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Designers Lighting Forum

Lighting Application Efficacy (LAE): The What, Why, and How

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Learning Objectives

At the end of this course, participants will be able to:

1. Understand the lighting application efficacy metric in the context of lighting efficiency in buildings.
2. Outline the role of spatial efficiency (the proportion of light that reaches the eye) in the computational lighting design process.
3. Calculate the spatial efficiency of a room with lighting fixtures using our spatial efficiency spreadsheet tool and compare results from Radiance software.
4. Identify parameters that affect LAE in the near- and long-term with moderate and high complexity conditions.

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Lighting quality requires an optimum balance among human needs, architectural considerations, and energy efficiency.

https://iald.org/Advocacy/Advocacy/Quality-of-Light

“Measurement is the first step that leads to control and eventually to improvement. If you can’t measure something, you can’t understand it. If you can’t understand it, you can’t control it. If you can’t control it, you can’t improve it.”

— H. James Harrington

How many people live in extreme poverty worldwide (e.g., below $1 per day)?

In 2019, there were 115 million people living in extreme poverty worldwide (living on less than $1 a day).

Data from:
World Bank’s Poverty and Inequality Platform (PIP)
https://ourworldindata.org/poverty

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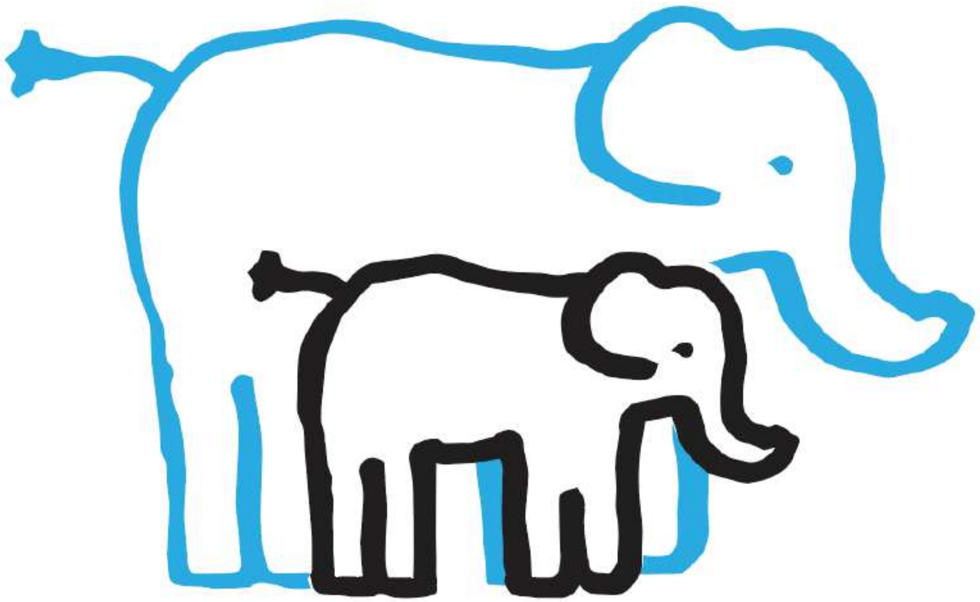
A lonely number seems impressive (small or large).

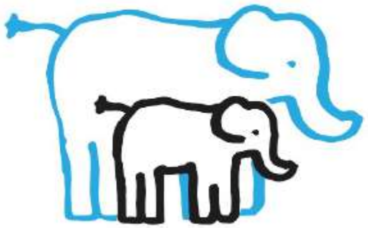


The Size Instinct

Rosling, H., Rosling, O., & Rönnlund, A. R. (2018). *Factfulness: ten reasons we're wrong about the world--and why things are better than you think*. Flatiron books.

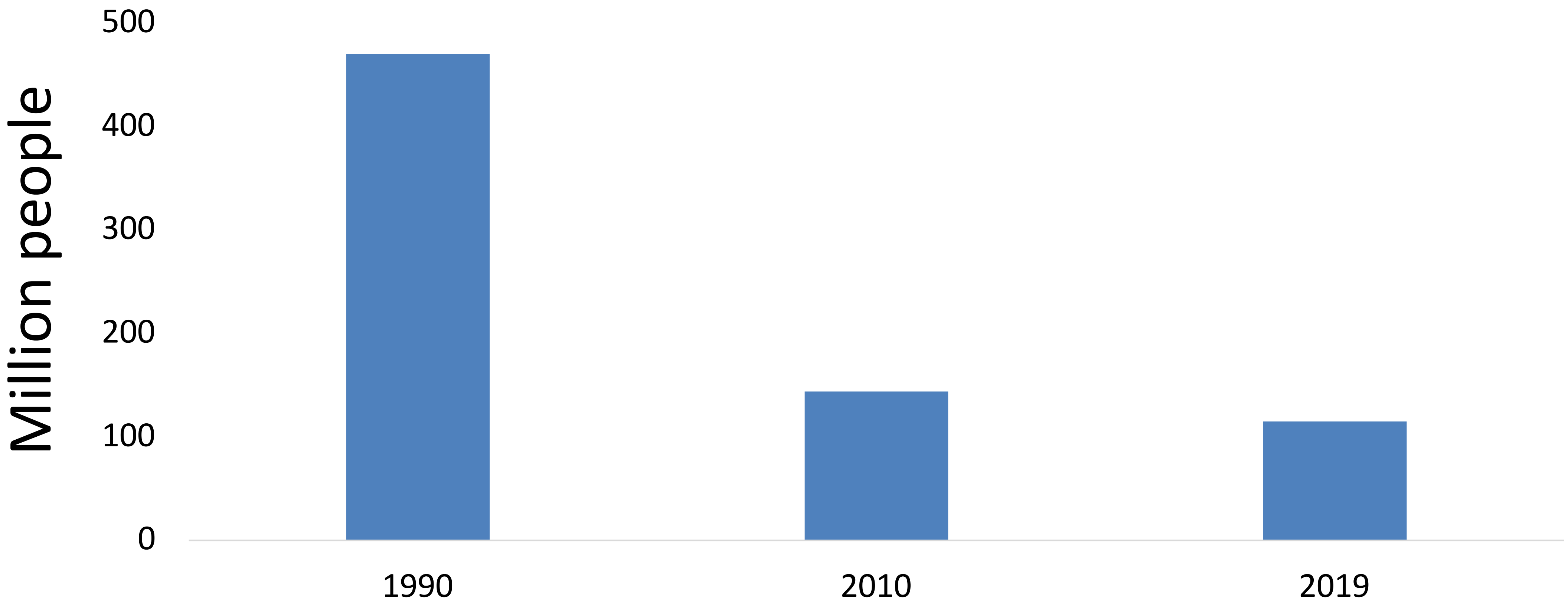
To control the size instinct, get things in proportion.

- **Compare.** Big numbers always look big. Single numbers on their own are misleading and should make you suspicious. Always look for comparisons.
- **Divide.** Amounts and rates can tell very different stories.



Rosling, H., Rosling, O., & Rönnlund, A. R. (2018). *Factfulness: ten reasons we're wrong about the world--and why things are better than you think*. Flatiron books.

Extreme poverty ⇆



Data from: World Bank's Poverty and Inequality Platform (PIP)
https://ourworldindata.org/poverty

Extreme poverty rate

115 million people living in extreme poverty worldwide

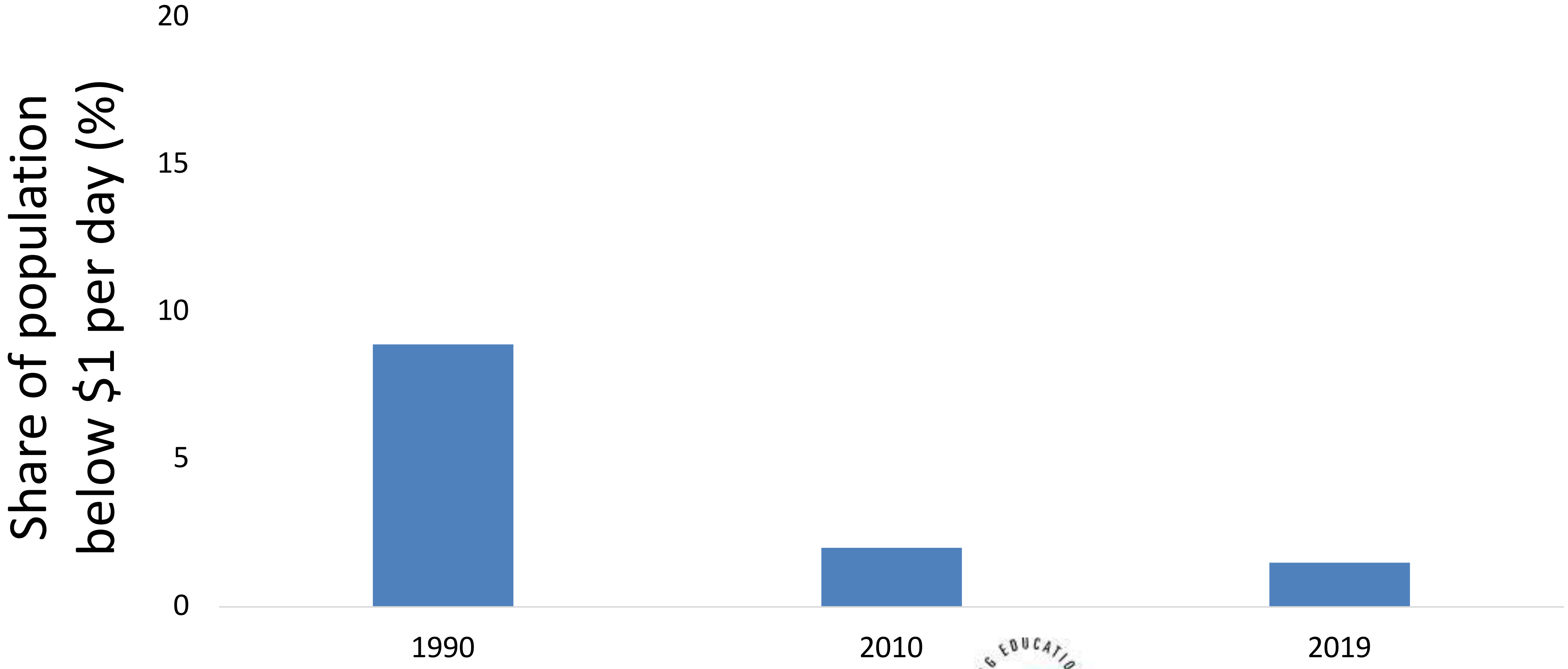
÷

~7.5 billion people

=

1.5% of the world population.

