comparing calibrated HDR images and simulated visualizations from the same viewpoint

Geraldine Quek



Scatter plots of measured vs simulated horizontal and vertical illuminance

Validation Results



Simulated daylight and electric light illuminances of Office 7 and 10 as stacked column plots, and field-measured horizontal illuminance as a red line

Validation Results

Suggestions when dealing with errors

1. Identify problematic data points (large discreet errors):
   resolve modelling issues depending on sources of error (daylight/electric lighting) *by comparing HDR images to visualizations*

2. Typical electric lighting modeling issues:
   missing luminaire fixtures, not coplanar with ceiling plane, incorrect luminous power

3. Typical daylighting related issues:
   adjustments of roller blind position and missing roller blinds were common modelling errors, or properties of rollerblinds (transmission and angular properties)

Still several limitations to proposed workflow… that can be improved

1. Difficulty in discerning source of modelling error as lighting measurements include contributions from both daylight and electric light concurrently
   (unless we ask the offices to turn lights off, which wasn't an option)

2. Roller blind statuses may be uncertain throughout the year
   (but can be further monitored/use blind control algorithms)

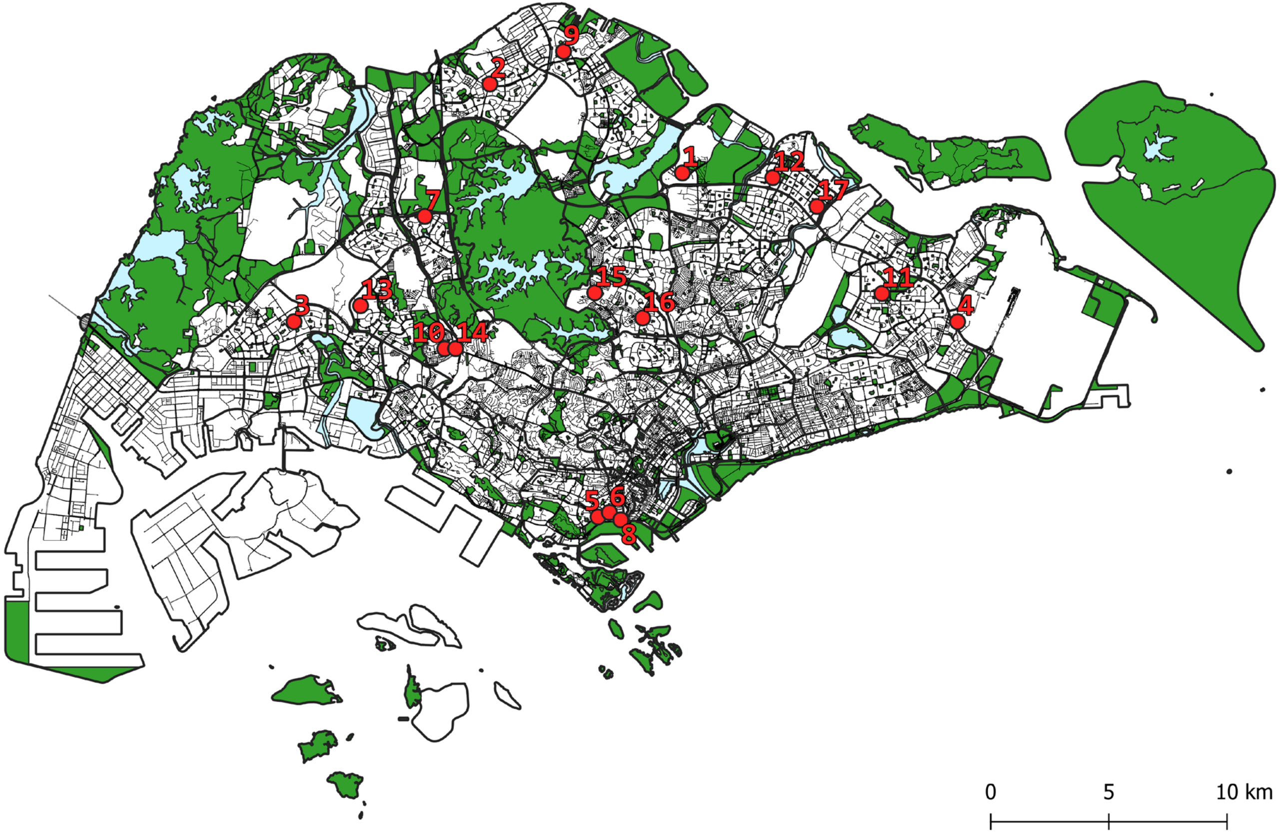
3. Difficulty in selecting IES photometric files
   (unknown luminaire models, proxy geometry unlike reality, maintenance cycles, …)

4. Difficult to obtain information of glazing transmittances and measuring roller blind transmittances / angular properties

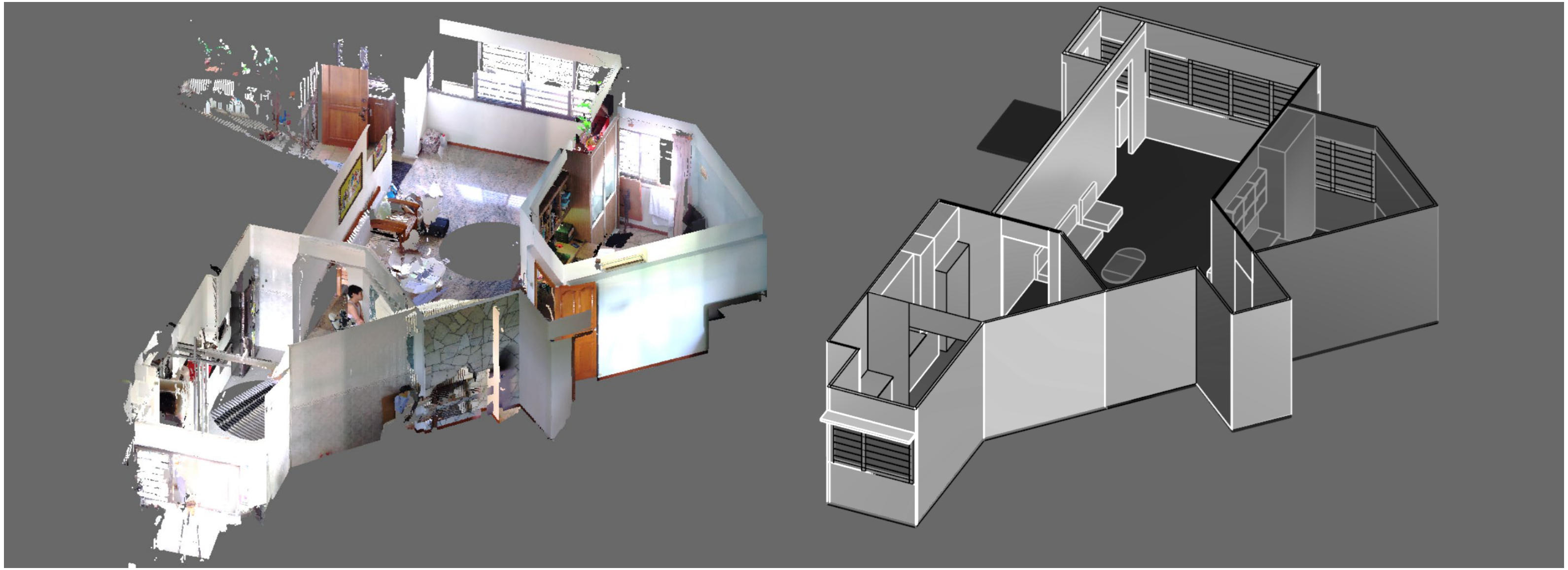
5. Location of weather-station can be far from the actual building (up to 25km away)
   (portable irradiance data loggers can be utilized during field measurement period)

Some practical limitations in modelling occupied spaces that must be accepted:

- variety monitor screen brightness (image, settings or turned off)
→ main cause of discrepancies in vertical illuminance
- variety of objects on a typical work desk

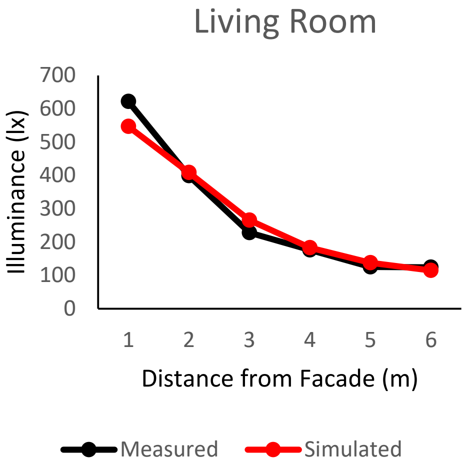


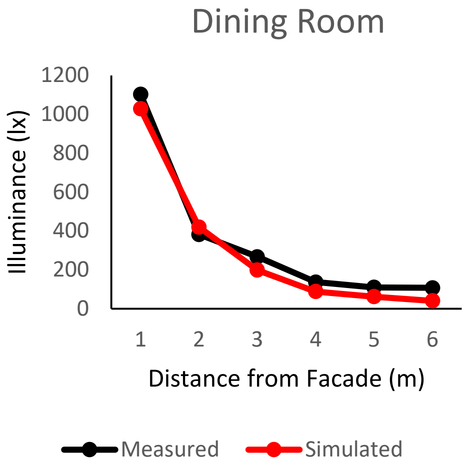
Location of 17 studied residences in Singapore;
Models were calibrated based on the nearest public weather station's irradiance data.



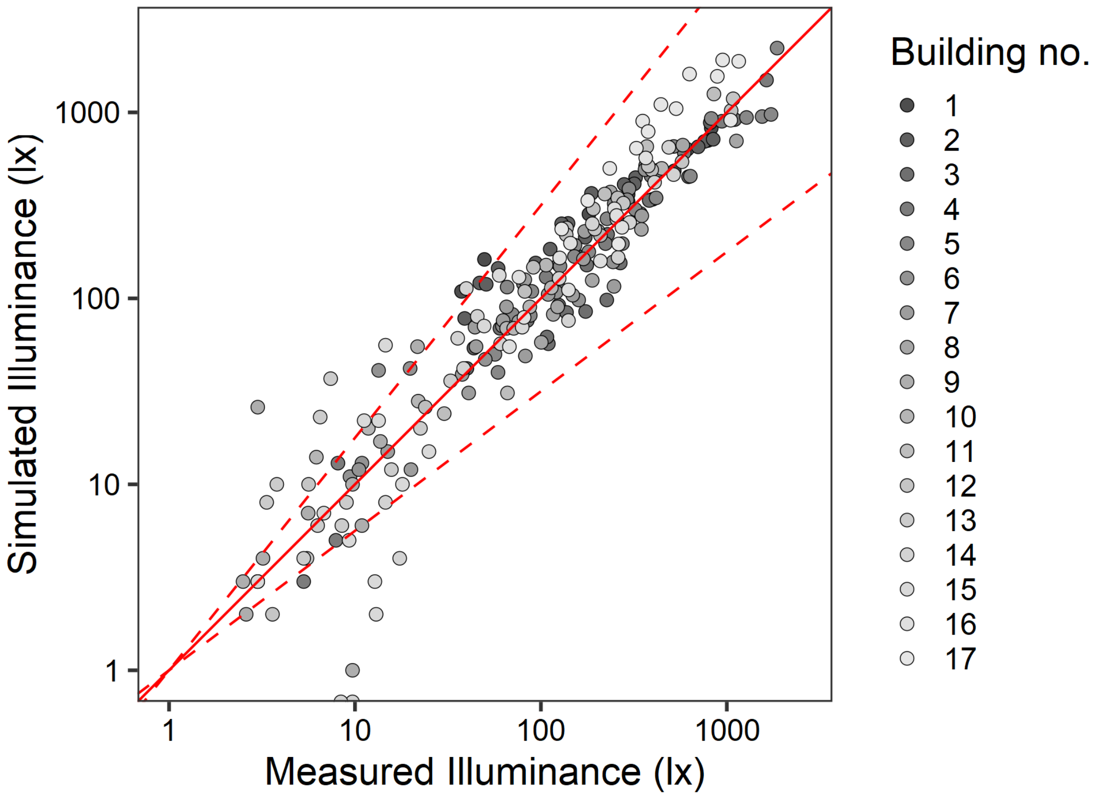
3D Scan and model of a single studied unit. Note the amount of furniture!

Furniture / stuff in residential models: Some more examples



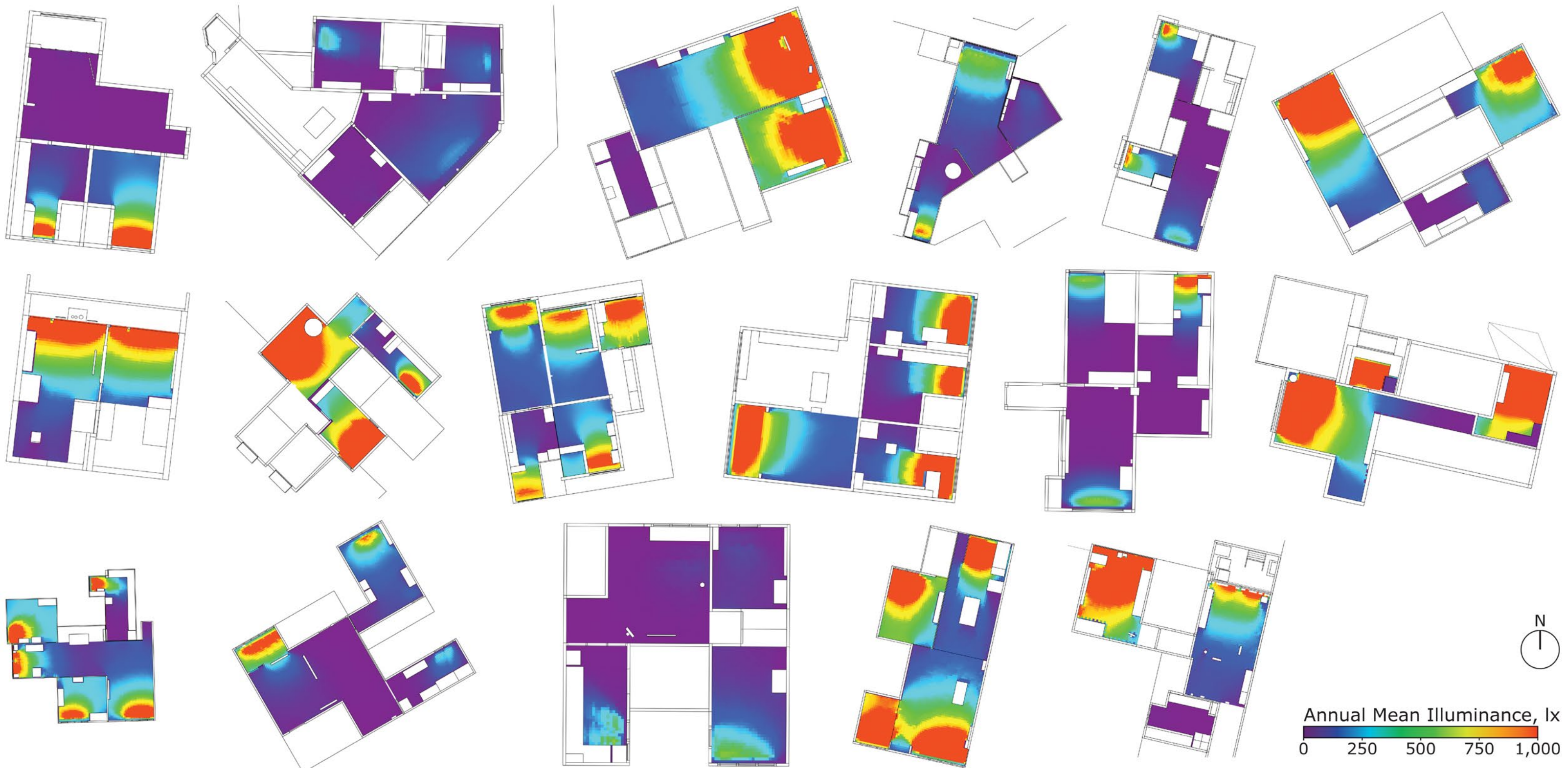


Measurements were taken every 1 m along a window centerline for validation



RMSE = 168.2 lx
MBE = 31.6 lx

Measured vs. simulated illuminance for 17 residential units



17 calibrated residential models, mean annual illuminance of studied spaces

Daylight Model Calibration for POE Studies Towards Subjective Metrics in the Tropics

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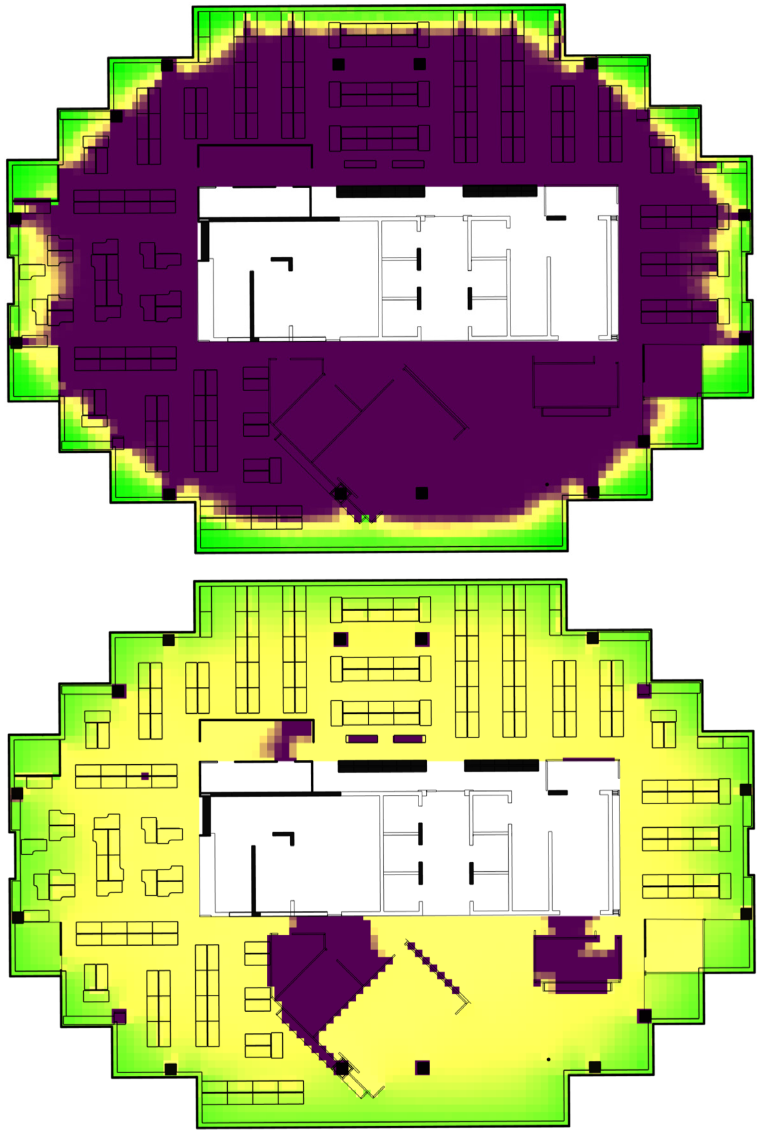
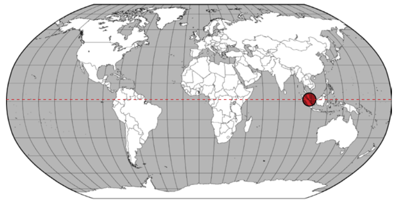
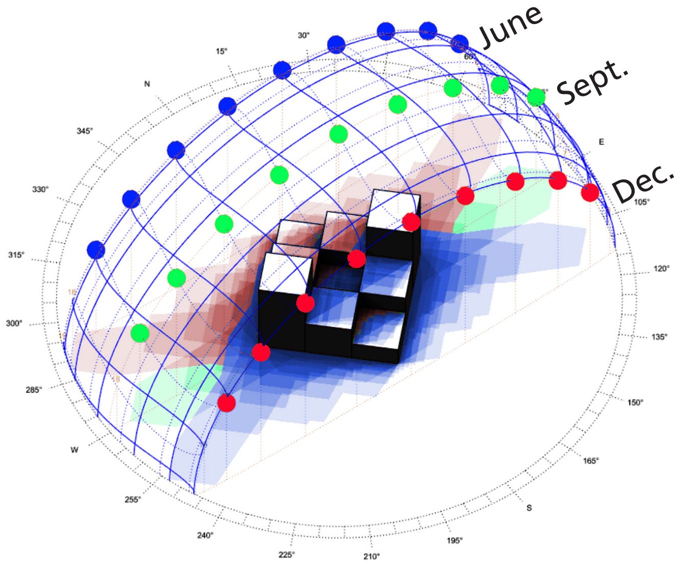
1. University of Toronto
2. École Polytechnique Fédérale de Lausanne
3. Meiji University
4. Southeast University
5. Loughborough University



Before we begin, a note on the climate of Singapore...