Extreme poverty rate



Data from: World Bank's Poverty and Inequality Platform (PIP)
https://ourworldindata.org/poverty

We do something similar in the lighting industry.

Luminous flux = 2,000 lm

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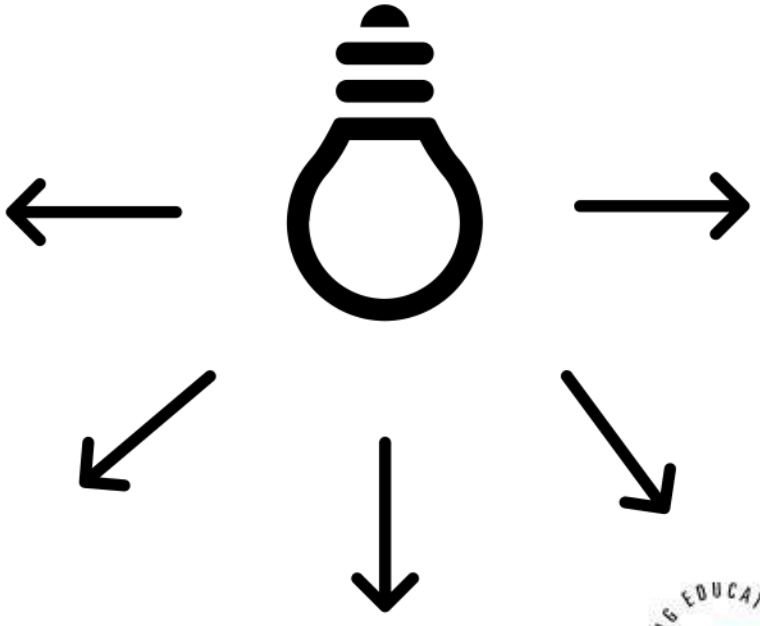
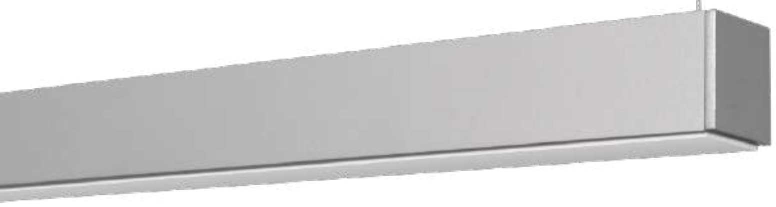
2,000 lm ⇆ 24,000 lm

Luminous efficacy: the ratio of total emitted luminous flux (lumens, lm) to electrical input power (W)



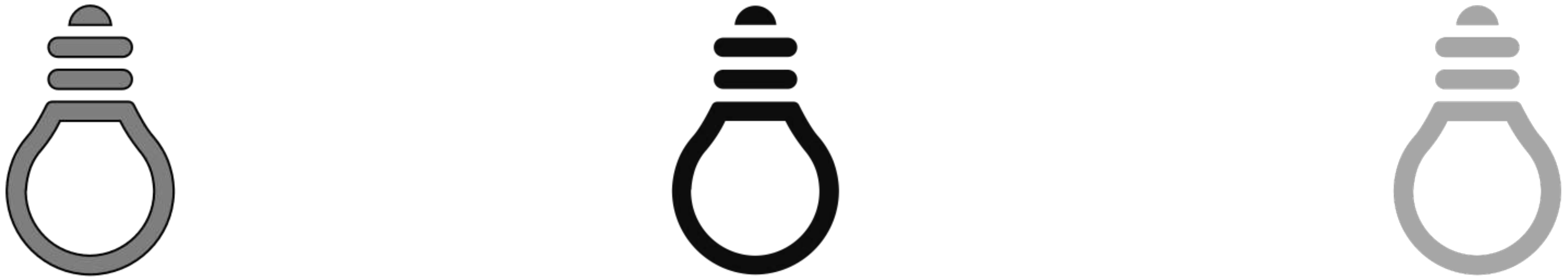


2,000 lm	24,000 lm
÷	÷
20 W	150 W
=	=
100 lm/W	160 lm/W

Is this enough?

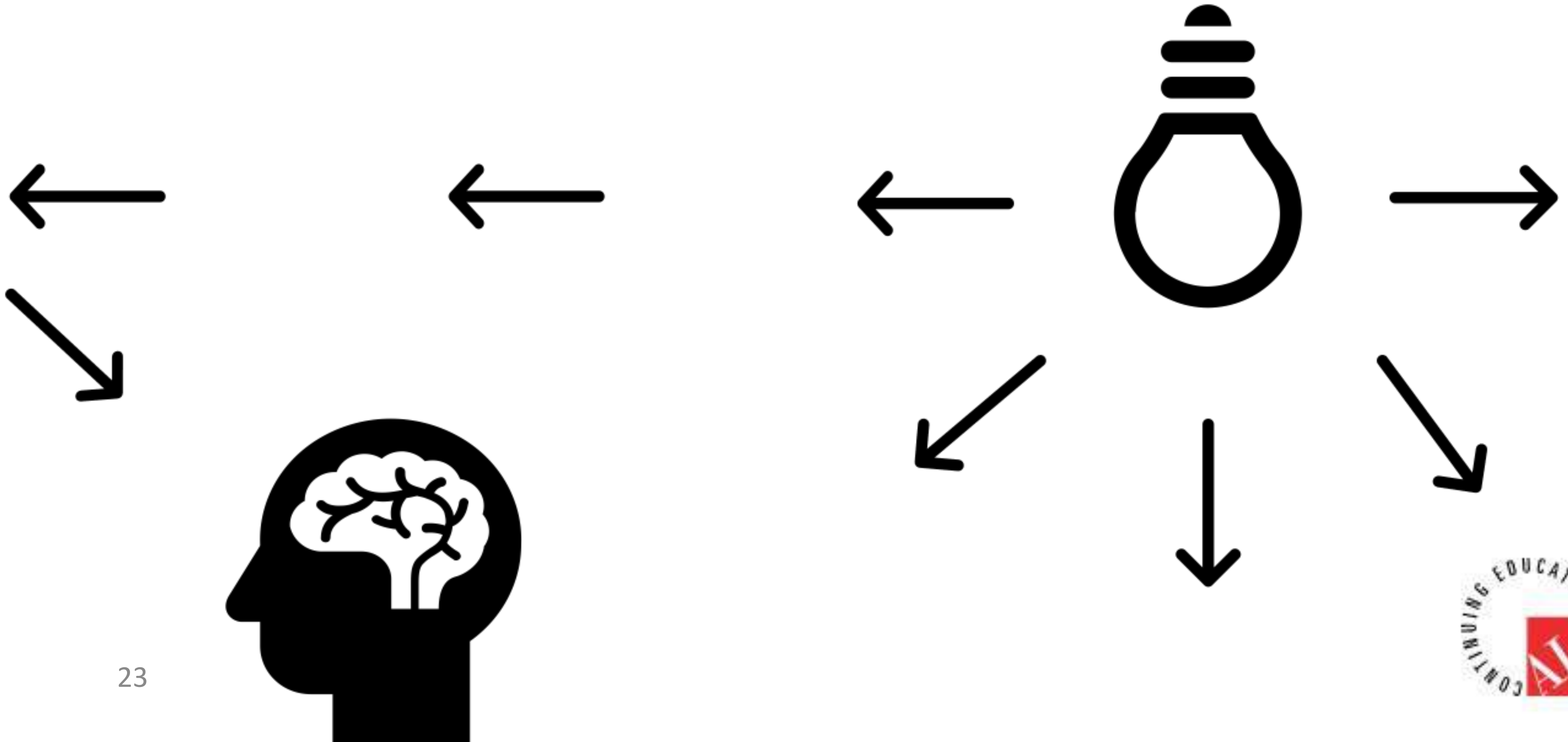
Luminous flux is based on the 2-degree visual field of view.

Luminous efficacy only applies to individual light sources.



The total luminous flux emitted from light source goes all directions.

Not all the light is useful (reaches the eye).



We need better tools to holistically evaluate the usefulness of architectural lighting.

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How can we capture the usefulness of lighting systems in architectural spaces?

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[Enter]

Lighting application efficacy (LAE)

noun

the relationship between the electrical power consumed by lighting hardware and the amount of light that contributes to the visual perception of building occupants.

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Earlier Ideas…

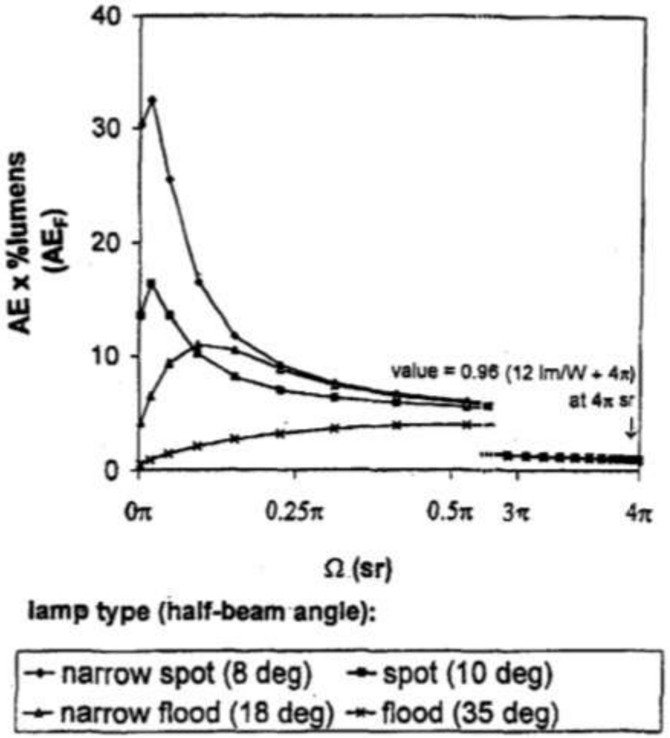


Figure 1—Application efficacy for the lumens within a solid angle for four 150 W incandescent PAR lamps.

Luminaire application efficacy

LE = luminous flux/power (lm/W)

↓

LE/Ω = luminous flux/power/solid angle (lm/W/sr)

↓

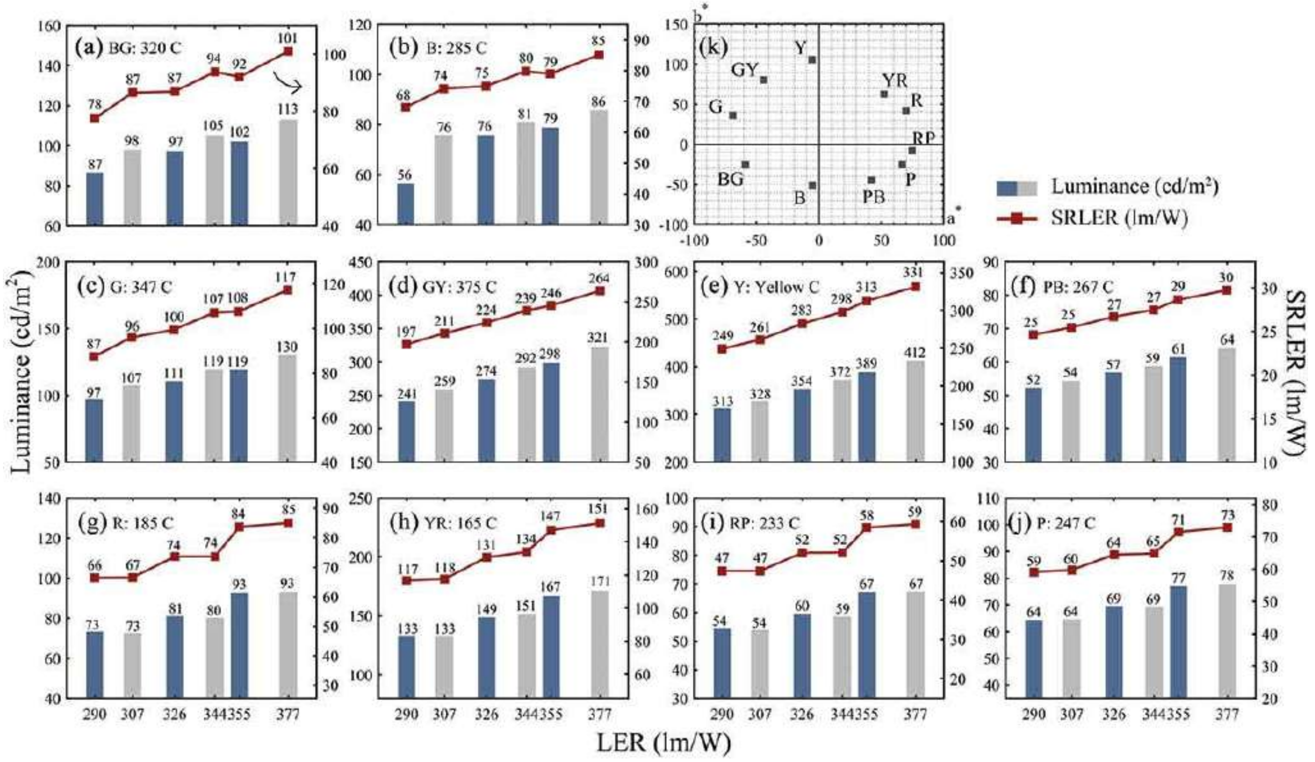
LE/Ω = luminous intensity/power (cd/W)

↓

AE = LE/Ω

Rea, M. S., & Bullough, J. D. (2001). Application efficacy. *Journal of the Illuminating Engineering Society*, *30*(2), 73-96.

Earlier Ideas…



Surface reflectance LER

$$SRLER = \frac{K_m \int P(\lambda)\rho(\lambda)V(\lambda)\mathrm{d}\lambda}{\int P(\lambda)\mathrm{d}\lambda}$$

Wu, P., Lin, Y., & Yao, Q. (2021). Effectiveness of Light Source Efficiency for Characterization of Colored Surface Luminance. *LEUKOS*, 1-13.

Earlier Ideas…

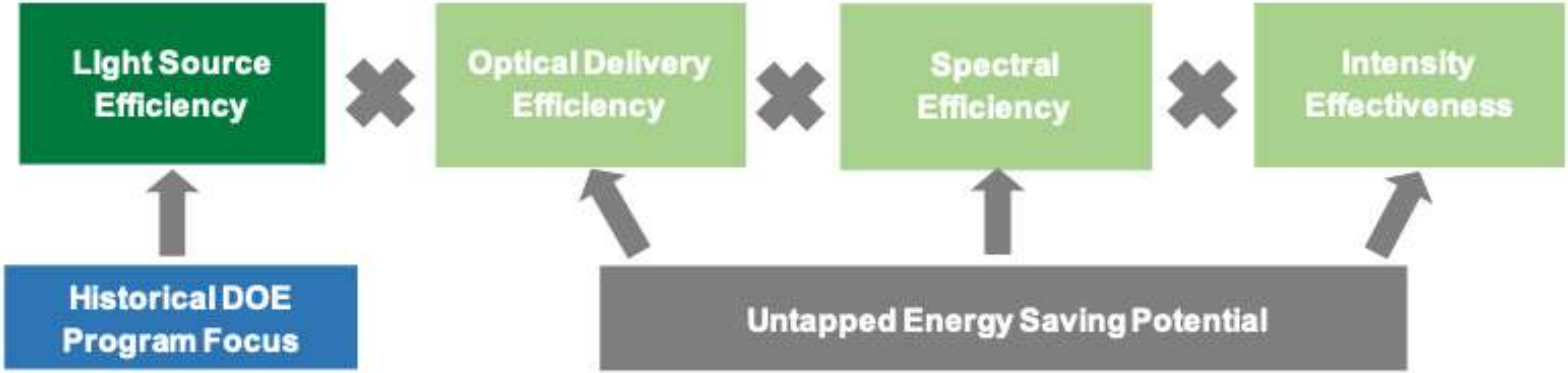


Figure 4.1 Proposed Lighting Application Efficiency (LAE) framework. Each of the four major efficiency elements are multiplied to provide the overall lighting application efficiency.

Pattison, M., Hansen, M., Bardsley, N., Elliott, C., Lee, K., Pattison, L., & Tsao, J. (2020). *2019 Lighting R&D Opportunities* (No. DOE/EE-2008). Solid State Lighting Solutions (SSLS) Inc., Santa Barbara, CA (United States).