1.34 °N, 103.84 °E

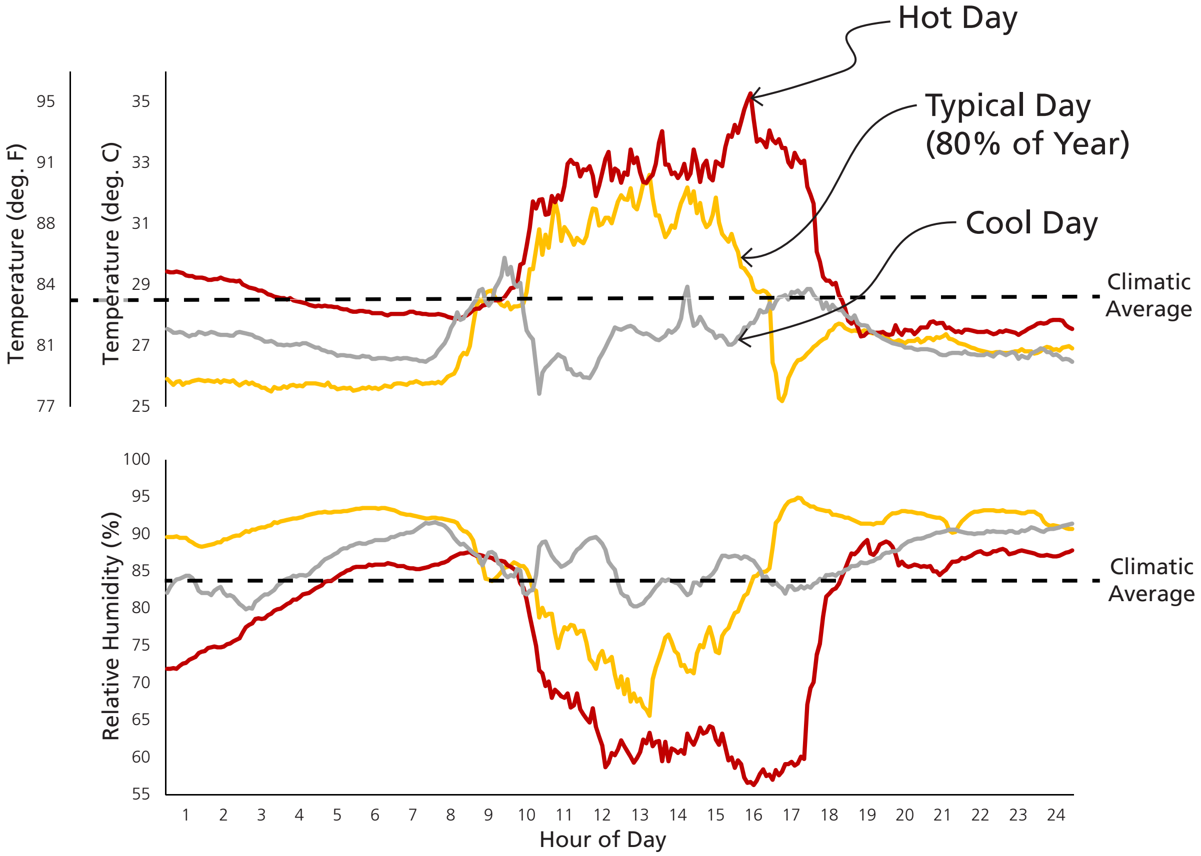


Sunpath and Shadows

- The path of the sun is predominantly east to west, high altitude, and overhead.

Wind Velocity

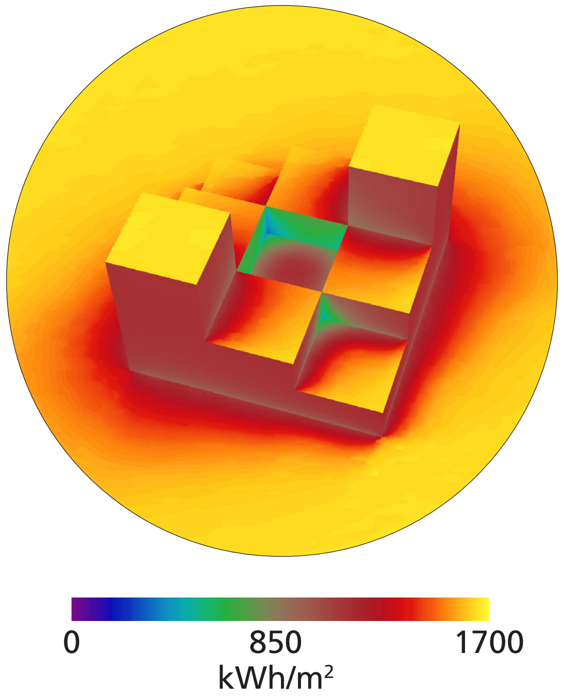
- Averages 2.2 m/s during the year.



Typical Daily Temperature and Humidity Patterns

- The weather is hot and humid year-round.
- A cool evening is about 26 °C. A hot day is about 35 °C.
- The annual average relative humidity is 83%.

31.4% Direct Irradiation
68.6% Diffuse Irradiation

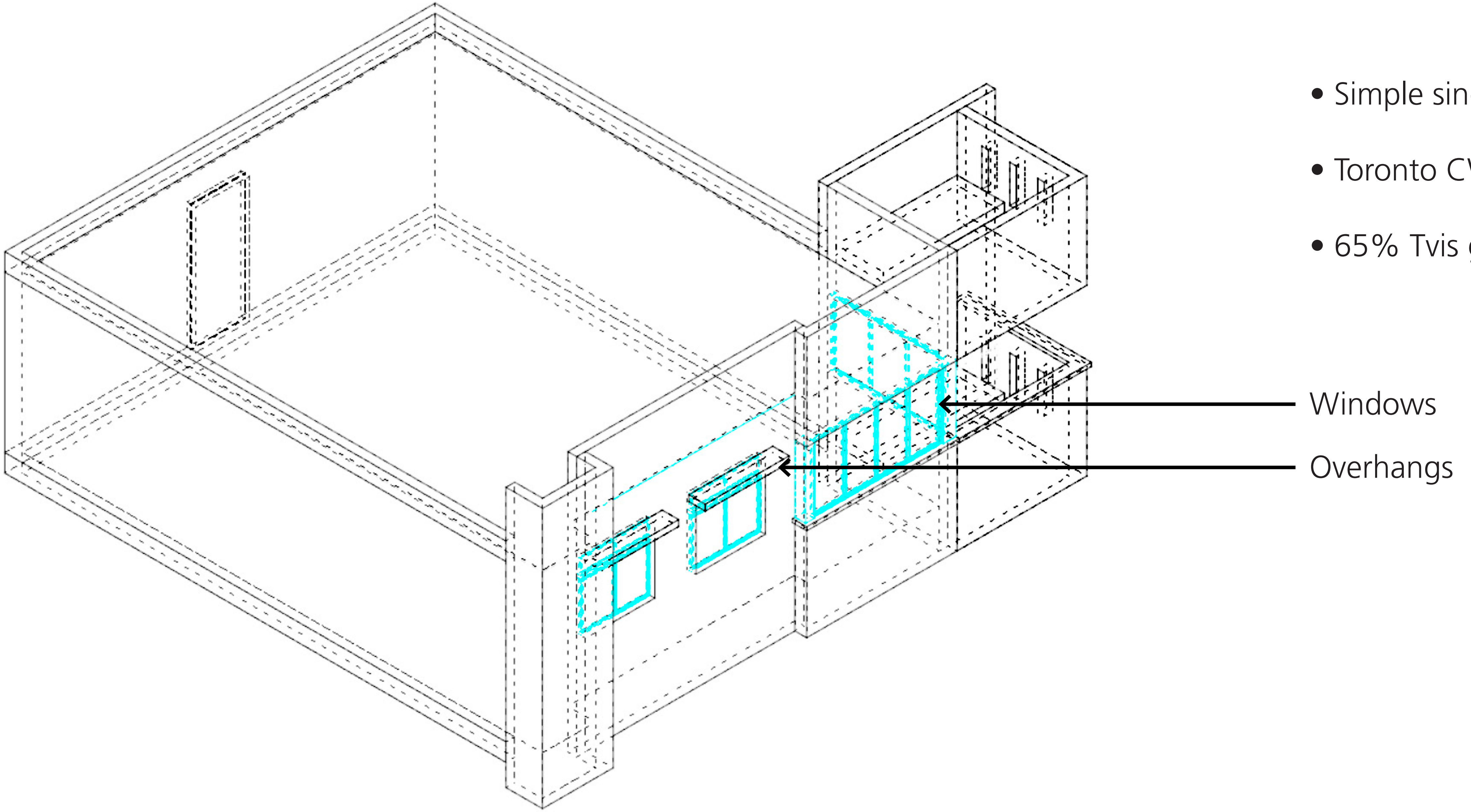


Annual Solar Irradiation

- A horizontal surface receives around 1650 kWh/m^2 irradiation per year of mostly diffuse light.
- The predominant sky condition is intermediate / partly cloudy.

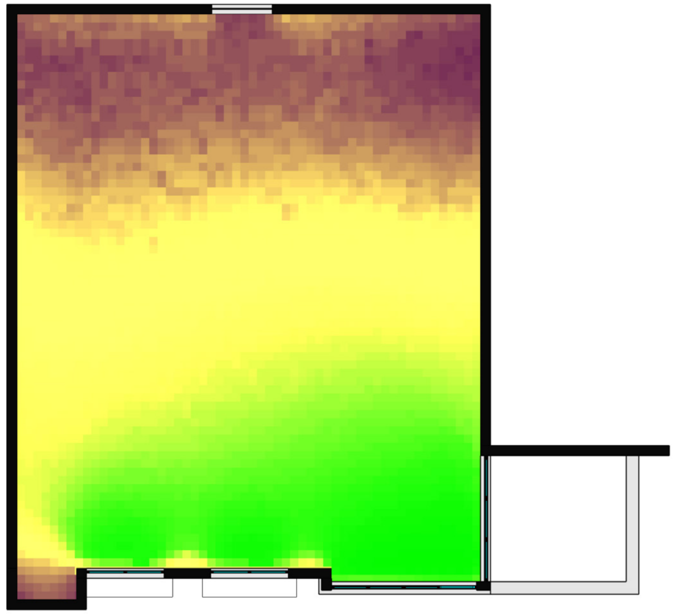
CBDM overview

Comparison of CBDM's—Baseline calculation model



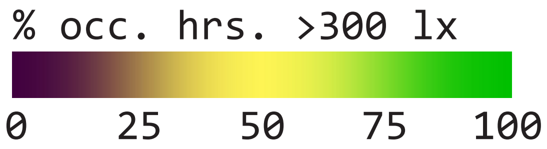
- Simple single-room model
- Toronto CWEC climate file
- 65% Tvis glazing

Daylight Autonomies: DA, CDA, & sDA



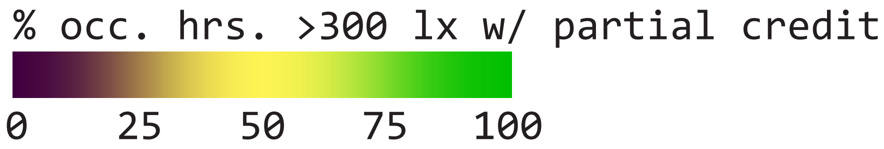
Daylight Autonomy 300 lx

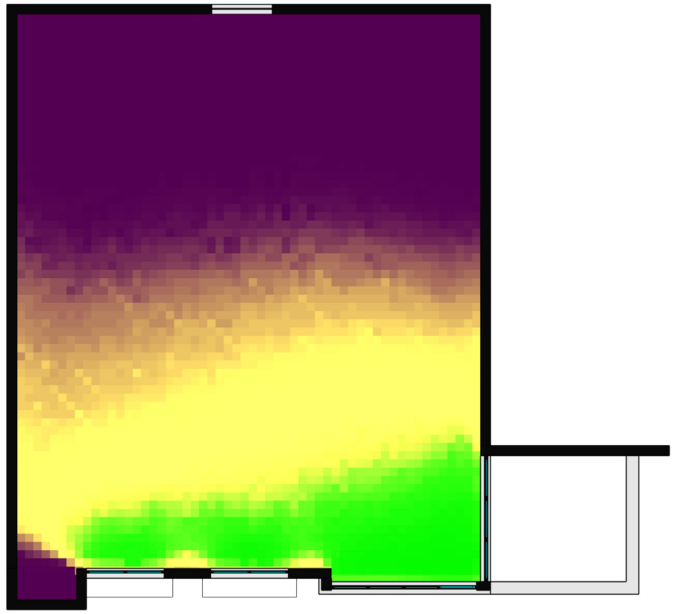
(Reinhart, Mardaljevic, Rogers 2006)



Continuous Daylight Autonomy 300 lx

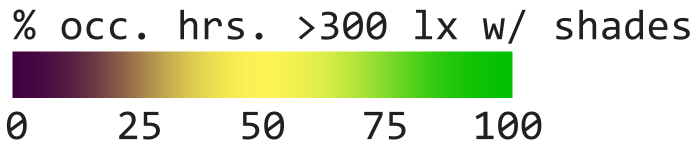
(Rogers and Goldman 2006)



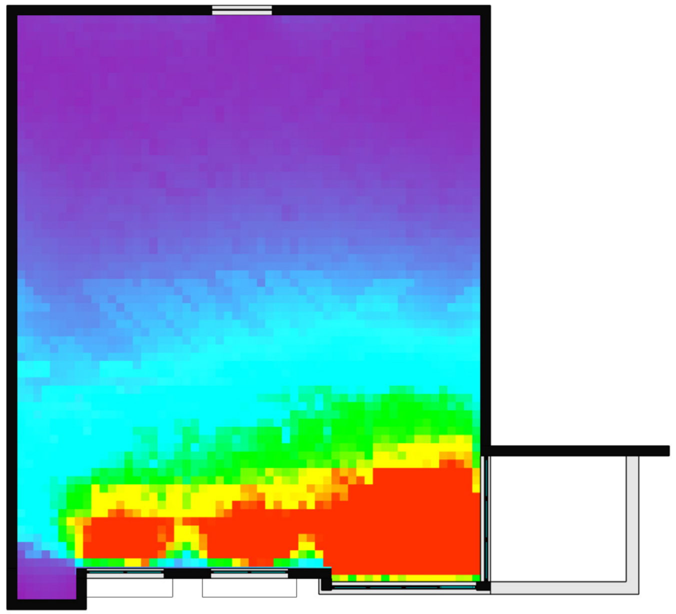


Spatial Daylight Autonomy 300 lx

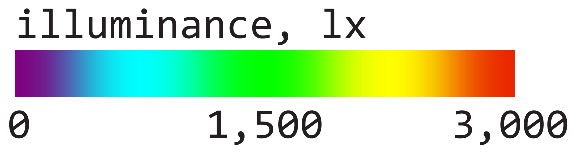
(IES LM-83 2012)

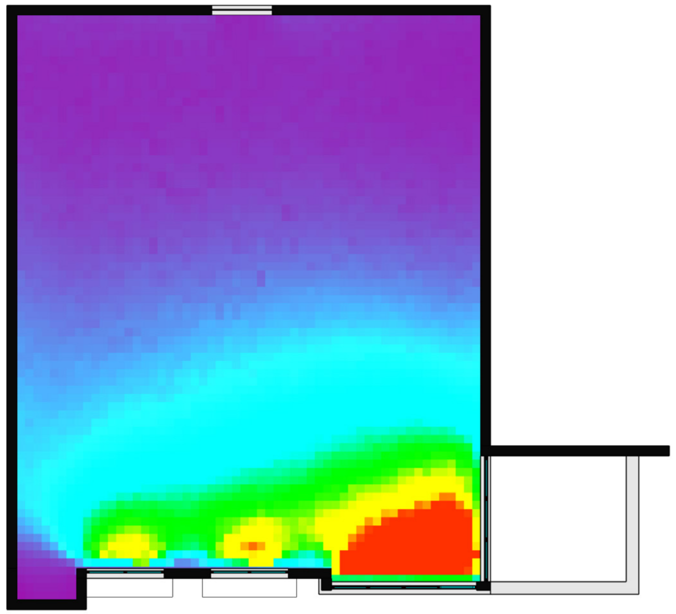


Mean & median illuminance

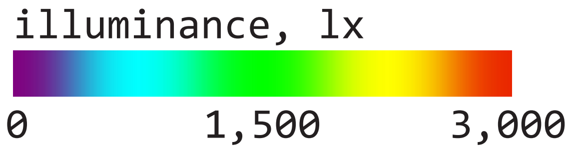


Mean Occupied Illuminance (lx)