Our LAE framework considers the primary pathway of light:

- the generation and emission of light from a luminaire,
- the travel of the light throughout the space into occupants’ eyes,
- and the process of visual perception.

$$\mathrm{LAE} = \sum_{t} \eta_{\mathrm{luminaire}} \times \eta_{\mathrm{spatial}} \times S_{\mathrm{visual}}$$

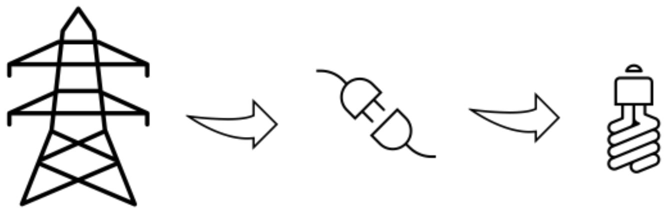
Temporal | Electrical | Spatial | Spectral

Durmus, D., Hu, W., & Davis, W. (2022). Lighting application efficacy: A framework for holistically measuring lighting use in buildings. *Frontiers in Built Environment*, *8*, 986961.

$$\text{LAE} = \eta_{\text{luminaire}} \times \eta_{\text{spatial}} \times S_{\text{visual}}$$

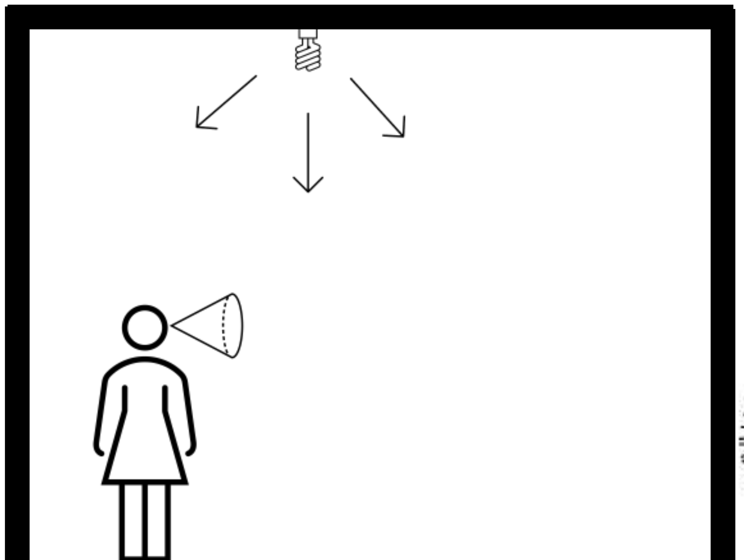
Luminaire efficiency

$\Phi_{\text{e,total}} / P_{\text{e}}$



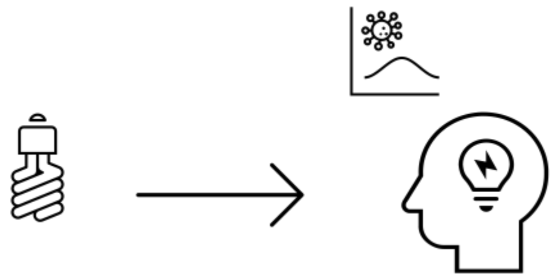
Spatial efficiency

$\Phi_{\text{e,target}} / \Phi_{\text{e,total}}$



Visual sensitivity

$V_{\text{x}}(\lambda)$



Project Structure

- Existing knowledge
- DOE project
- Future research
- ARC project

We are here now →

	Luminaire efficiency $\eta_{luminaire}$	Spatial efficiency $\eta_{spatial}$	Visual sensitivity S_{visual}
Version 1: Near-term Low complexity	• Radiant efficiency • Light output ratio	• Proportion of emitted light directed to areas within occupants' visual fields • Proportion of emitted light directed to task area(s)	• Spectral luminous efficiency (V_λ)
Version 2: Medium-term Moderate complexity	All of the above +		
	• Efficiency changes as a function of operating time		• Effect of contrast on perceived brightness
Version 3: Long-term High complexity	All of the above +		
	• Control system efficiency • Efficiency changes from altered conditions (e.g., temperature)	• Spatially dynamic lighting (e.g., gaze-dependent lighting)	• State of visual adaptation • Occupant age • Sensitivity as a function of location within visual field

Lighting Application Efficacy

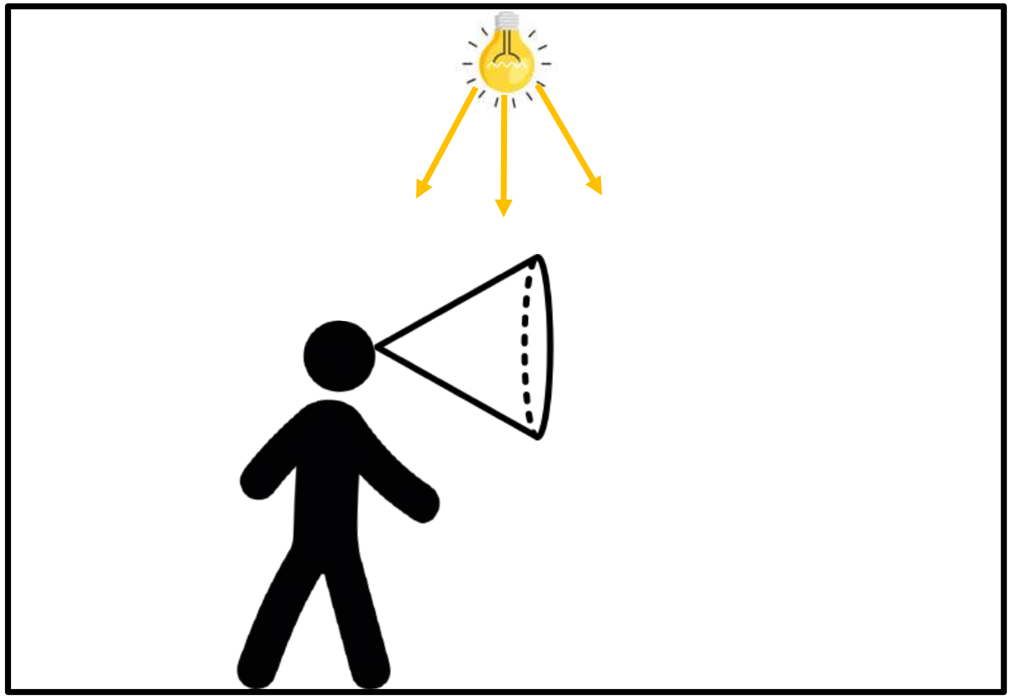
$$\text{LAE} = \sum_{t} \eta_{\text{luminaire}} \times \eta_{\text{spatial}} \times S_{\text{visual}}$$

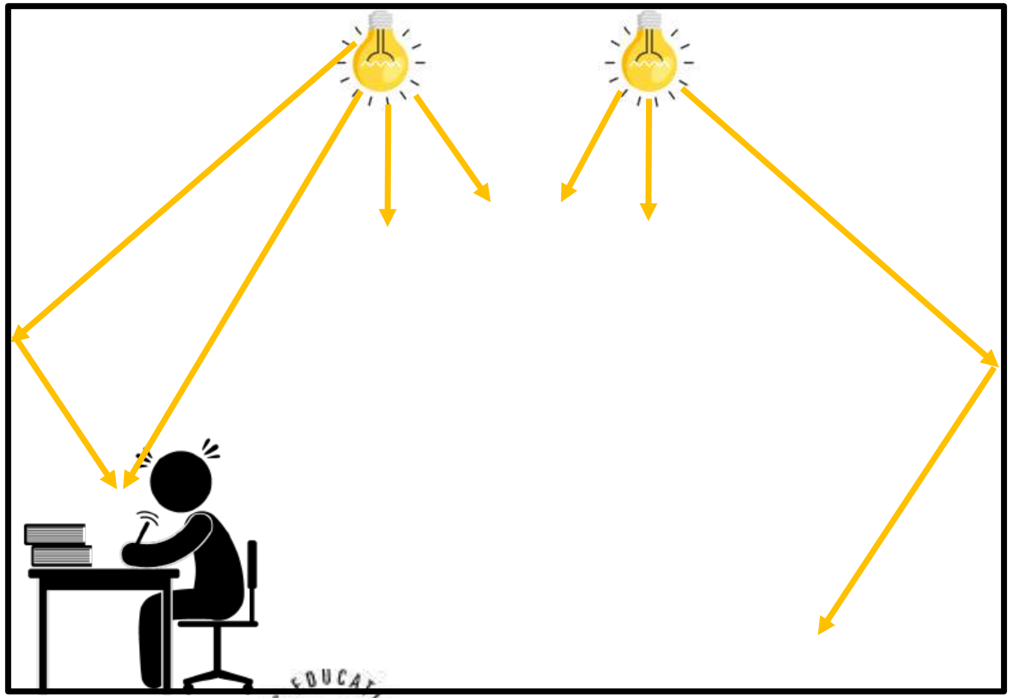
Durmus, D., Hu, W., & Davis, W. (2022). Lighting application efficacy: A framework for holistically measuring lighting use in buildings. *Frontiers in Built Environment*, *8*, 986961.

Where do photons go, and how can we count them?

Spatial efficiency

The proportion of electromagnetic energy emitted by the luminaire(s) that reflects off visually meaningful surfaces and ultimately reaches the eyes of occupants.





Calculating spatial efficiency

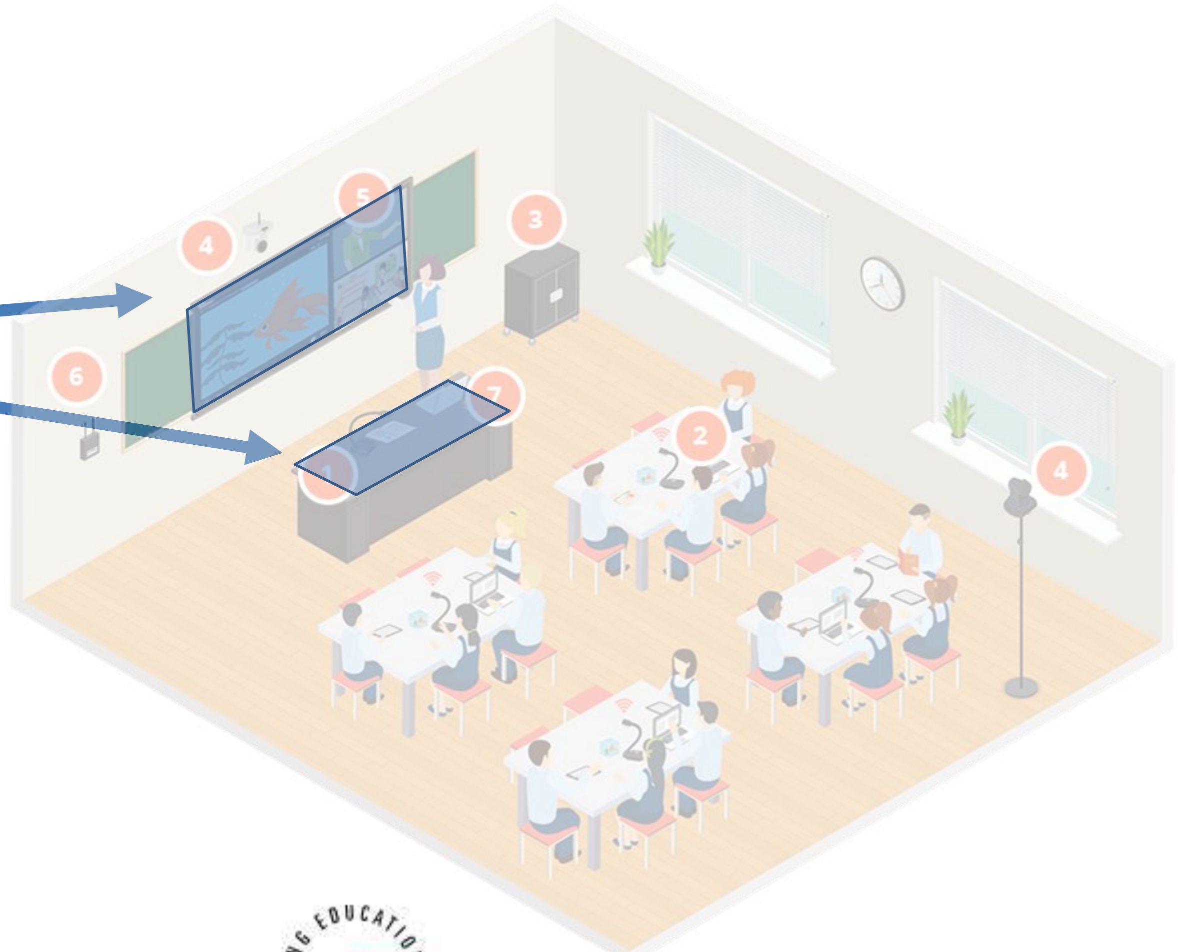
$$\eta_{\text{spatial}} = \frac{\phi_{e,target}}{\phi_{e,total}}$$

radiant flux at the target (W)

total radiant flux emitted in a room (W)

Spatial efficiency per work plane

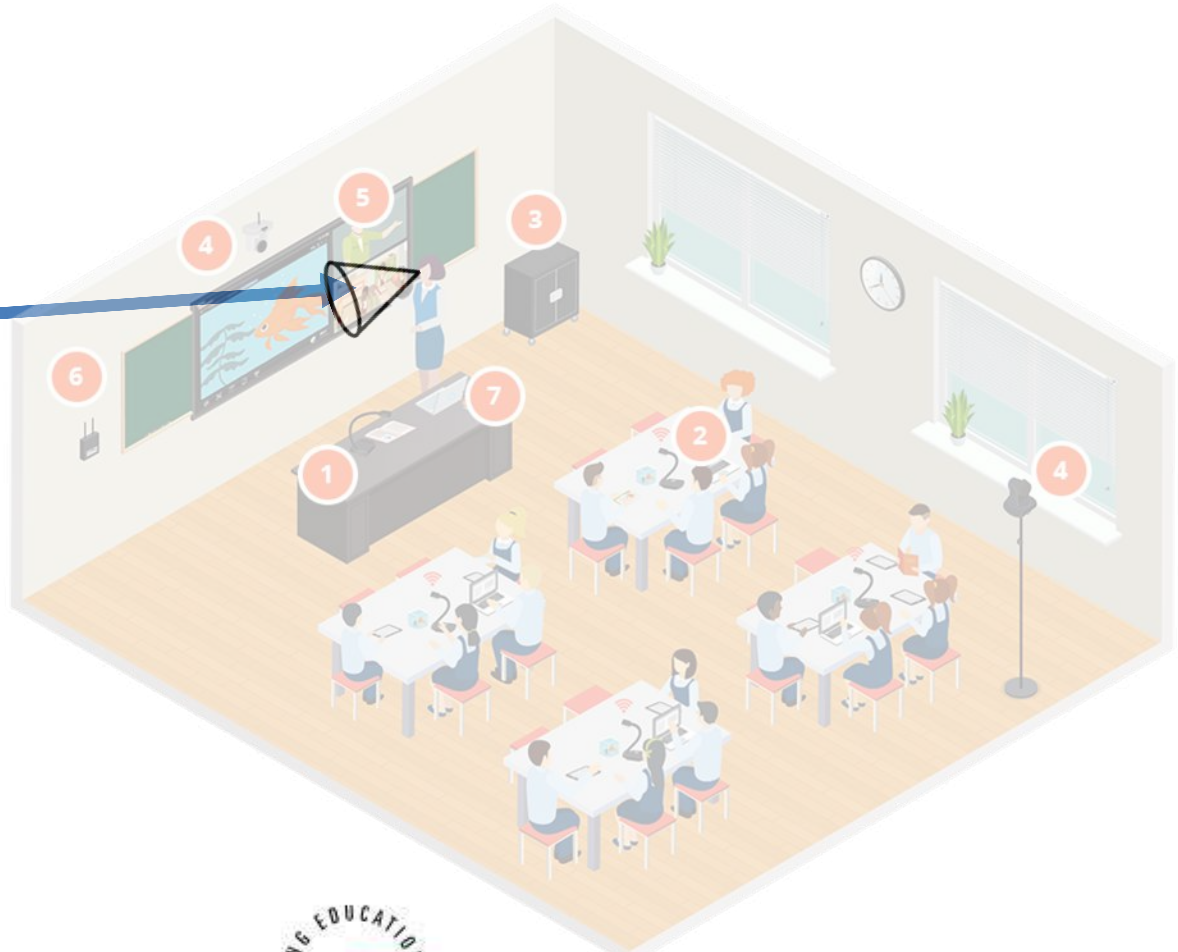
$$\eta_{\text{spatial}} = \frac{\phi_{e,target}}{\phi_{e,total}}$$



https://www.aver.com/solution/classroom-technology

Spatial efficiency per field of view

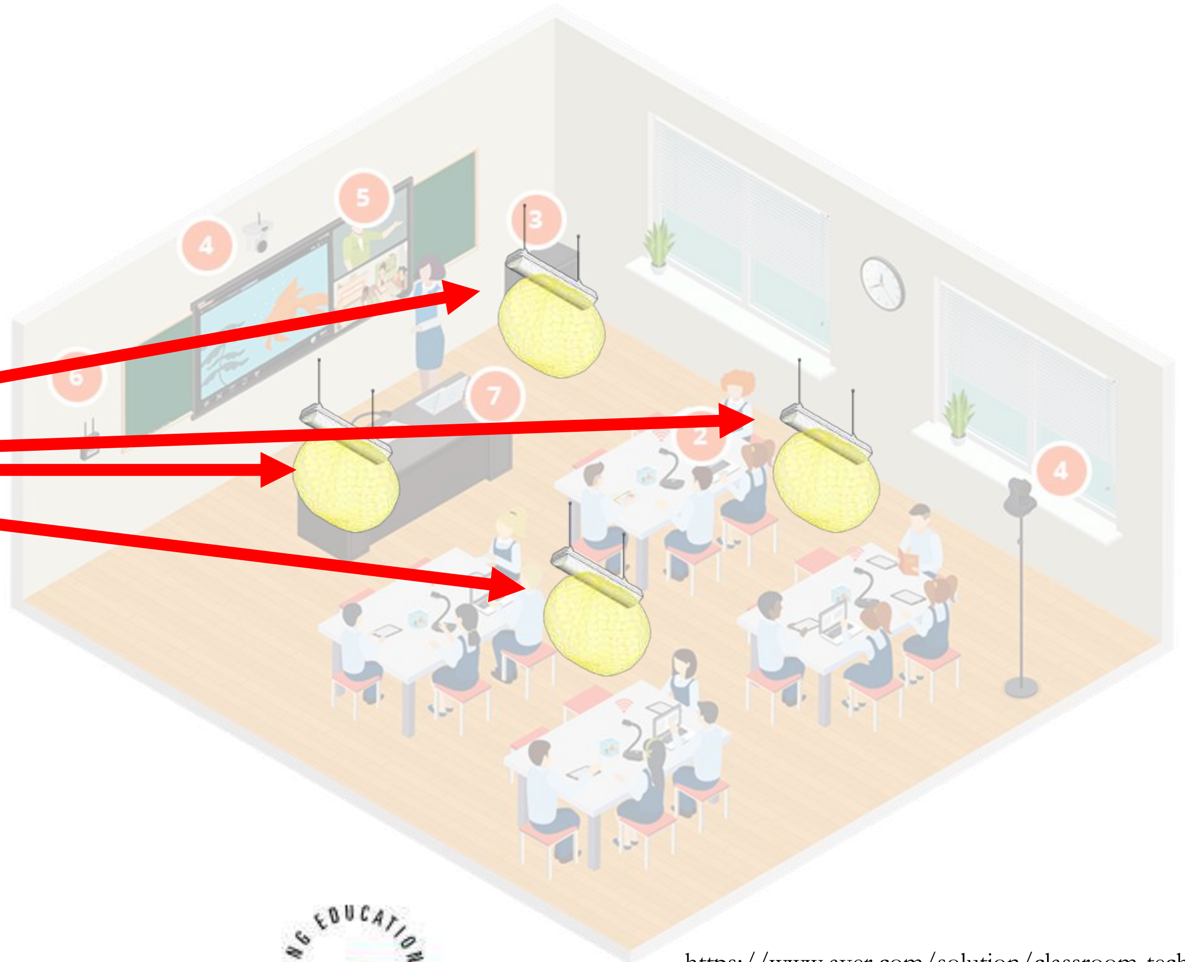
$$\eta_{\text{spatial}} = \frac{\phi_{e,target}}{\phi_{e,total}}$$



https://www.aver.com/solution/classroom-technology

Spatial efficiency

$$\eta_{\text{spatial}} = \frac{\phi_{e,target}}{\phi_{e,total}}$$



https://www.aver.com/solution/classroom-technology

Notes:
1- Ignore the incorrect graphical representation of troffers.
2- Photometric webs show luminous intensity, not radiant intensity.