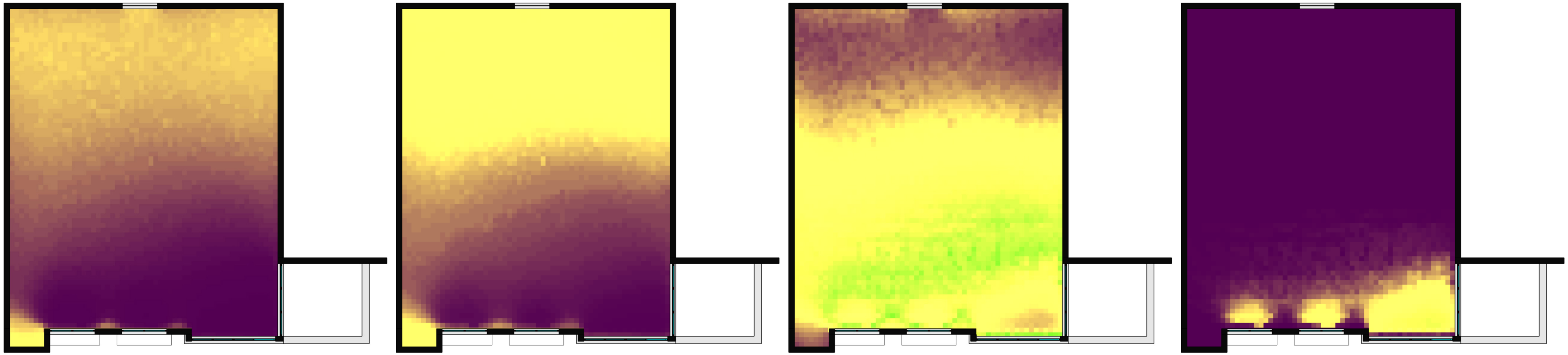




Median Occupied Illuminance (lx)



Useful Daylight Illuminances (UDI)

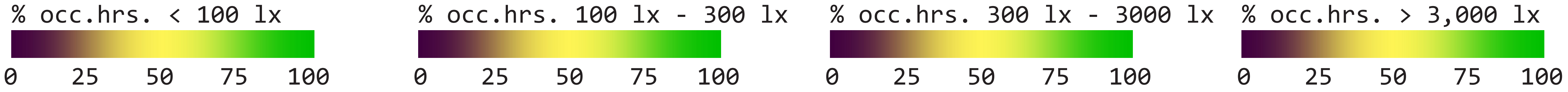


UDI f
(fell short, <100 lx)
(Nabil and Mardaljevic 2006)

UDI s
(supplemental, 100 lx-300 lx)

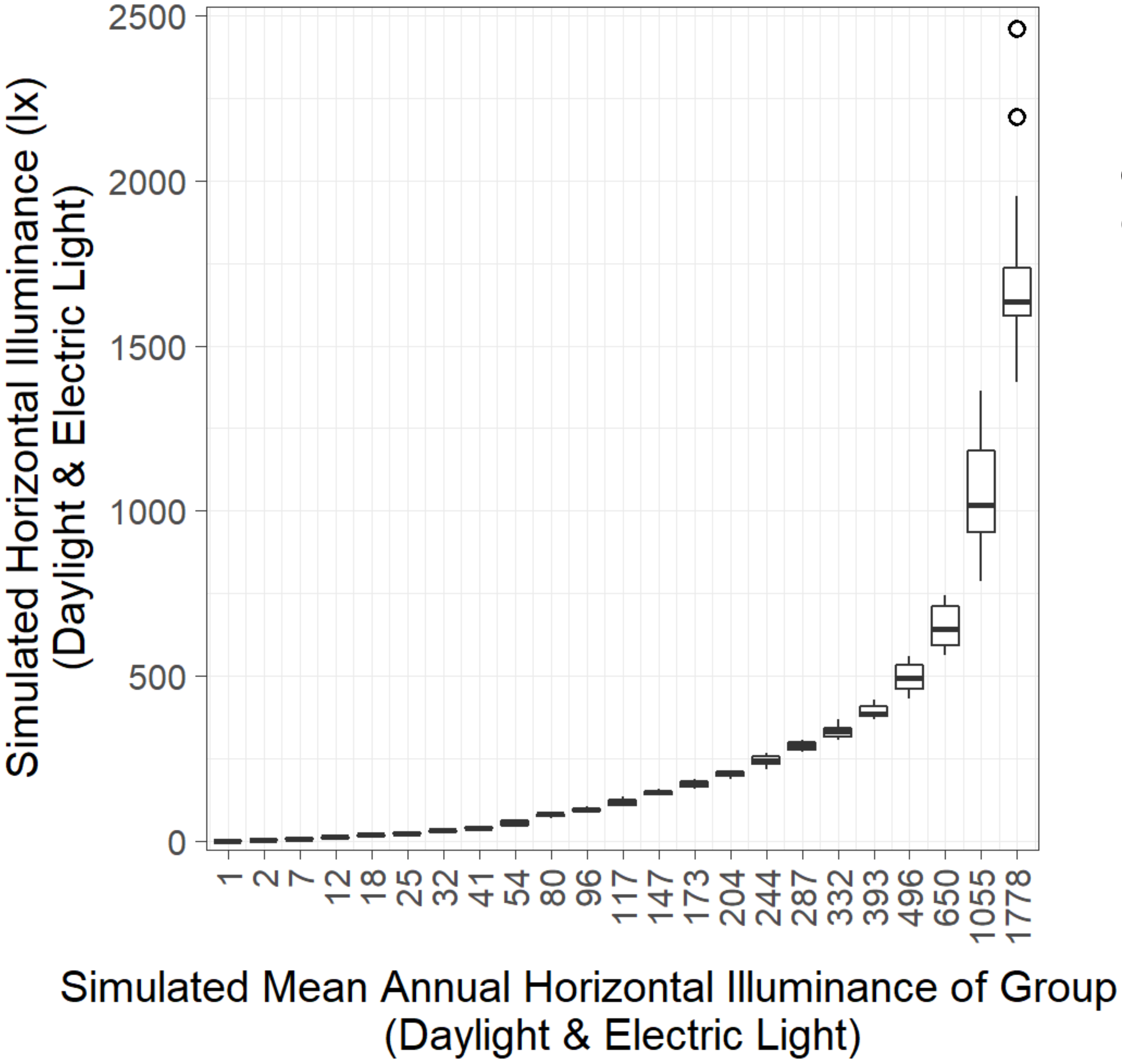
UDI a
(autonomous, 300 lx-3,000 lx)

UDI e
(exceeded, >3,000 lx)



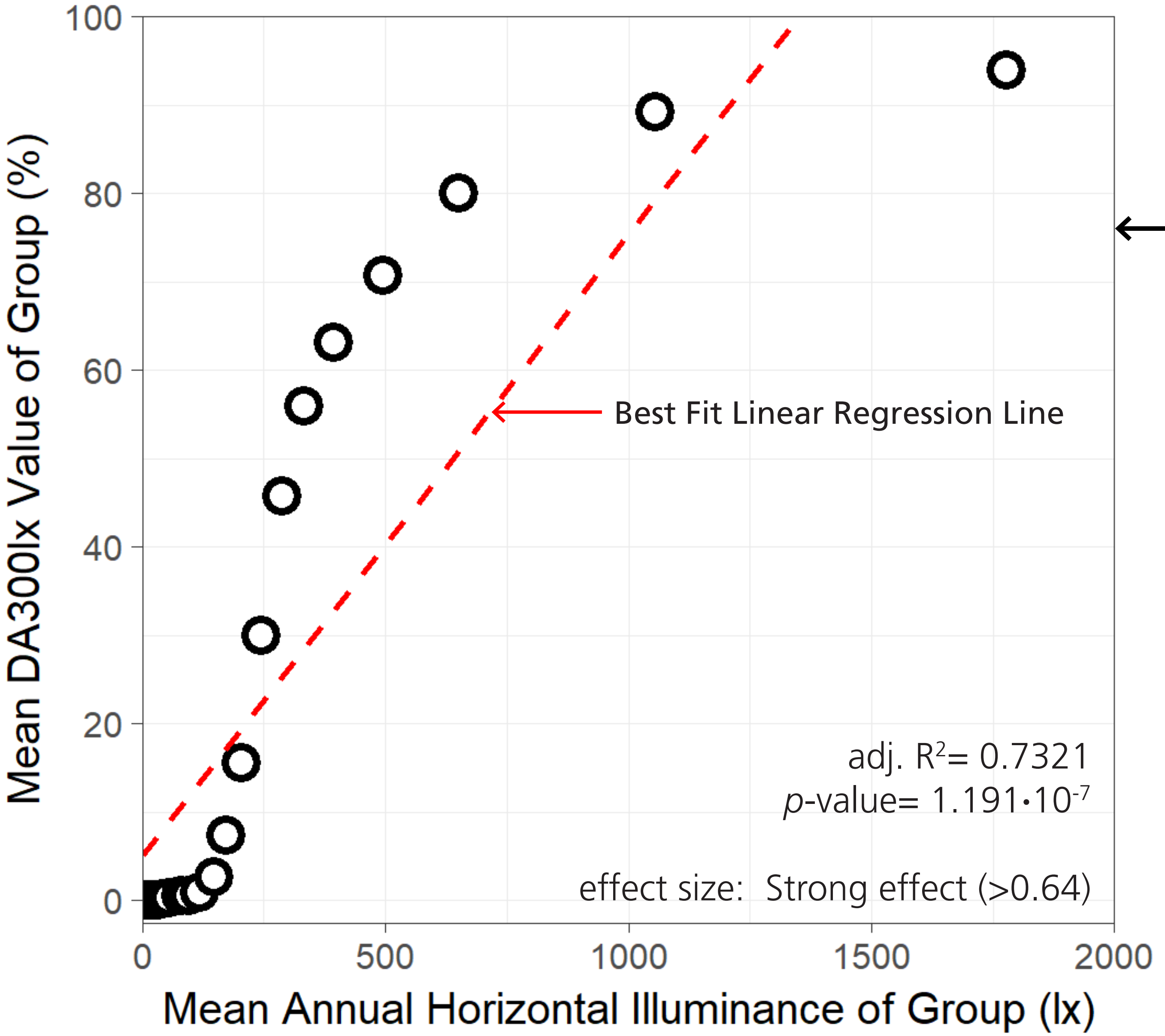
Office: Brief methods and results

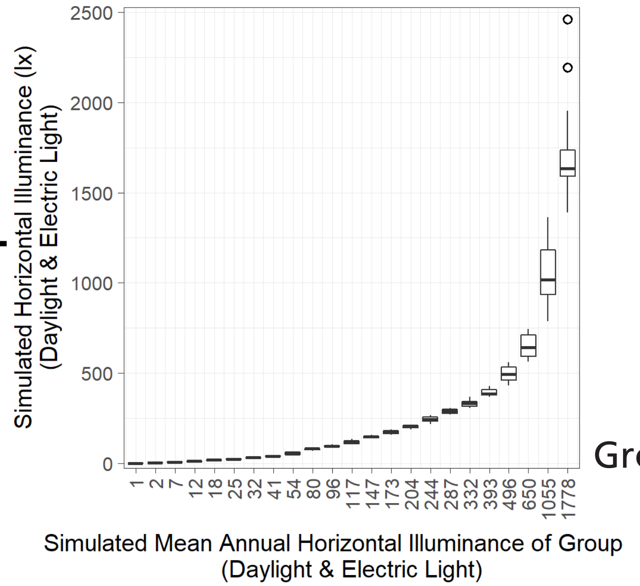
Grouping data by predictor variables



- First, simulated data is grouped based on a predictor variable.
- Group number and size are always based on the square root of the sample size. $\sqrt{543} \approx 23$, so we have 23 groups based on quantile cuts of the predictor variable.

Survey data is correlated with simulated results





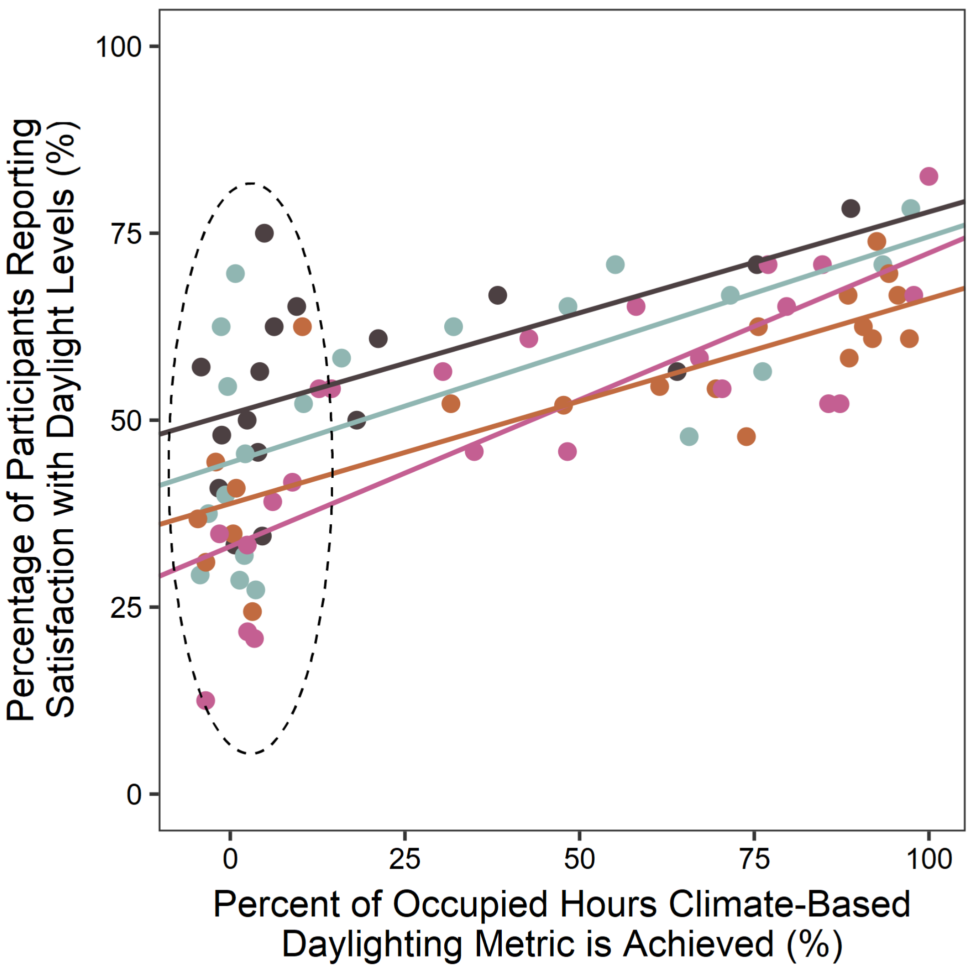
Grouped Data

- Based on the grouped predictor variable, statistics from the rest of the data are computed per group.

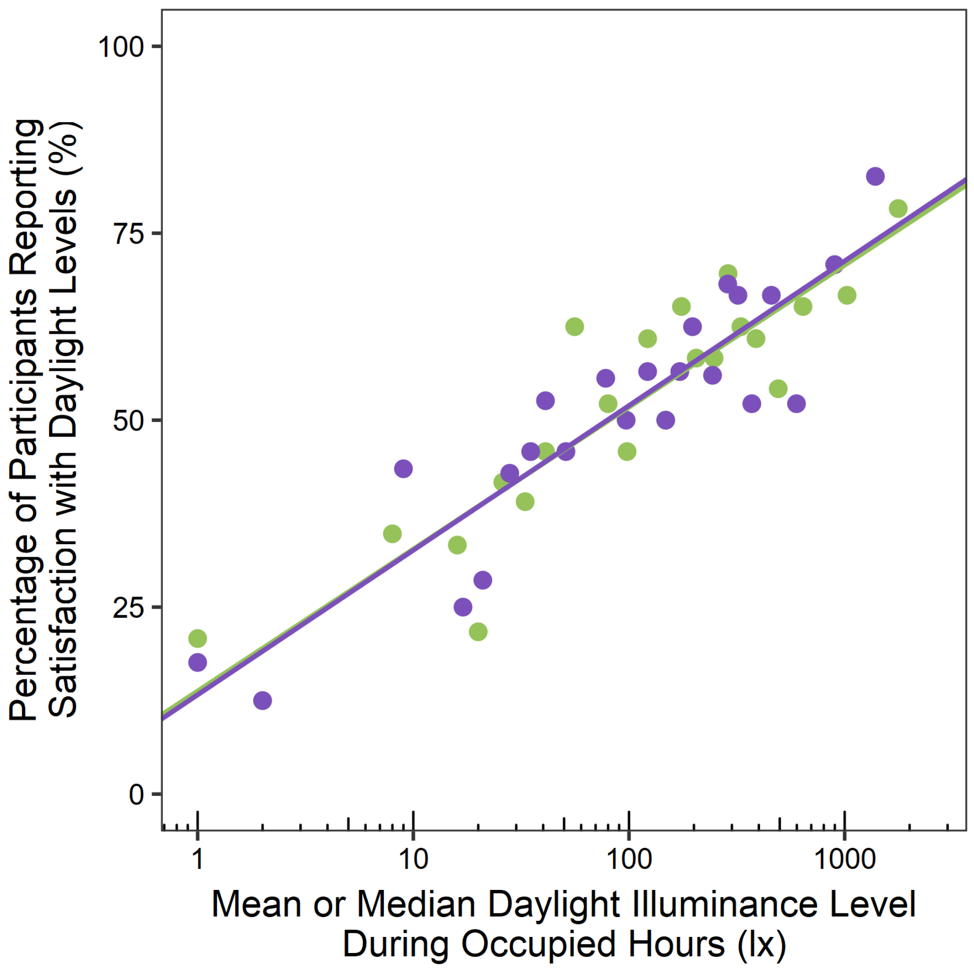
- Simple regression analysis is applied. The adjusted R^2 (effect size) and *p*-value (probability of a false conclusion) are calculated.

- These statistics are currently in the process of being refined to remove grouping; however, at the Radiance Workshop we can share some results and reflect on their meaning.