Spatial efficiency

Calculation methods for the work plane level and visual field angles

1. Precise method
   - Step-by-step guidelines for Radiance and ALFA software (DIY)

2. Approximate method
   - The spreadsheet calculator (based on sample simulations)

Spatial efficiency
Simulation parameters

Parameters

- Room area
- Area per luminaire (luminaire density)
- Reflectance levels
- Light distribution type

1. Spatial efficiency on the work plane level

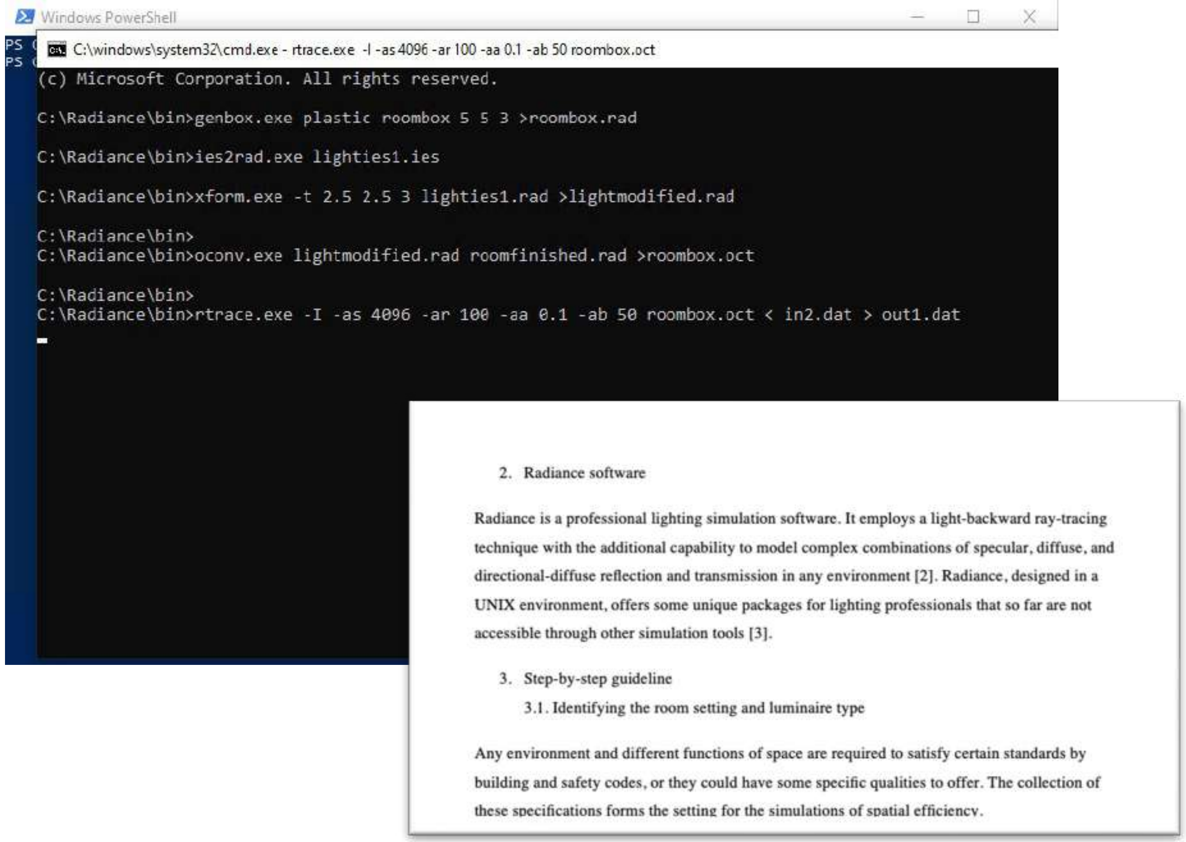
- Visual field angle

2. Spatial efficiency based on visual field angles

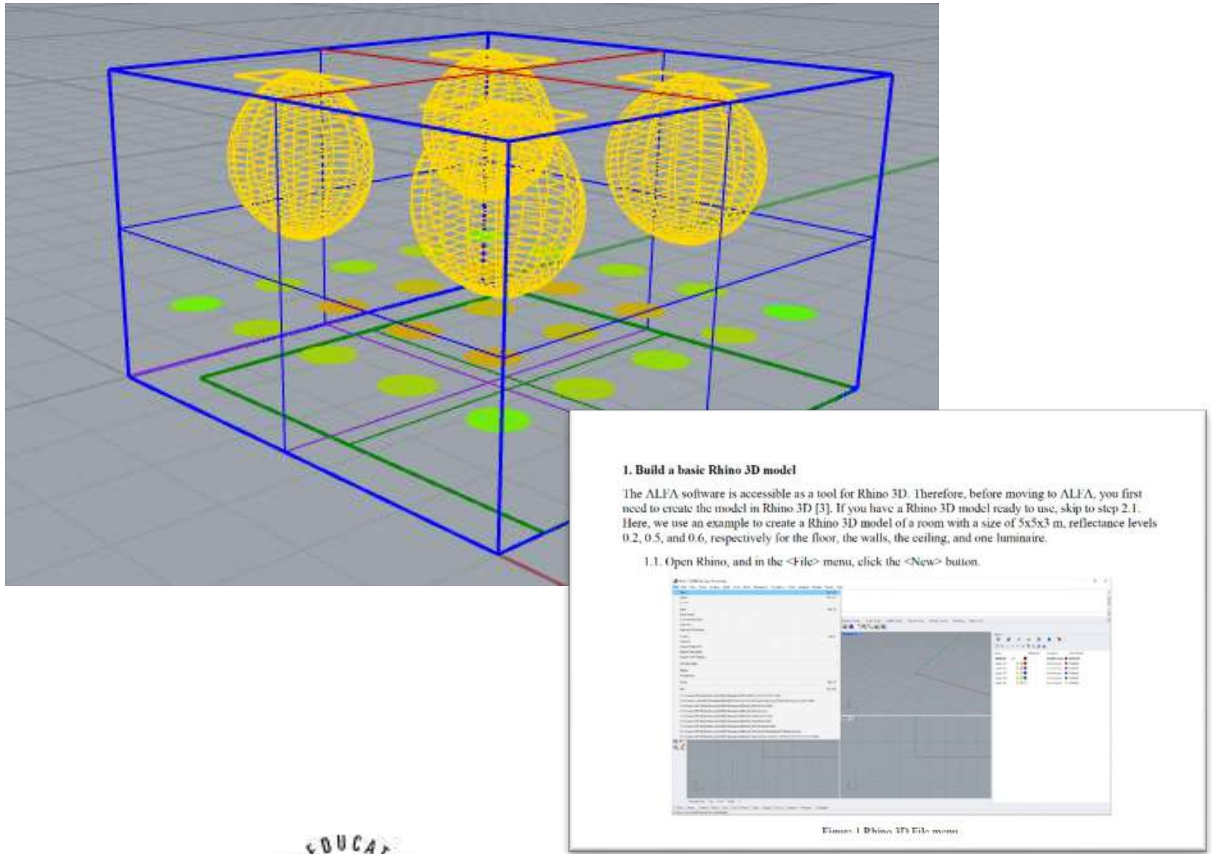
Spatial efficiency

Precise calculations on work plane level

Radiance



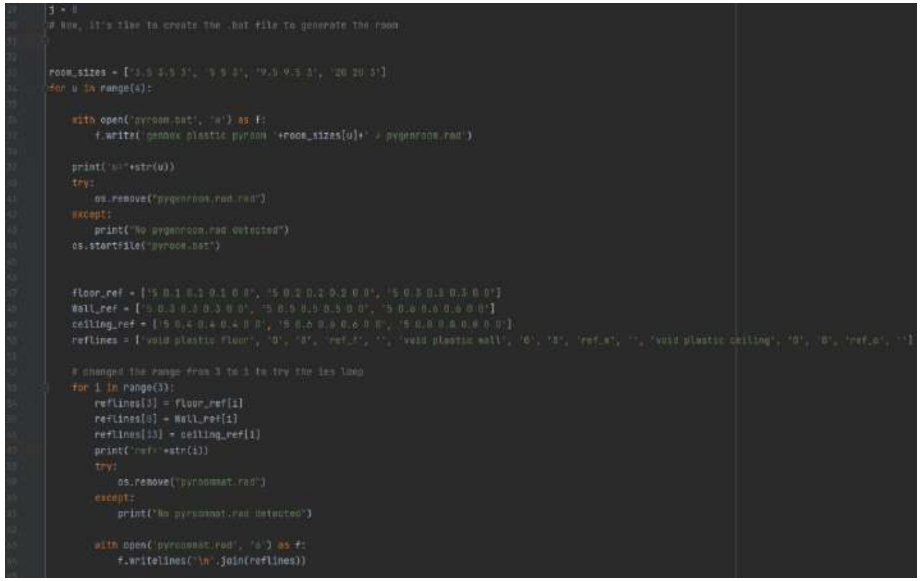
ALFA Solemma



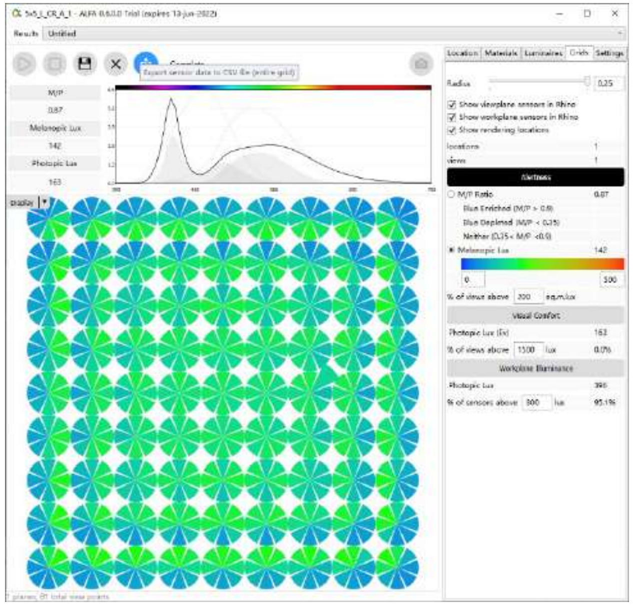
Spatial efficiency

On work plane level: software comparisons

Radiance



ALFA Solemma

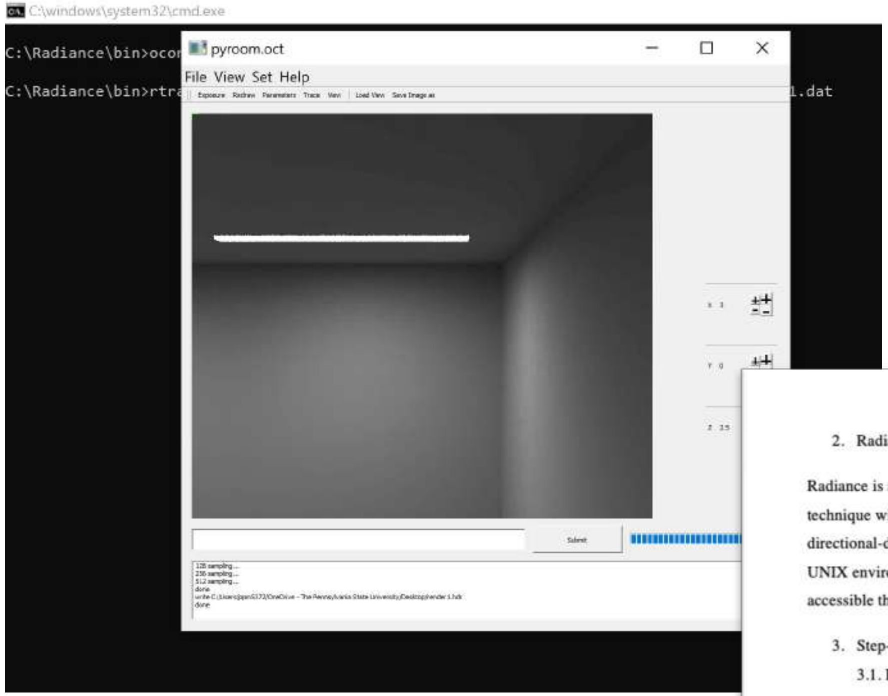


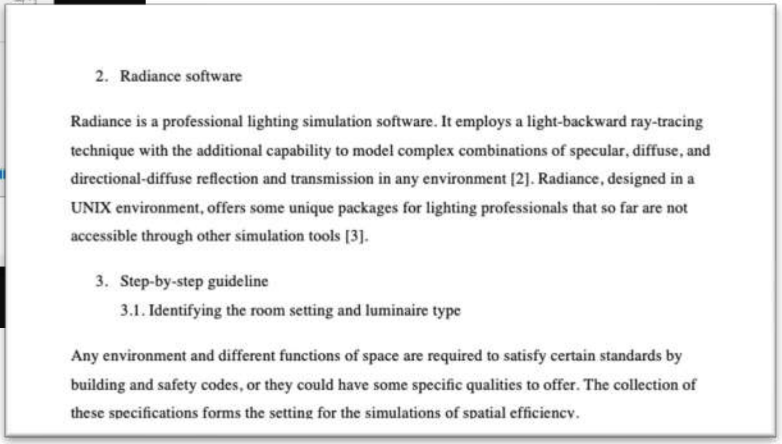
A total number of 162 room settings, 2556 distinct values for spatial efficiency

No significant difference between the values ($p = 0.1092$)

Spatial efficiency

Precise calculations for visual field using Radiance





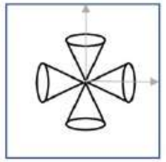
2. Radiance software

Radiance is a professional lighting simulation software. It employs a light-backward ray-tracing technique with the additional capability to model complex combinations of specular, diffuse, and directional-diffuse reflection and transmission in any environment [2]. Radiance, designed in a UNIX environment, offers some unique packages for lighting professionals that so far are not accessible through other simulation tools [3].

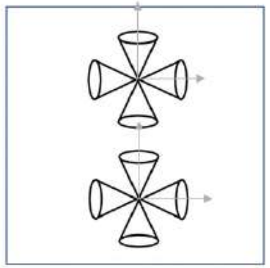
3. Step-by-step guideline

3.1. Identifying the room setting and luminaire type

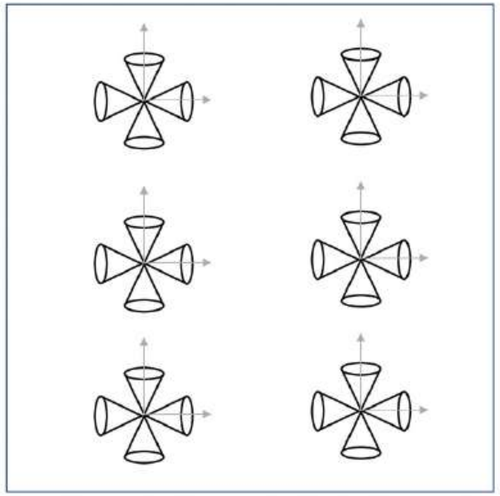
Any environment and different functions of space are required to satisfy certain standards by building and safety codes, or they could have some specific qualities to offer. The collection of these specifications forms the setting for the simulations of spatial efficiency.



$3.5 \times 3.5 = 12.25\ m^2$
(per occupant)



$5 \times 5 = 25\ m^2$
($12.5\ m^2$ per person)



$9.5 \times 9.5 = 90.25\ m^2$
6 occupant ($15.04\ m^2$ per occupant)

Spatial efficiency

Work plane level

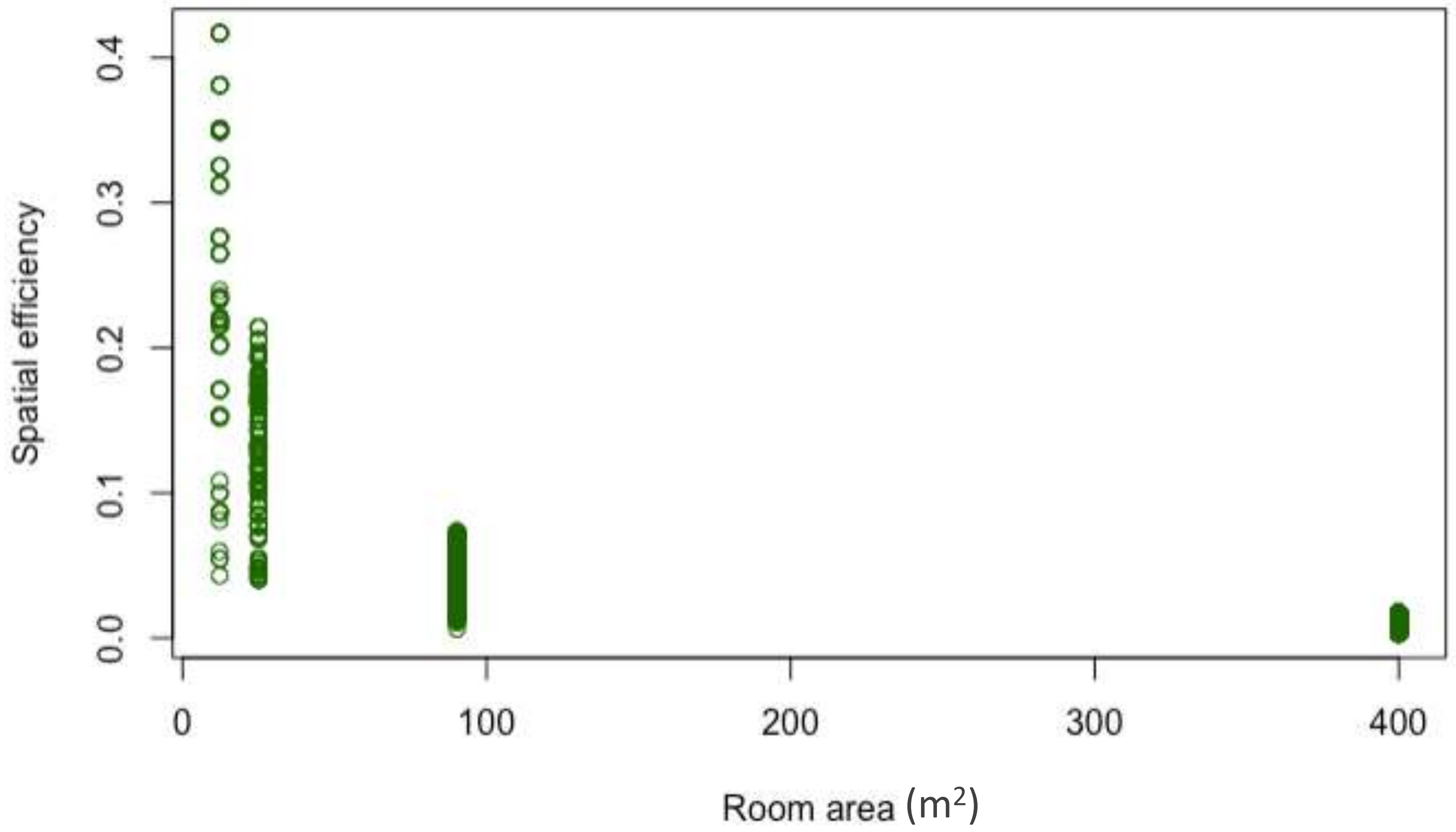
Descriptive statistics of spatial efficiency: a total of 72 room settings and 3924 distinct values for spatial efficiency.