Reporting satisfaction with access to daylight



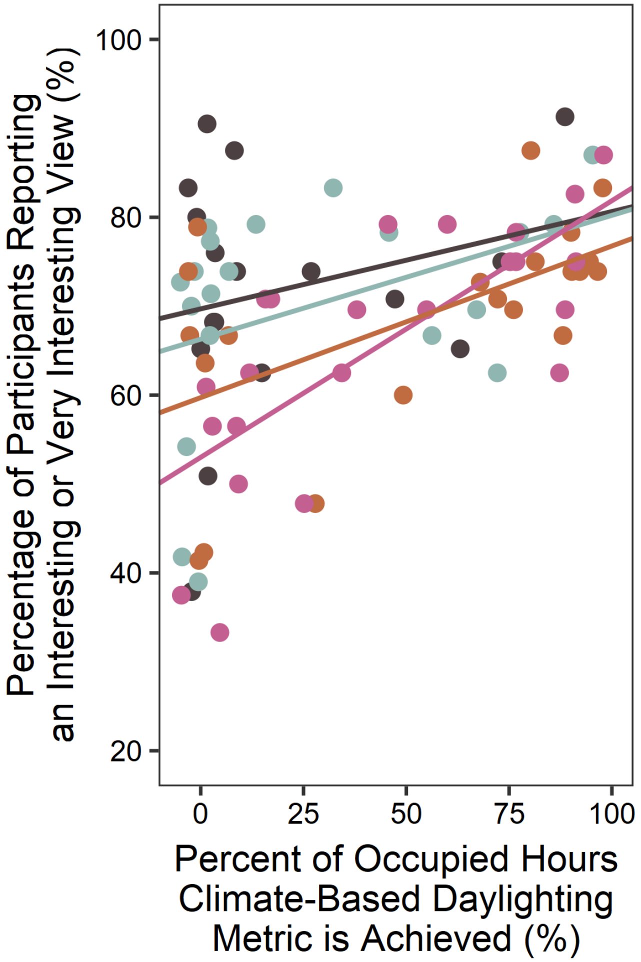
- DA500 lx
  adj. R^2 0.3249, p-value 0.0010
- DA300 lx
  adj. R^2 0.4032, p-value 0.0016
- CDA300 lx
  adj. R^2 0.6190, p-value $5.14 \cdot 10^{-6}$
- UDIc = UDIs + UDIa
  adj. R^2 0.6593, p-value $4.76 \cdot 10^{-6}$



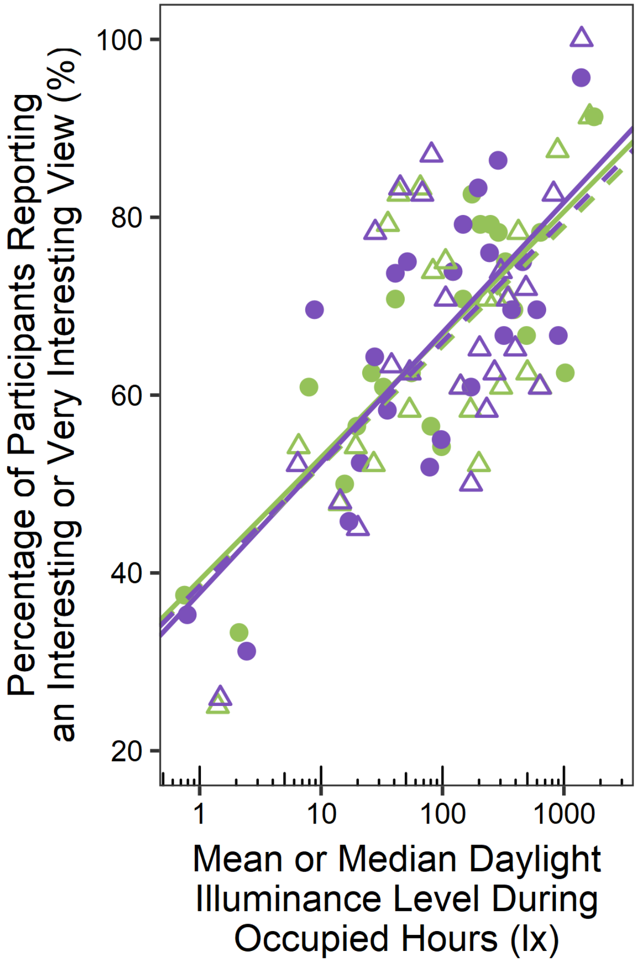
- Mean Daytime Illuminance
  adj. R^2 0.8216, p-value $1.58 \cdot 10^{-9}$
- Median Daytime Illuminance
  adj. R^2 0.8149, p-value $2.34 \cdot 10^{-9}$

- Traditional CBDM's (DA, CDA, UDI) correlate well with reported satisfaction, especially when the CBDM > 25% occupied hours.
- Log10(mean) and log10(median) illuminance correlate very strongly (adj. $R^2 > 0.8$), partially because they represent daylighting differences below the CBDM thresholds of 100 lx, 300 lx, and 500 lx.
- Looking at the dashed line on the traditional CBDM chart, this difference is very apparent.

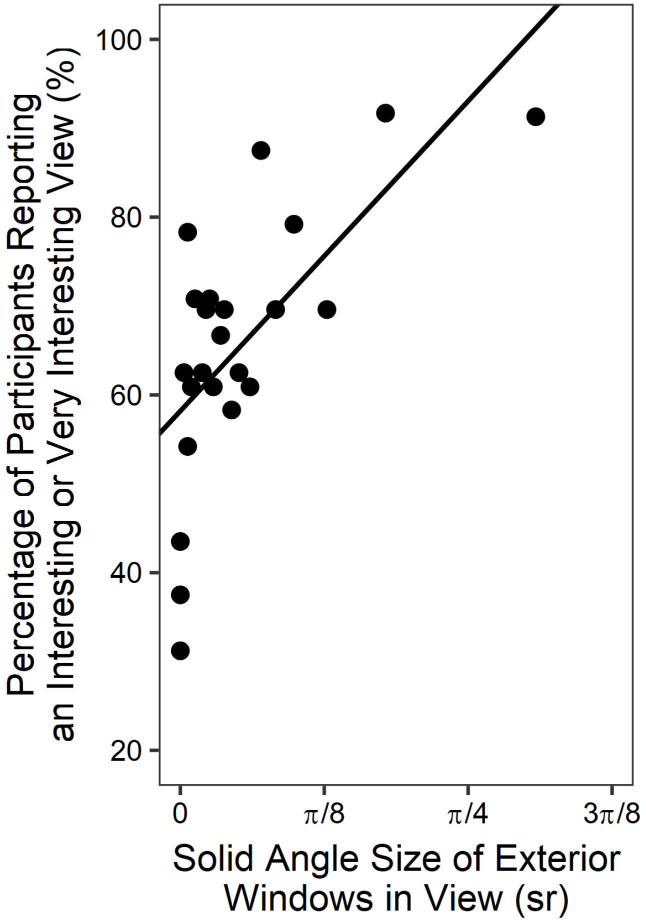
Reporting of an interesting or very interesting view



- DA500 lx
  adj. R^2 -0.0067, p-value 0.3599
- DA300 lx
  adj. R^2 0.1011, p-value 0.0935
- CDA300 lx
  adj. R^2 0.5245, p-value $5.63 \cdot 10^{-5}$
- UDIc = UDIs + UDIa
  adj. R^2 0.2872, p-value 0.0072



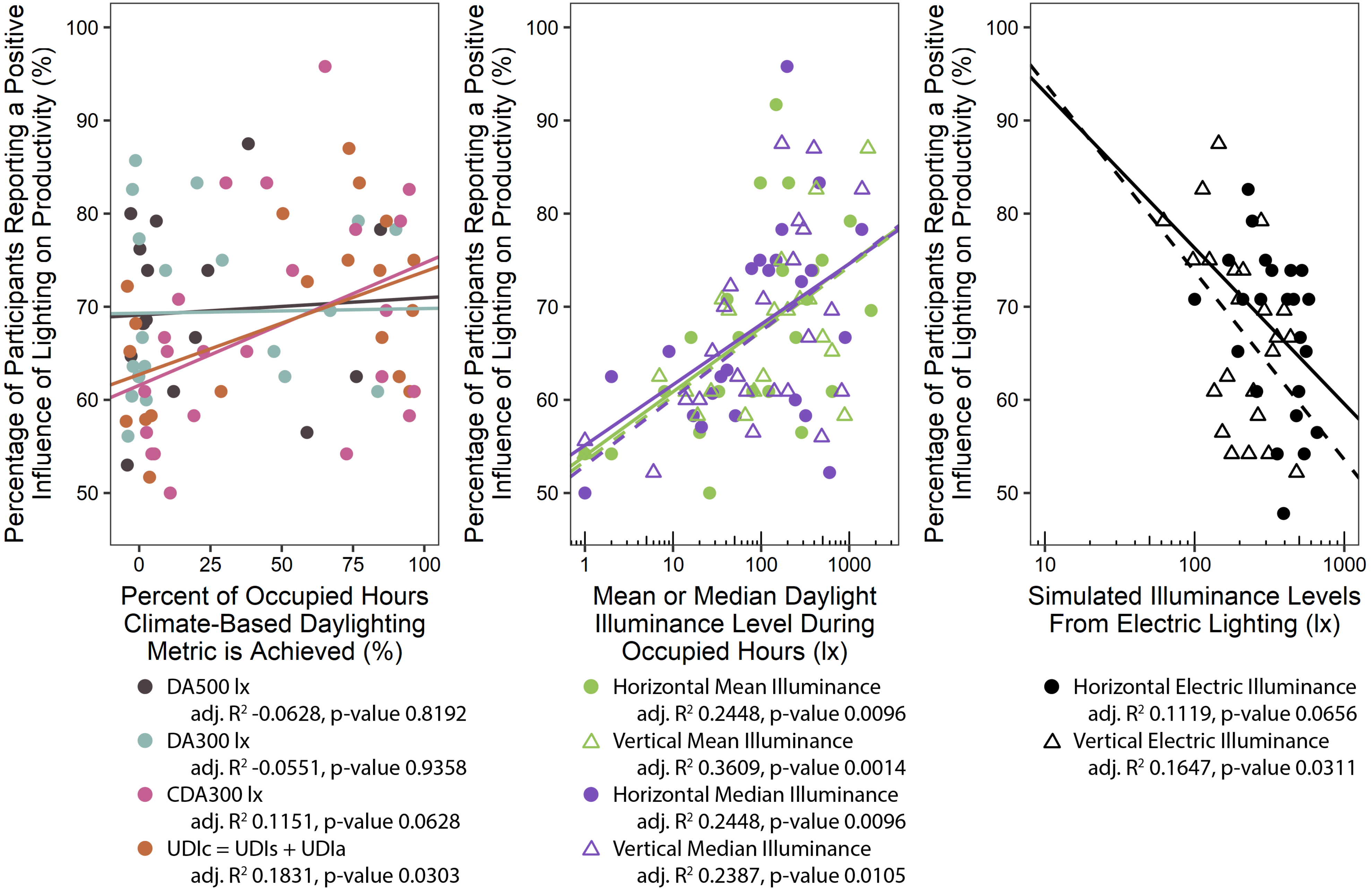
- ● Horizontal Mean Illuminance
  adj. R^2 0.6581, p-value $1.61 \cdot 10^{-6}$
- △ Vertical Mean Illuminance
  adj. R^2 0.3883, p-value 0.0009
- ● Horizontal Median Illuminance
  adj. R^2 0.5480, p-value $3.25 \cdot 10^{-5}$
- △ Vertical Median Illuminance
  adj. R^2 0.3440, p-value 0.0019



adj. R^2 0.4098, p-value 0.0006

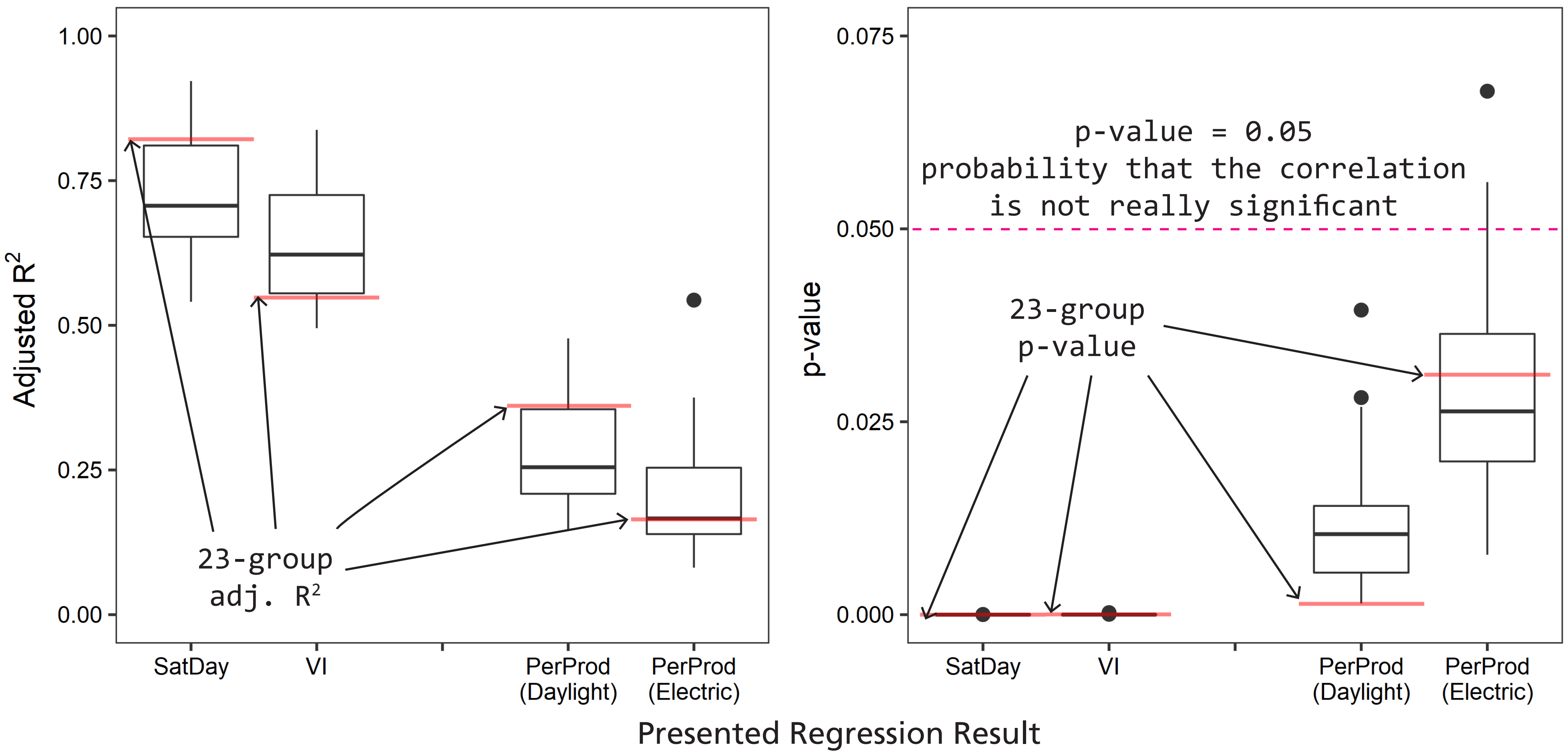
- Besides CBDM's, we add one more predictor here—the view to windows in solid angle steradian (sr).
- High-illuminance threshold CBDM's (DA500 lx, DA300 lx) work poorly here.
- CDA does a good job of correlating with the subjective response of an
- Mean illuminance has the best correlation however (adj. R^2 ~ 0.65), better than the actual view to windows.

Self-reported positive influence on lighting on productivity



- Besides CBDM's, we also add one more predictor here—the illuminance from electric lighting.
- adj. R^2 values are overall less when correlating with reported productivity, with the best correlations being around 0.35.
- But most interesting is that daylight illuminance has a clear positive and significant (p-value < 0.05) correlation while electric illuminance has a negative correlation.

Reliability of results—Changing the group size



- We changed the group size for analysis from 23 to a range from between 10 and 35 to estimate the impact of correlation coefficients and significance, since many other studies use grouping methods for analysis (see DGP, Hirning et al.'s work).

- adj. R^2 varies within a range of ~40% per metric.

- p-values can vary up to 0.06 in the case of loosely-correlated metrics like electric lighting's impact on productivity.

- My argument: Almost all of the p-values are still below 0.05, so the results are real, but it is possible to 'hack' your R^2 without much effort...

Thinking about thresholds for lighting design

300 lx / 500 lx

Daylight Autonomy 300 lx

(21.8% Daylit / DA300lx,50%)

% occ. hrs. >300 lx

0 25 50 75 100

Thinking about thresholds for lighting design

300 lx / 500 lx	**100 lx** (51.7% satisfaction rate)

Daylight Autonomy 300 lx

(21.8% Daylit / DA300lx,50%)

% occ. hrs. >300 lx

0 25 50 75 100

Satisfaction with Daylight

(45.8% occupants satisfied)

% satisfied with daylight

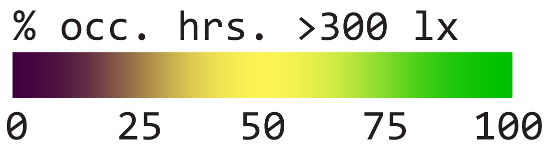
0 25 50 75 100

Thinking about thresholds for lighting design

300 lx / 500 lx

Daylight Autonomy 300 lx

(21.8% Daylit / DA300lx,50%)

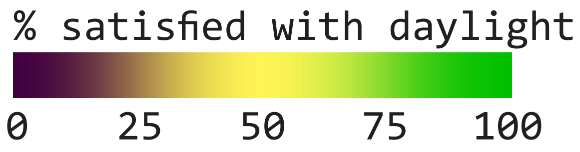


100 lx

(51.7% satisfaction rate)

Satisfaction with Daylight

(45.8% satisfied)

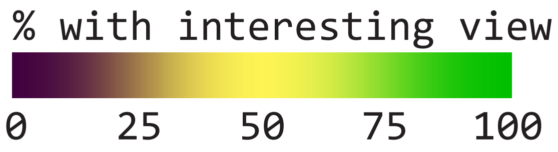


100 lx

(66.8% interest rate)

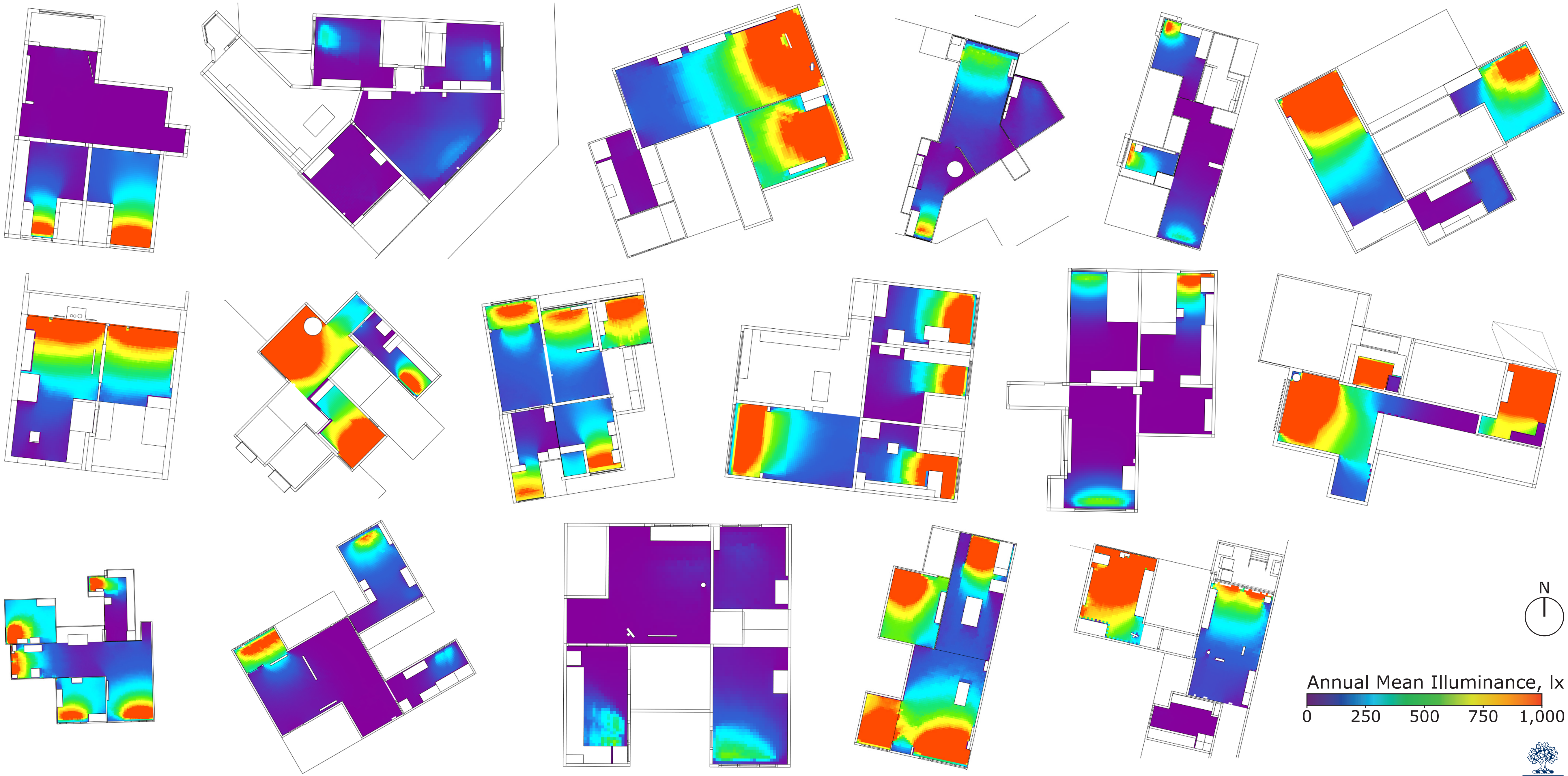
Interesting View

(60.6% view interest)



Residential: Introduction

Reminder, 17 units, 35 participants, 53 rooms



Data collection methodology

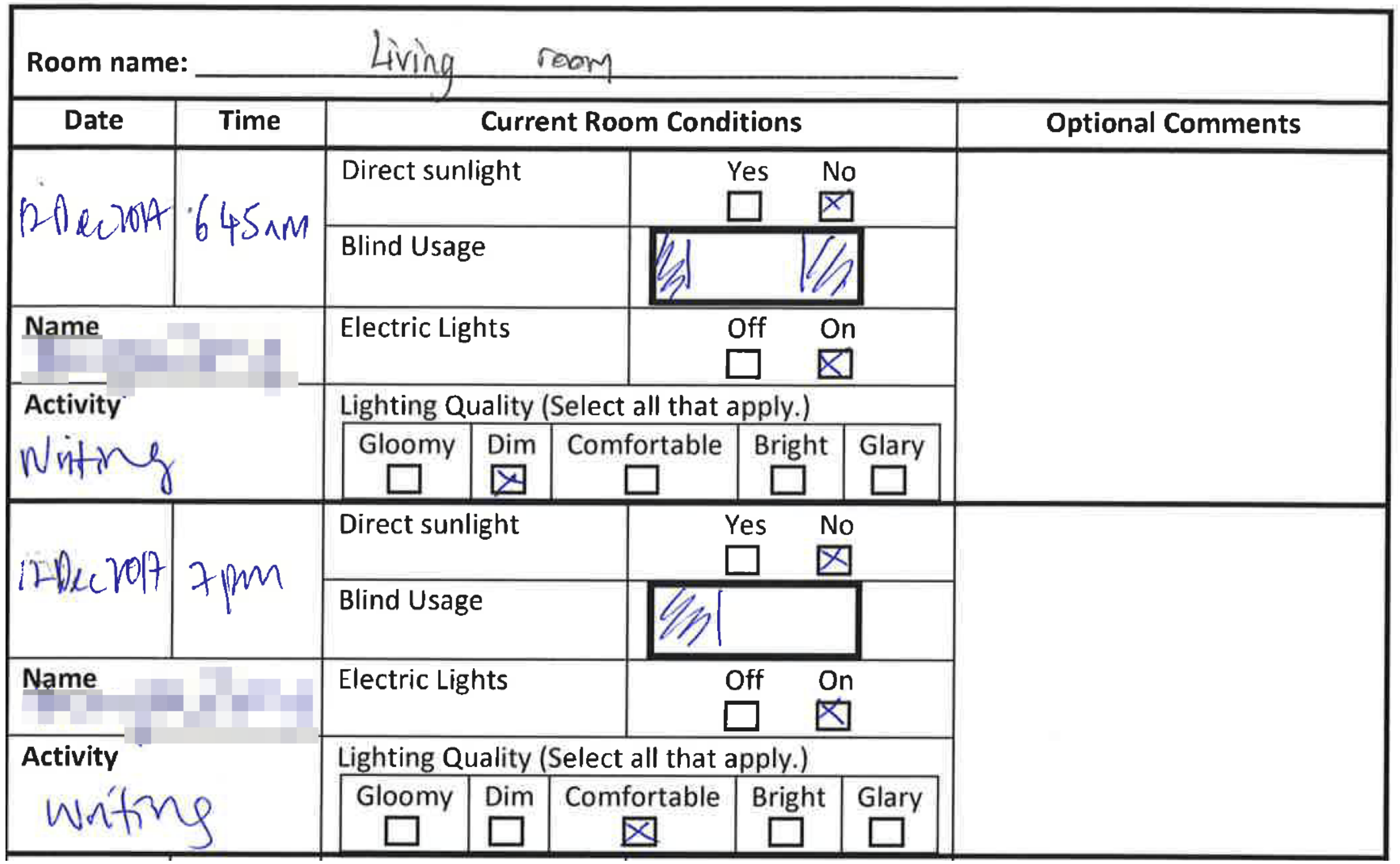
Two household visits:

(1) <u>Initial visit</u>
- Measure building and photometric properties
- Explain the study and ask permission
- Leave 'lighting journals' in each room to-be studied

(2) <u>One week (or more) later</u>
- Collect lighting journal data
- Engage participants in a long form survey (~30 minutes)
- Pay $50/person for participation

- We collected more data per household due to the necessarily smaller sample size.

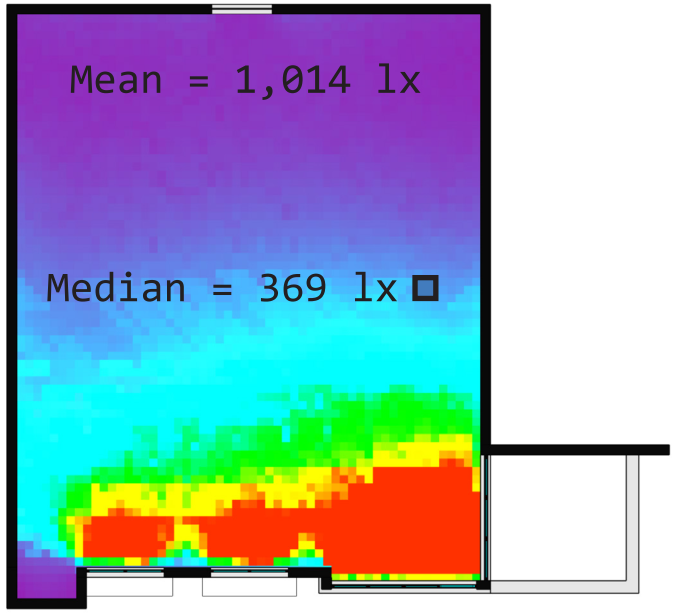
- 17 households
- n=35 participants



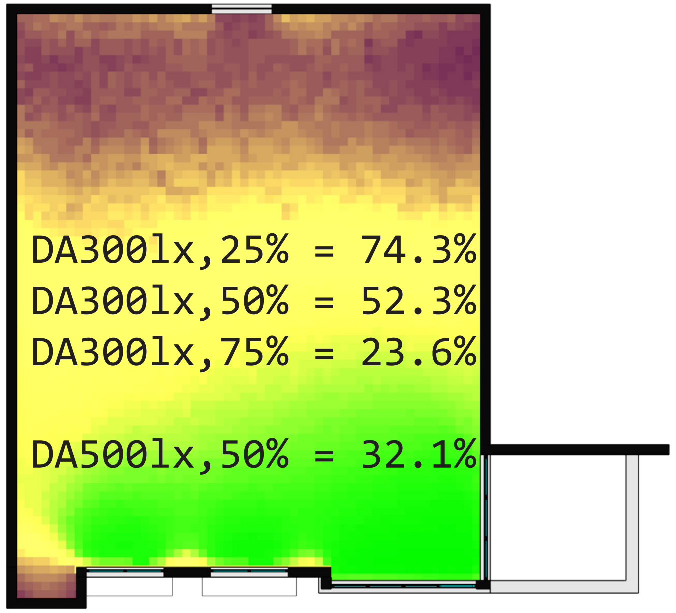
Room name: Living room

Date	Time	Current Room Conditions		Optional Comments
12 Dec 2017	6 45 AM	Direct sunlight	Yes ☐ No ☒	
		Blind Usage		
Name		Electric Lights	Off ☐ On ☒	
Activity: Writing		Lighting Quality (Select all that apply.) Gloomy ☐ Dim ☒ Comfortable ☐ Bright ☐ Glary ☐		
12 Dec 2017	7pm	Direct sunlight	Yes ☐ No ☒	
		Blind Usage		
Name		Electric Lights	Off ☐ On ☒	
Activity: writing		Lighting Quality (Select all that apply.) Gloomy ☐ Dim ☐ Comfortable ☒ Bright ☐ Glary ☐		

Calculating spatial metrics

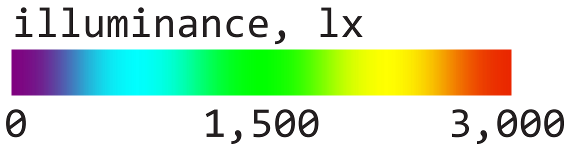


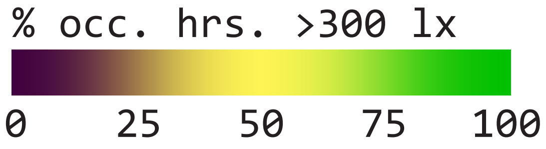
Mean Occupied Illuminance (lx)



Daylight Autonomy 300 lx

(Reinhart, Mardaljevic, Rogers 2006)

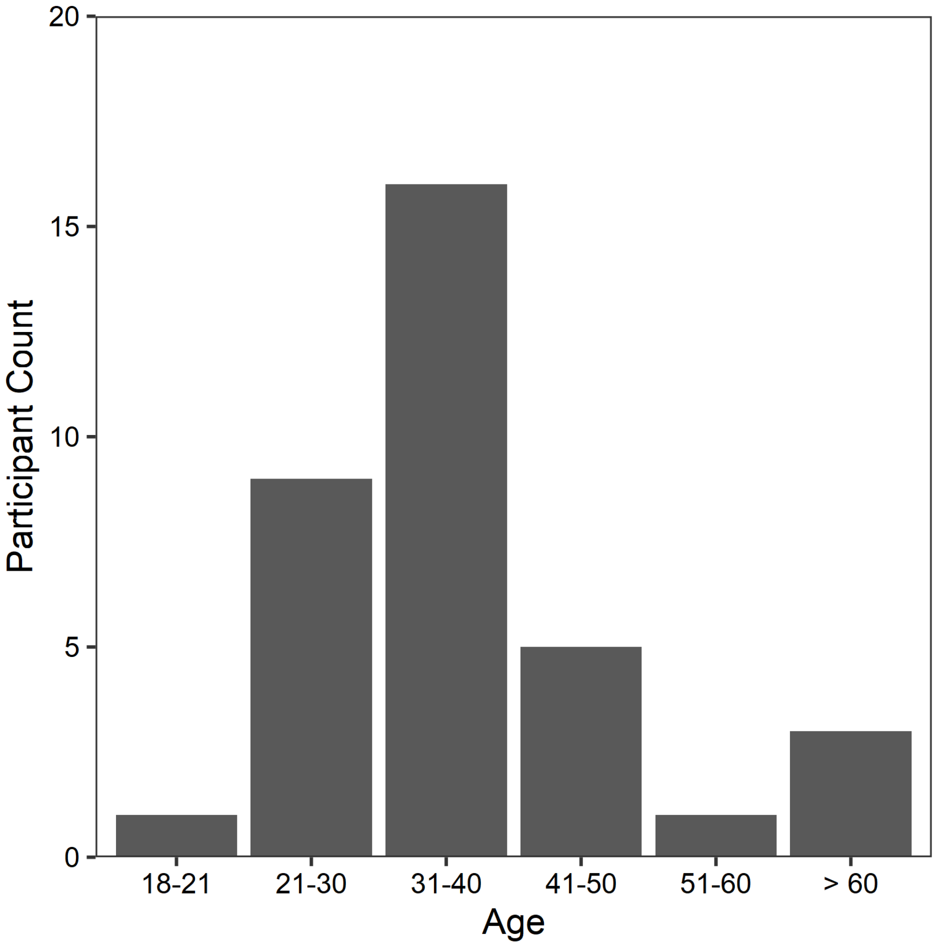


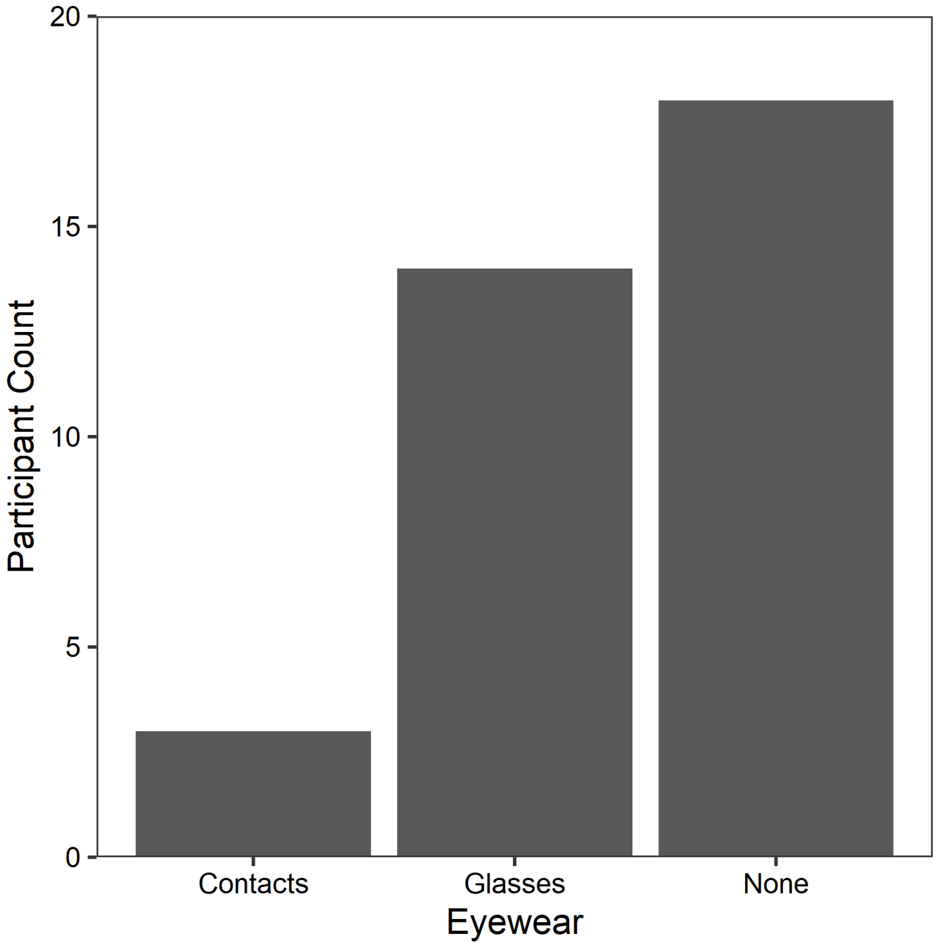


- Unlike the office study, in residences people don't have a relatively fixed position!
- When calculating spatial metrics, we use the percentile over a certain threshold, i.e. sDA300lx,50%, following the IES, LEED, etc.
- For the mean and median values of a space, the temporal mean of all sensors is calculated before extracting a spatial mean and median.

(One could argue this is not ideal.)

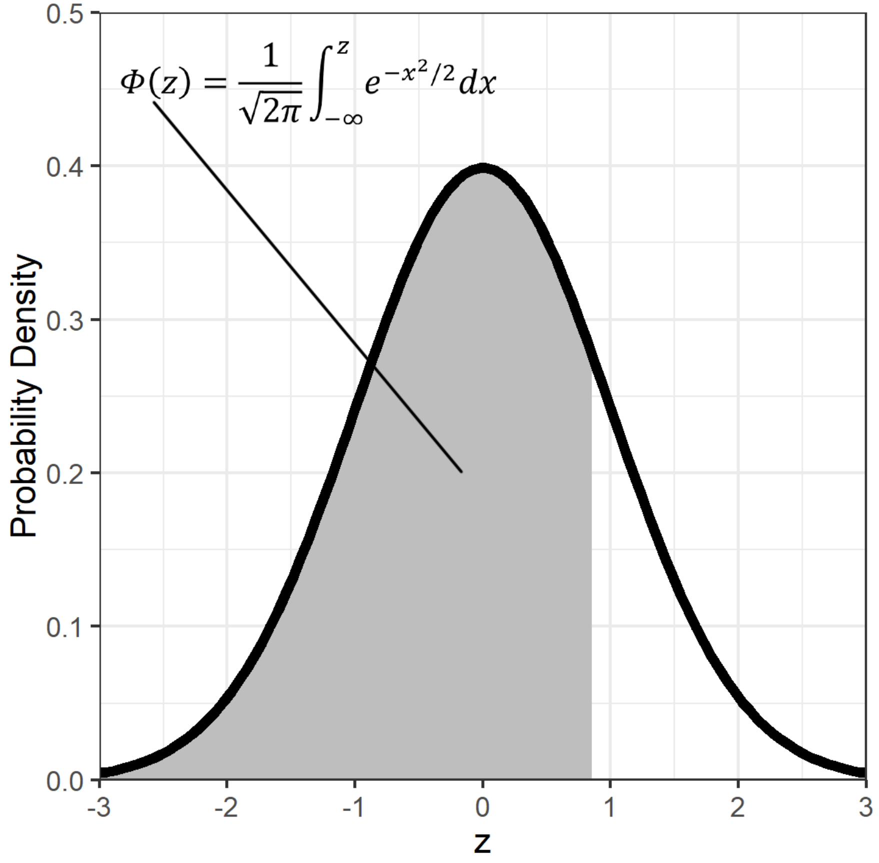
Demographics

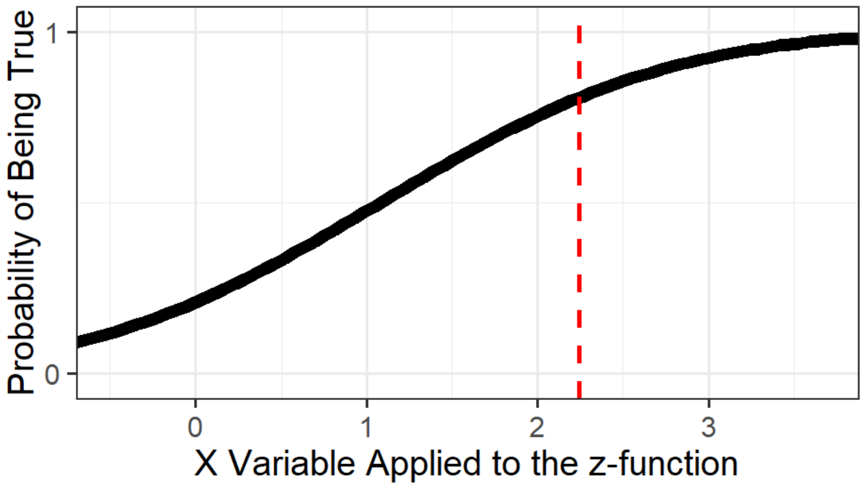




- Gender: 19 women (54%), 16 men (46%)
- Mostly college-aged young and middle-aged: 21-50 year olds account for 30 (86%) of the participants.
- Only 17 (49%) of the participants wear corrective eyewear compared to 64% in the office study

Statistical methodology: Probit regression





- Grouping for statistical analysis becomes dangerous at small samples (n=35, for example), so we use the data directly.

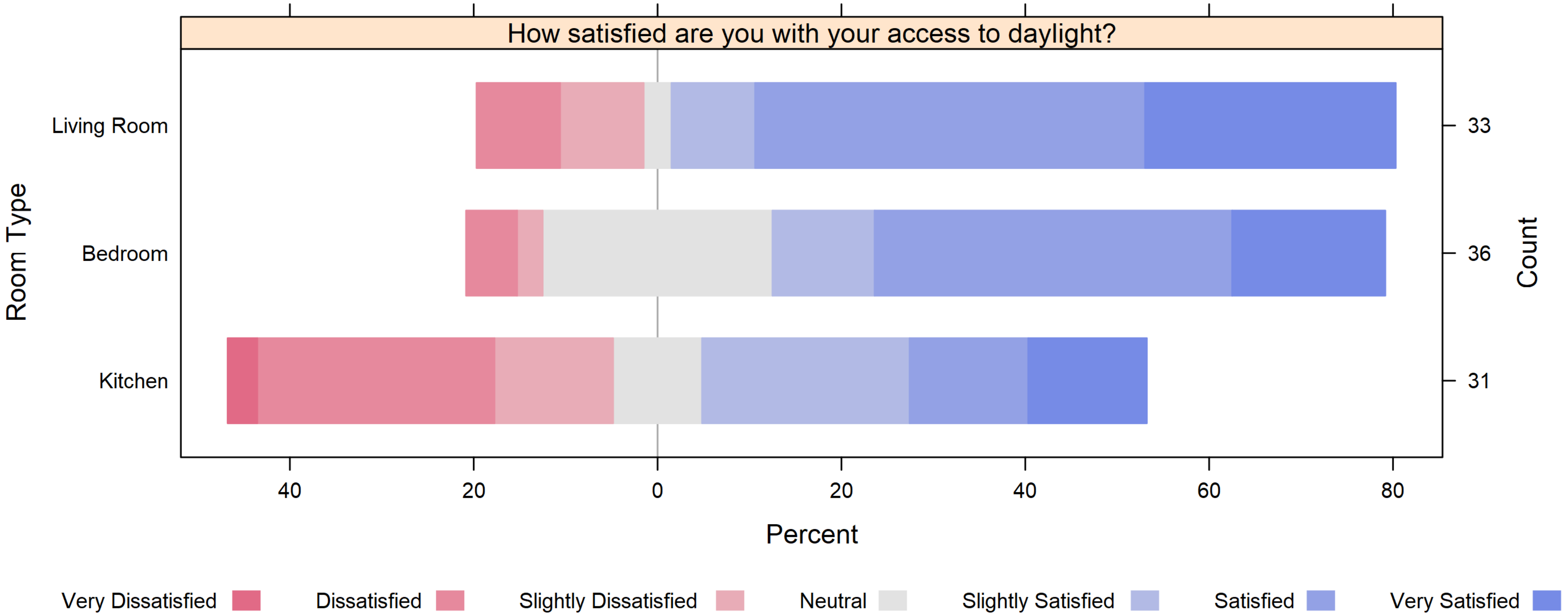
- Probit regression is a type of regression where the dependent variable is binary and is numerically limited between 0 and 1. The resulting probit function simply reports the probability that a member of a population will satisfy the binary criteria.

- Because the input data is binary, the correlation coefficients (adj. R^2) are obviously much less than in a grouping methodology where each group statistic can range between 0 and 100% of the population.

- We use McFadden's R^2 to estimate strength of correlation—results as low as 0.2–0.4 represent an excellent fit. 0.15 represent a very good fit, 0.10 a good fit, and 0.07 a fair fit to the data.

Residential: 3 early results

Satisfaction with access to daylight by room



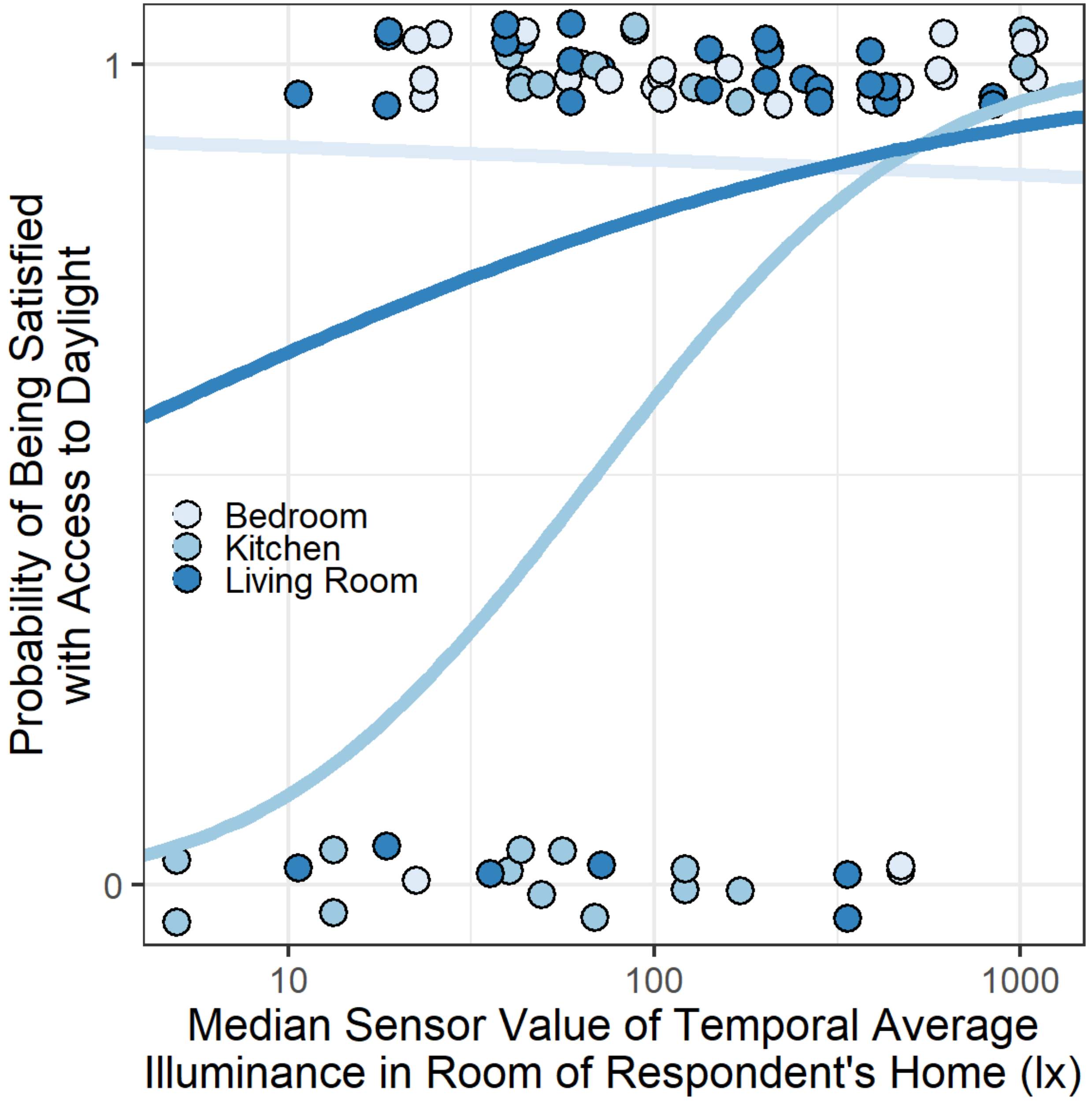
Correlation Matrix: McFadden's R^2

Program (Schedule)	DA200 (25%)	DA200 (50%)	DA300 (25%)	DA300 (50%)	DA500 (25%)	DA500 (50%)	UDIa+s (50%)	log10 Mean	log10 Median
Bedroom (9-5)	0.0596	0.0737	0.0691	0.0668	0.0486	0.0076	0.0863	0.0150	0.0013
Bedroom (7-10&4-7)	0.0681	0.0056	0.0391	0.0000	0.0003	0.0000	0.0143	0.0054	0.0002
Kitchen (9-5)	0.1006	0.0736	0.0792	0.0734	0.1011	0.0873	0.0896	0.0977	0.1849
Kitchen (7-10&4-7)	0.0722	0.0779	0.0754	0.0593	0.0652	0.0545	0.1620	0.0755	0.1596
Living (9-5)	0.0430	0.0249	0.0266	0.0156	0.0196	0.0243	0.0687	0.0597	0.0411
Living (7-10&4-7)	0.0243	0.0295	0.0259	0.0412	0.0455	0.0199	0.0647	0.0747	0.0577

Good and very good correlations, McFadden's $R^2 > 0.10$

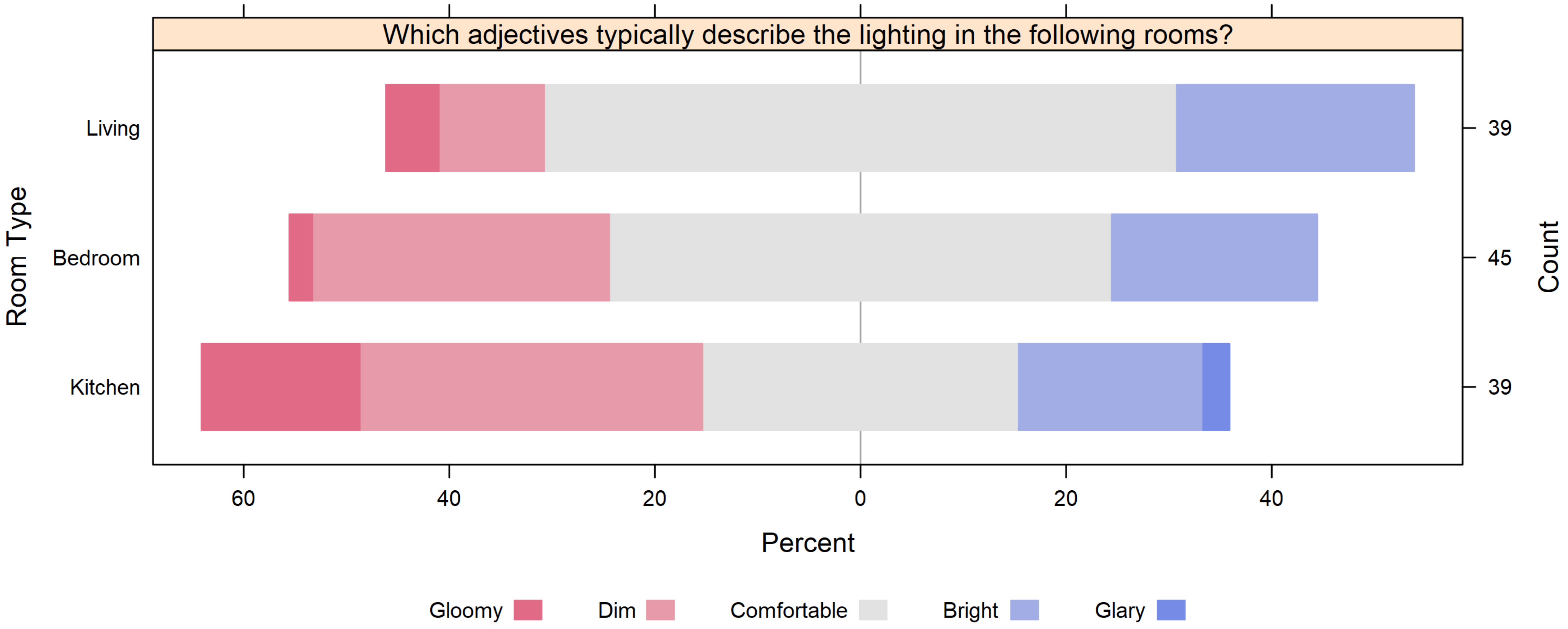
Fair correlations, McFadden's $R^2 > 0.07$

Satisfaction with access to daylight—Median illuminance

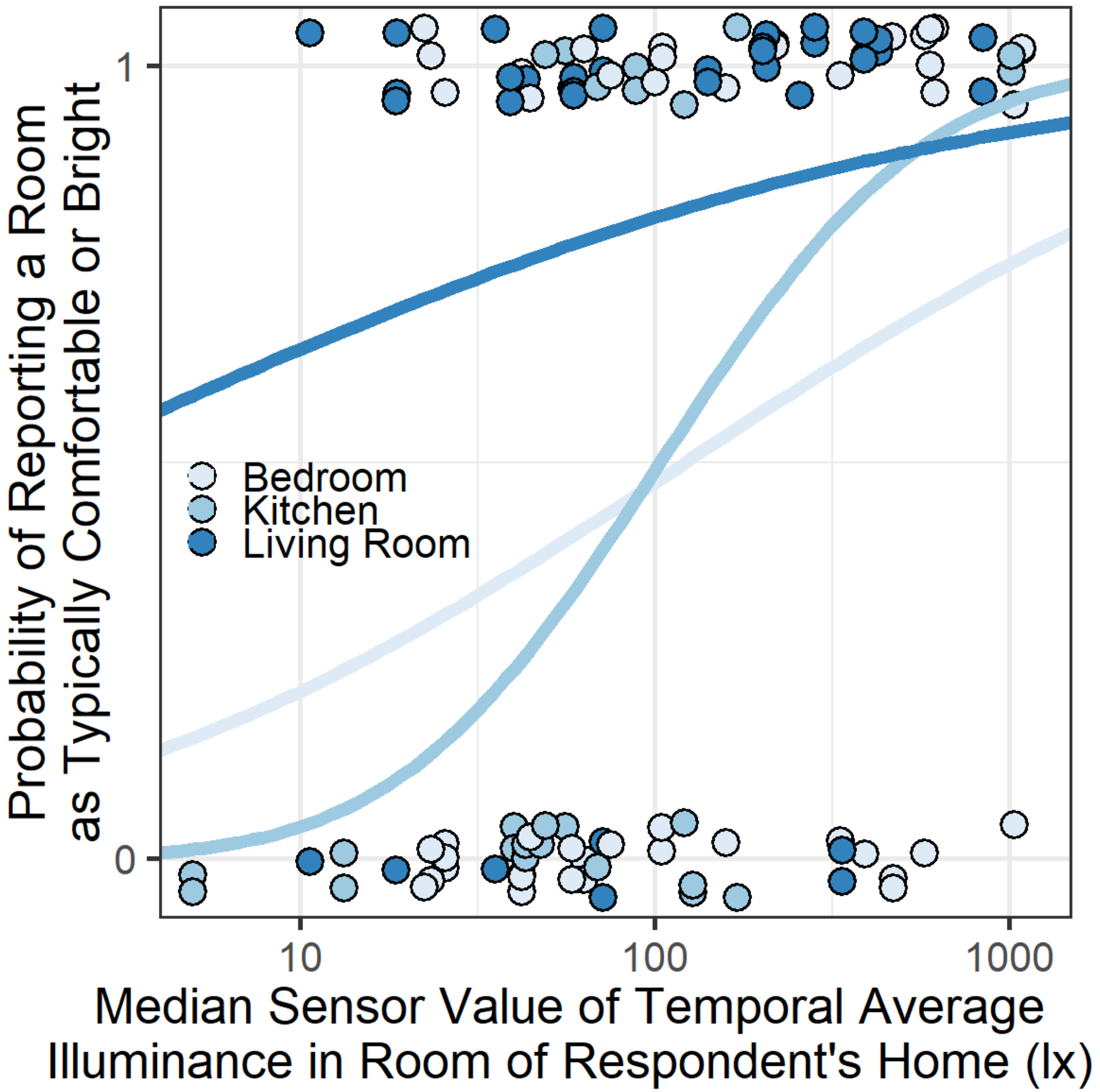


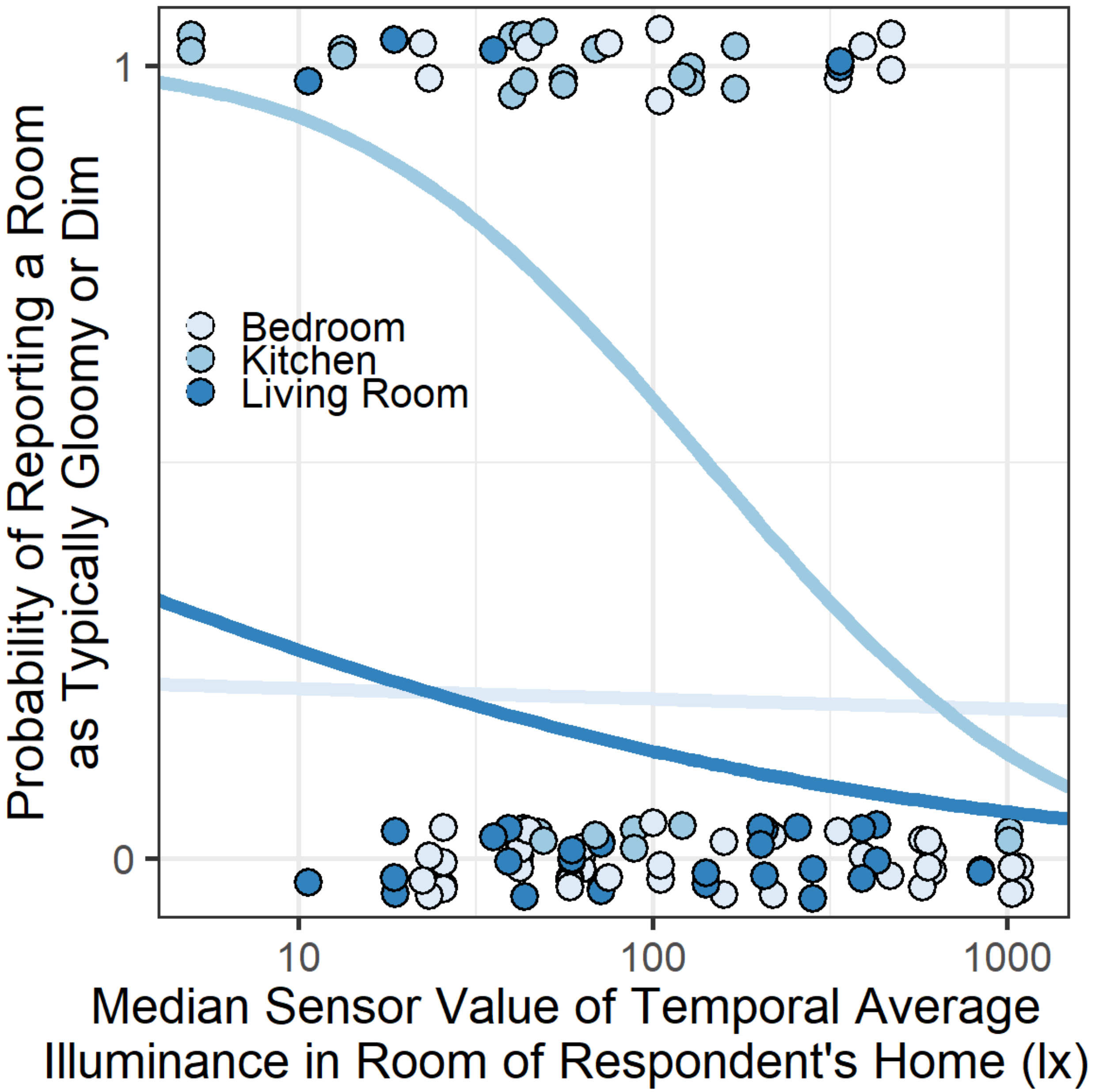
- Occupant response is much stronger kitchens.
- The bedroom and living room data is overwhelmingly positive with respect to satisfaction with daylight access, so the response to most daylight metrics is weaker.

Descriptive terms applied to rooms: Gloomy, Dim, Comfortable, Bright, Glary

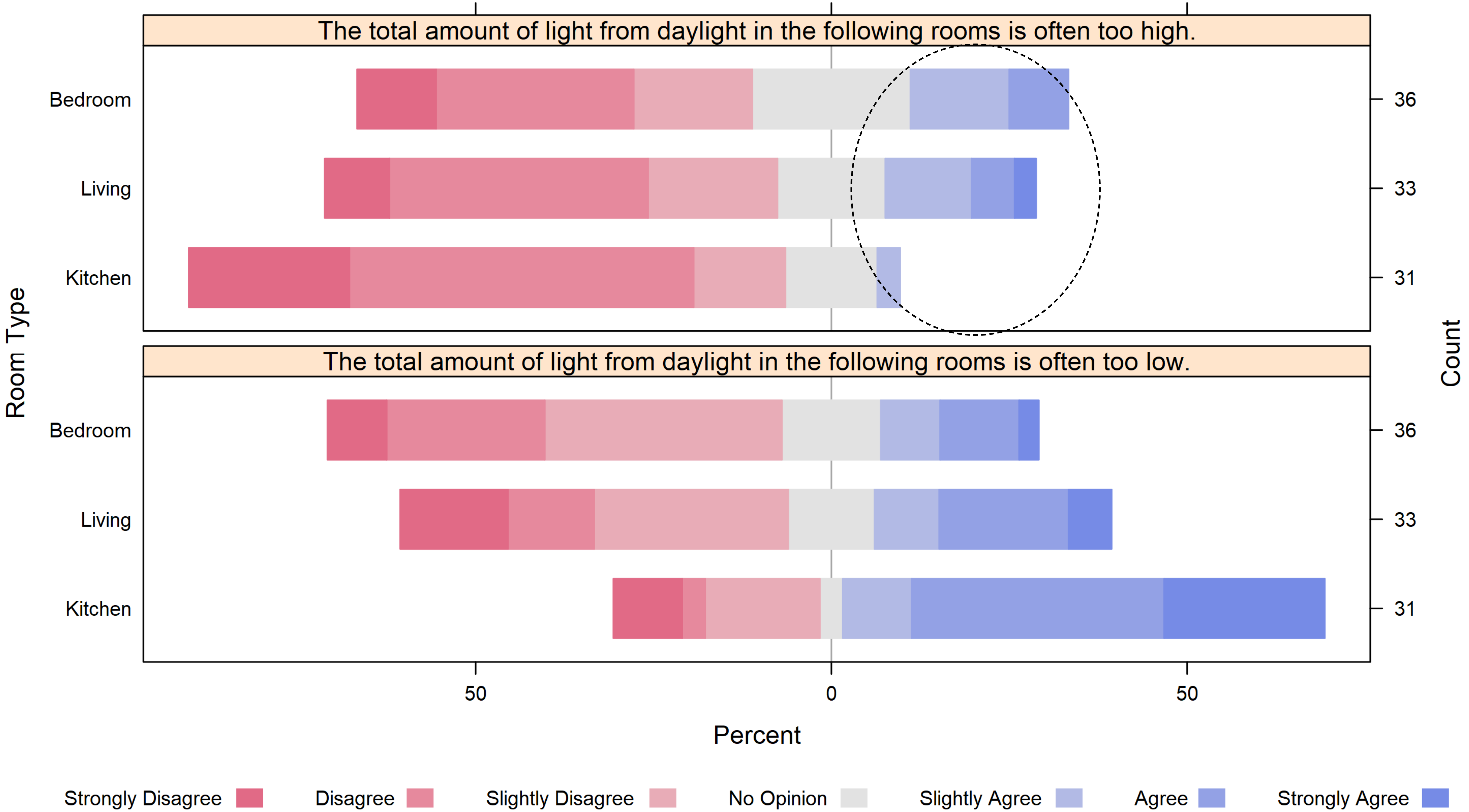


Descriptive terms applied to rooms: Gloomy, Dim, Comfortable, Bright, Glary

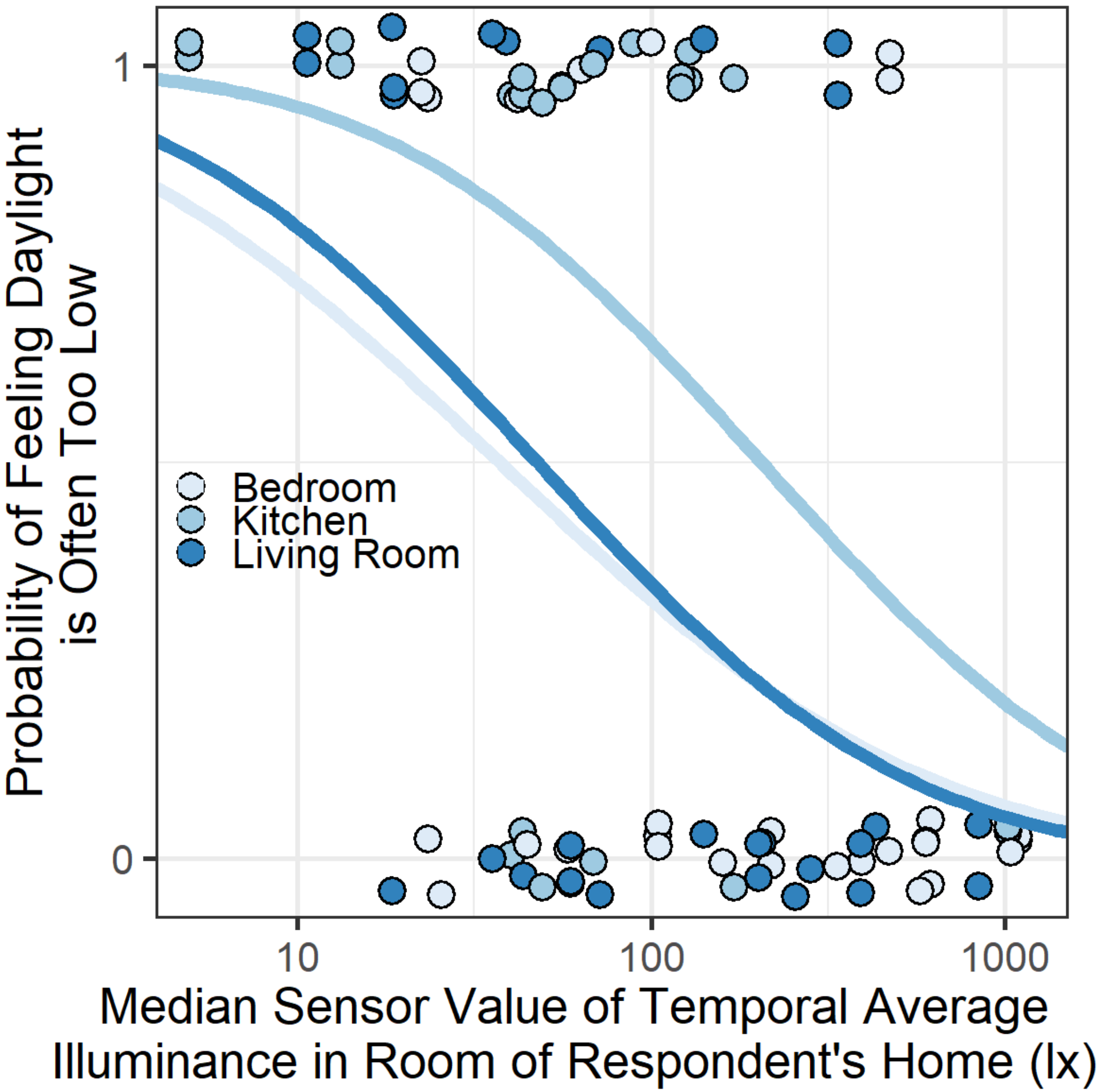




Daylight is often too high or too low



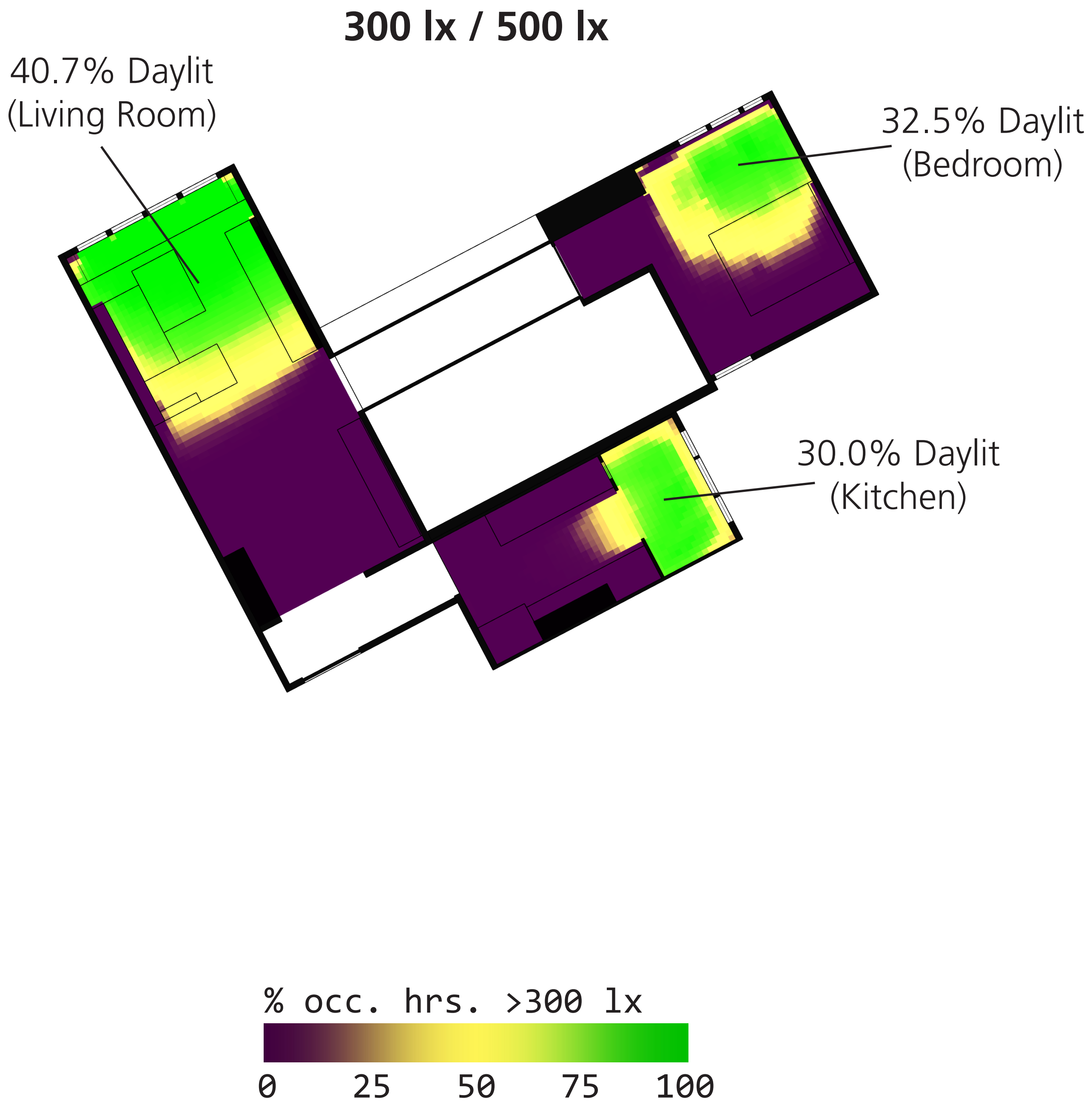
Daylight is often too low



- All 3 rooms have strong McFadden's R^2 correlation coefficients: 0.1236 for bedrooms, 0.1987 for kitchens, and 0.1800 for living room spaces.

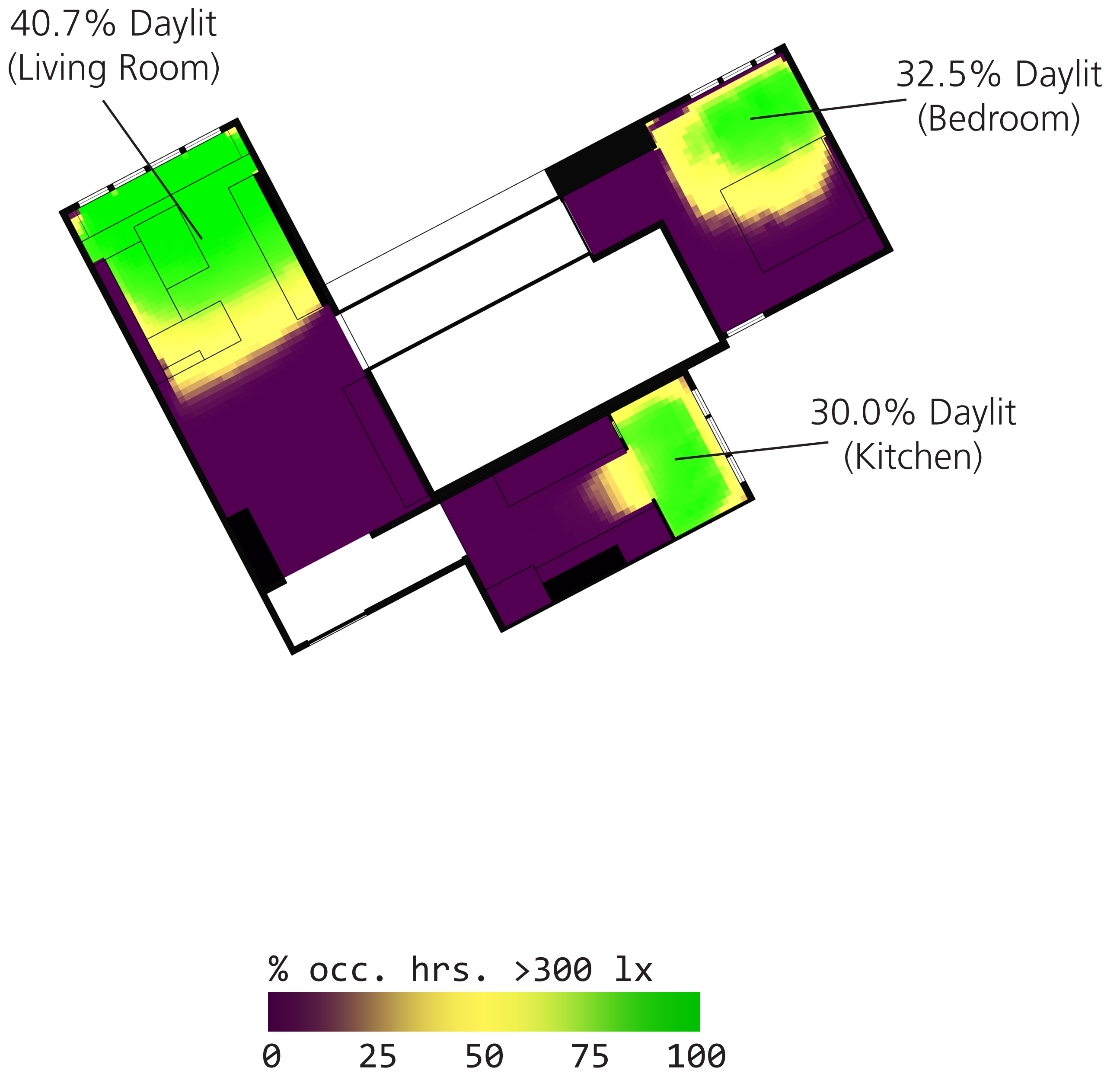
- At 300 lx median value in kitchens, ~20% of participants are likely to feel lighting levels are too low. A similar median illuminance percentile threshold is 150 lx in living rooms and bedrooms—i.e. they need half the daylight of kitchens.

Thinking about illuminance thresholds again...

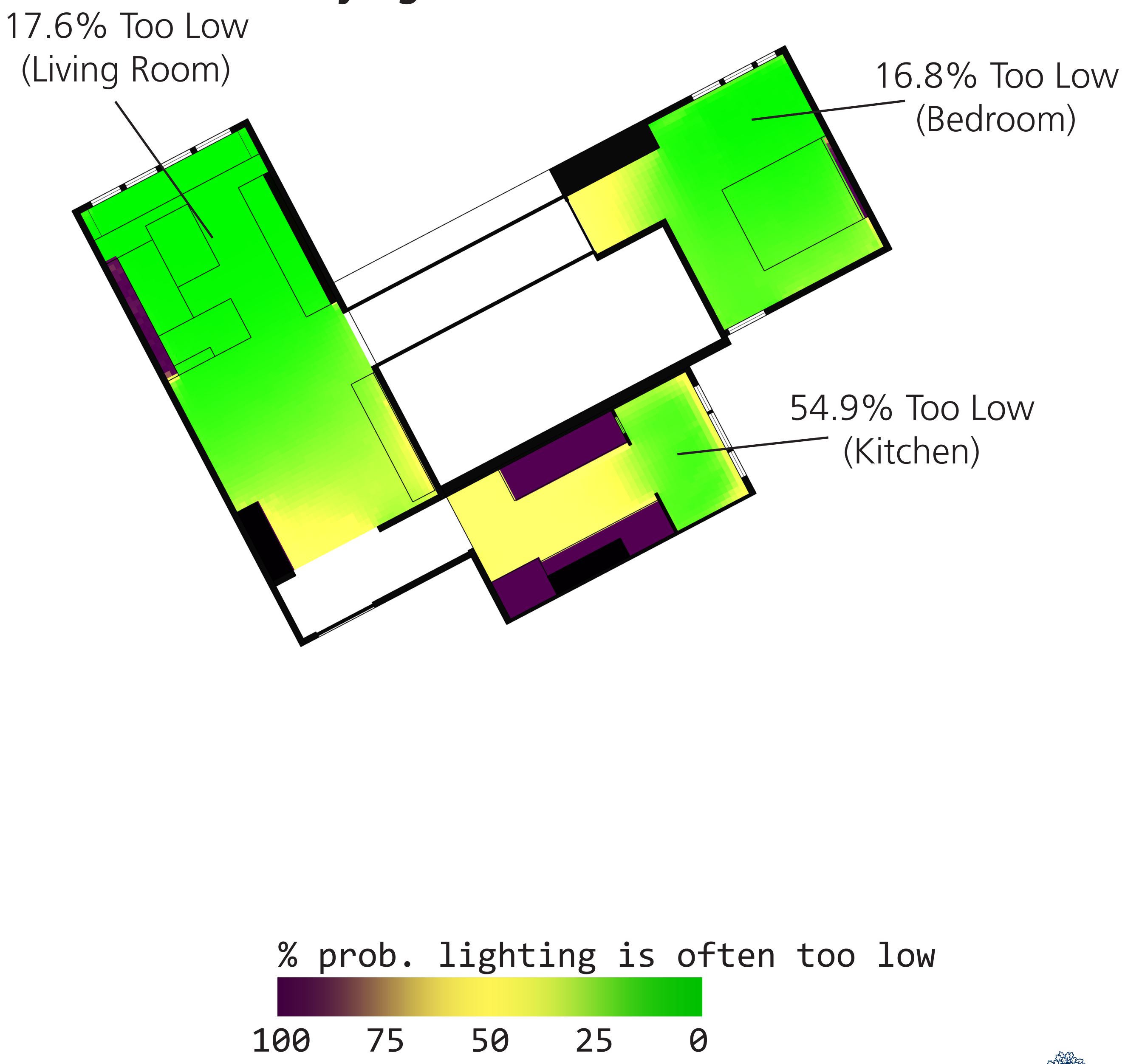


Thinking about illuminance thresholds again...

300 lx / 500 lx



Varying, 150 lx - 300 lx



Conclusions

- You can get away with a lot in the living room and bedroom in terms of daylight access, but the kitchen needs light.

- Participants still notice when daylight levels are low in all space types, but they are still satisfied in the case of living rooms and bedrooms and the thresholds for ‘low’ are lower.

- ‘Glare’ doesn’t manifest as an issue in tropical housing, despite what should be a strong aversion to the sun.

- The median illuminance value tends to be the best predictor of subjective output based on a small number of metrics tested thus far.

Publications

Jakubiec, J. A., Quek, G., & Srisamranrungruang, T. (2018). Towards subjectivity in annual climate-based daylight metrics. Proceedings of Building Simulation and Optimization; Cambridge, UK.

Quek, G., & Jakubiec, J. A. (2019). Calibration and validation of climate-based daylighting models based on one-time field measurements: Office buildings in the tropics. LEUKOS, 1-16.

Jakubiec, J. A., Srisamranrungruang, T., Kong, J., Quek, G., & Talami, R. (2019). Subjective and measured evidence for residential lighting metrics in the tropics. Proceedings of Building Simulation; Rome, Italy.

Daylight Model Calibration for POE Studies Towards Subjective Metrics in the Tropics

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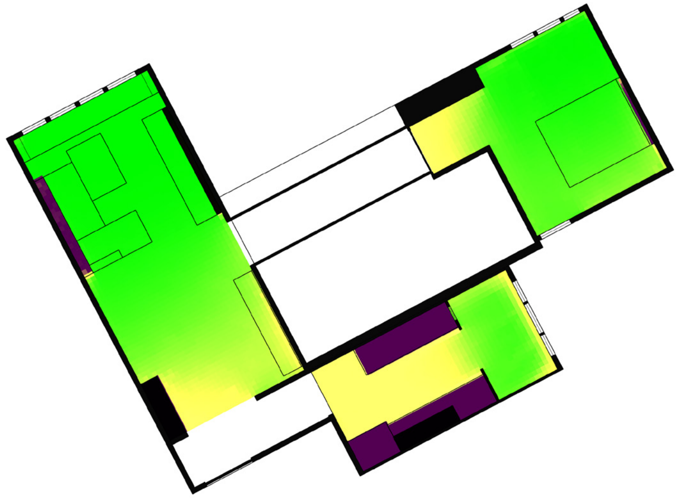
4. Southeast University
5. Loughborough University

Thank you!

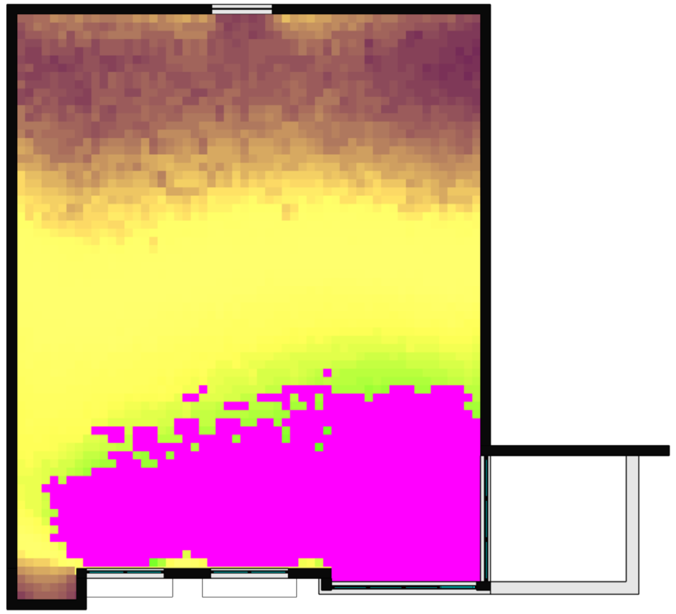


Work supported by:

1. National Research Foundation, Prime Minister's Office, Singapore Research, Innovation & Enterprise (RIE) Funding's Green Buildings Innovation Cluster (GBIC) program Grant number GBIC-R&D / DCP 05

2. SUTD-MIT International Design Centre (IDC)

DAvailability

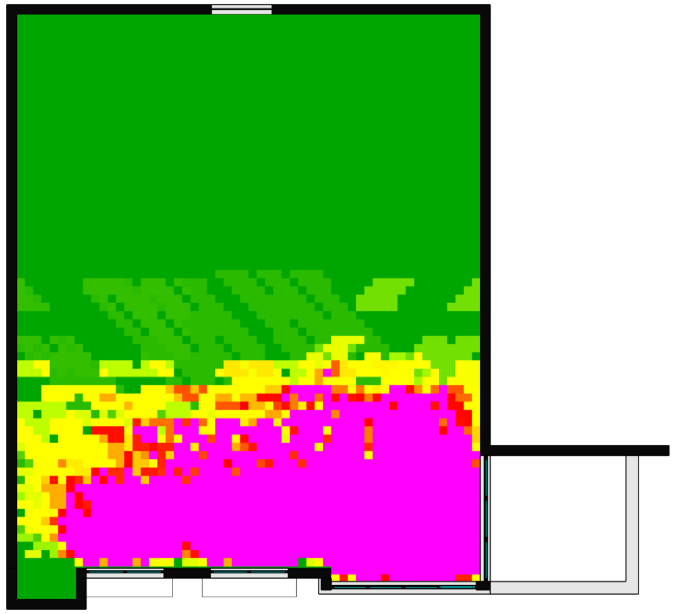


Daylight Availability 300 lx
>3000 lx, 5% hrs.
(Reinhart and Wienold 2011)

% occ. hrs. >300 lx

0 25 50 75 100

>3,000 lx, >5 % hrs.



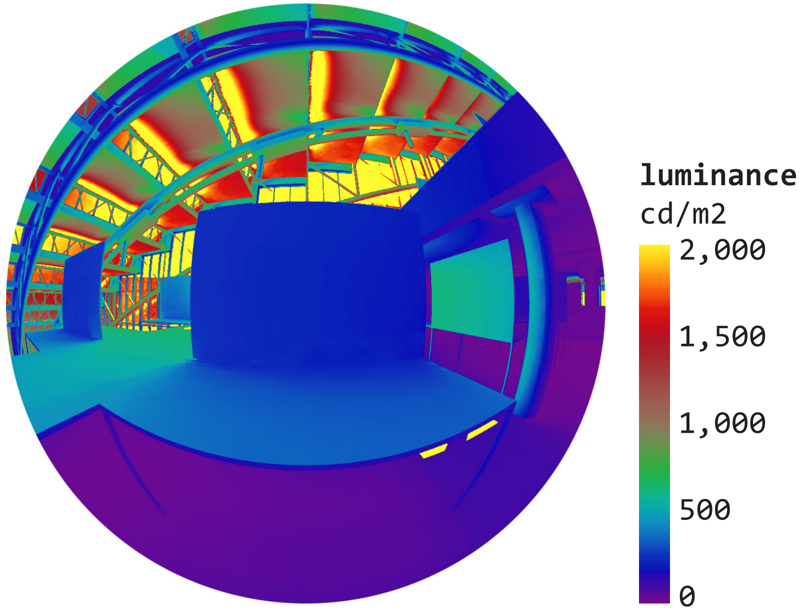
Annual Sunlight Exposure
>1000 lx direct, 250 hrs.
(IES LM-83 2012)

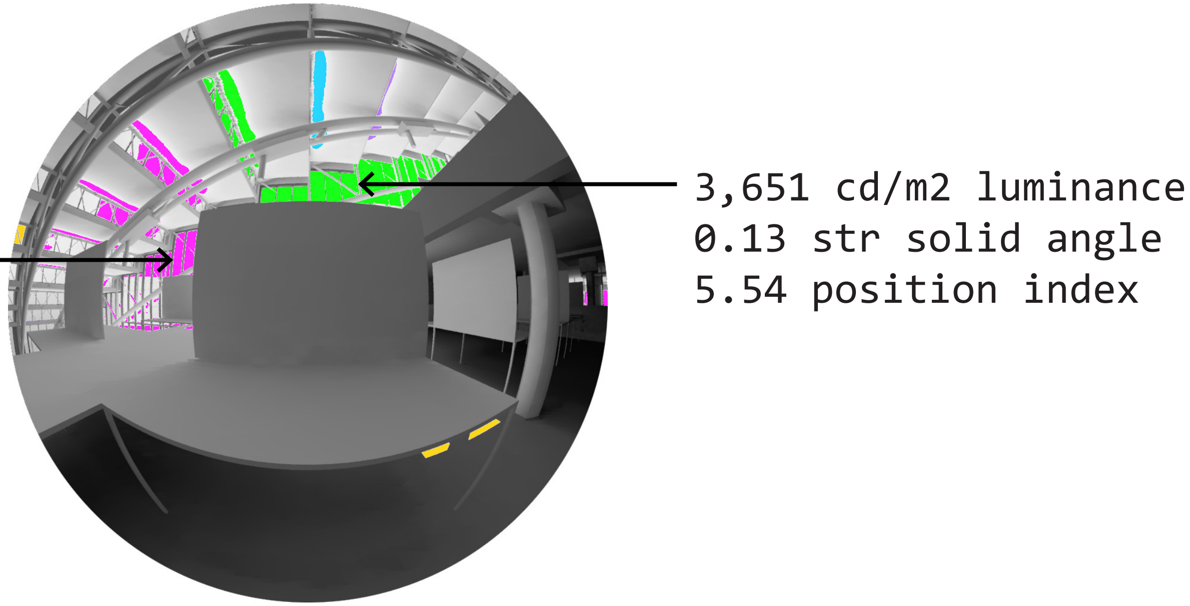
occ. hrs. >1,000 lx dir.

0 125 250

>250 hrs.

Glare Metrics: DGP & UGR (Point-in-time)





Ev = 1,746 lx

cd/m²
PIC

Luminance Image
(Measure or Simulation)

→ `evalglare -b 2000 luminance.pic` →

Glare Results

DGP = 0.265 (Wienold 2006)

UGR = 14.12 imperceptible (CIE 1995)

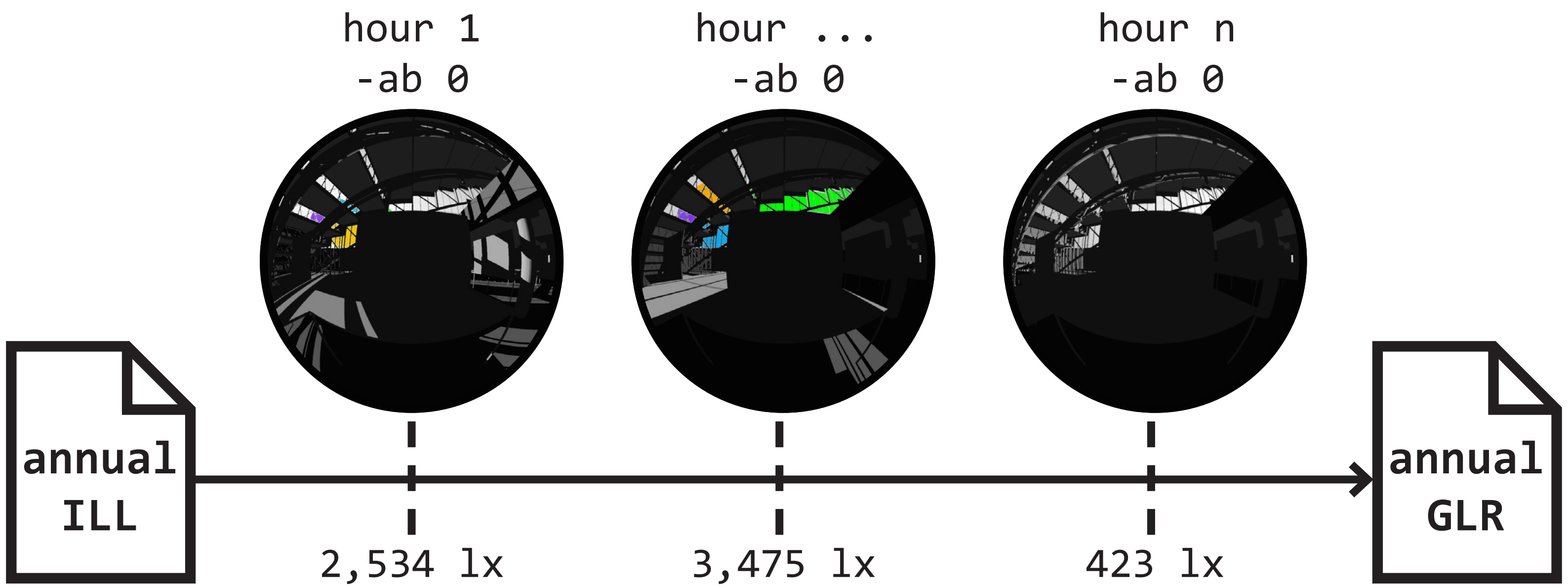
Decomposition for annual calculations

$$UGR = 8 \cdot log_{10} \overbrace{\frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{P_i^2}}^{\text{contrast term}}$$

(L_b: illuminance-based)

$$DGP = \overbrace{5.87 \cdot 10^{-5} E_v}^{\text{illuminance term}} + \underbrace{9.18 \cdot 10^{-2} \log_{10}\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)}_{\text{contrast term}} + \underbrace{0.16}_{\text{constant term}}$$

- Older visual discomfort measures such as UGR are fully contrast-based.
- DGP on the other hand is based on contrast and total overall brightness—vertical illuminance.
- Using a fast daylight coefficient-based raytracer, we can calculate annual illuminance accounting for full ambient reflections—accounting for overall brightness and the background portion of the contrast equation.
- Using ‘direct-only’ -ab 0 renderings, we can compute the source part of the contrast equation.



Annual DGP output, DIVA-for-Rhino