	Radiant flux (W)	Spatial efficiency
N	3924	3924
Mean	9.81	0.02
SD	5.48	0.04
Median	8.56	0.01
Min	0.80	0.00
Max	26.20	0.42
Range	25.40	0.41
SE	0.09	0.00

Spatial efficiency

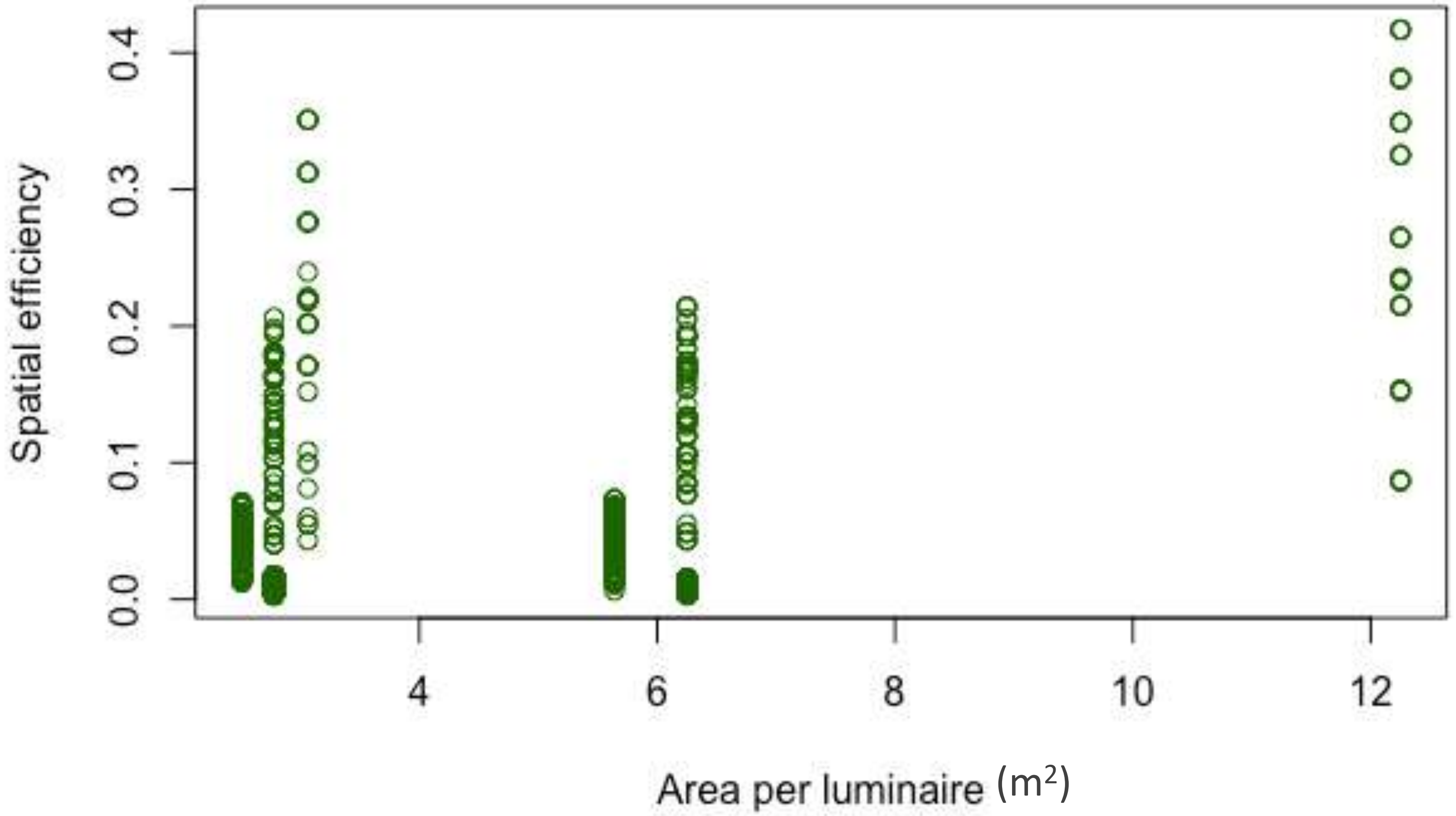
Work plane level

Spatial efficiency on the work plane level by room area



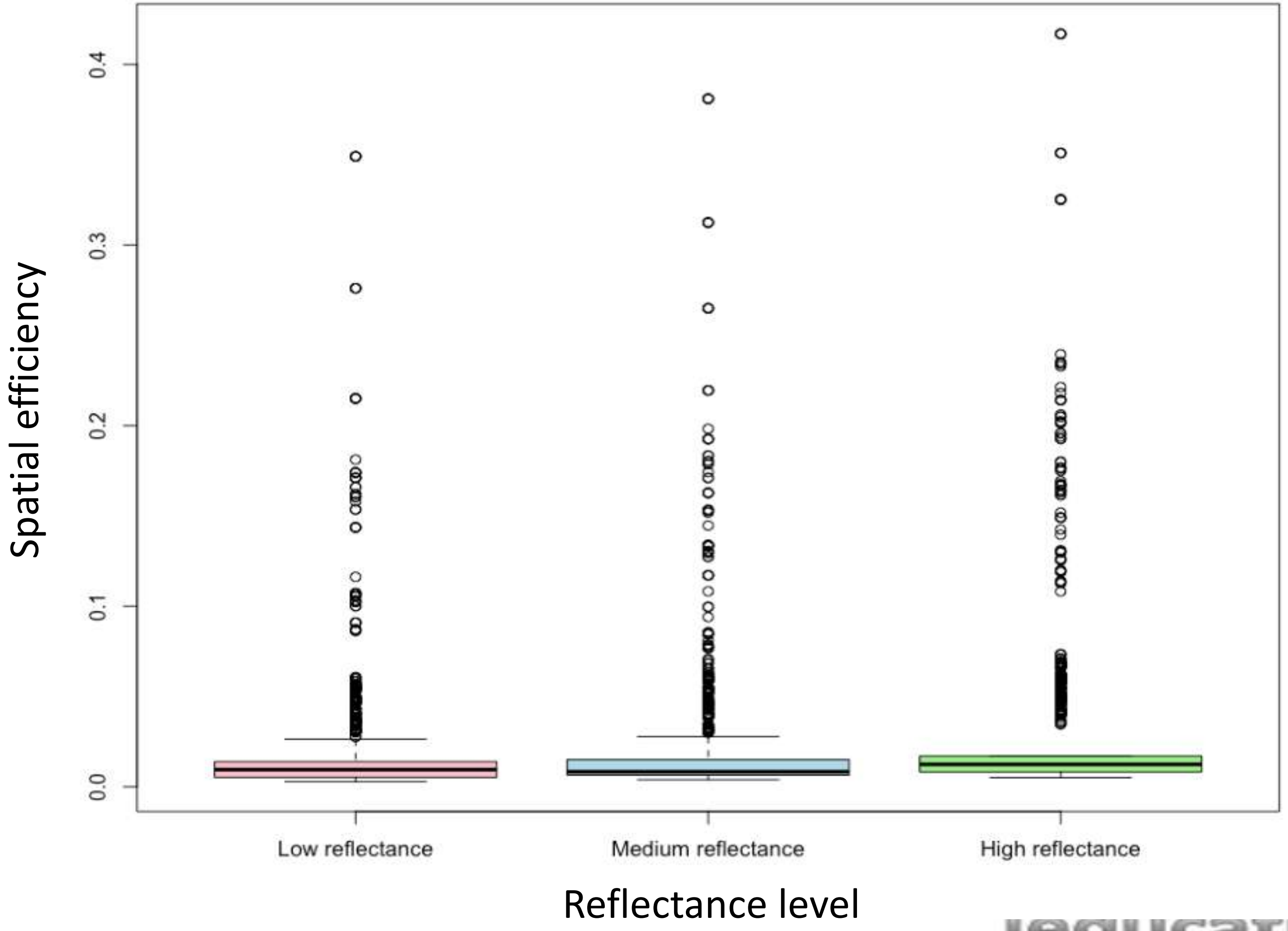
Spatial efficiency
Work plane level

Spatial efficiency on the work plane level by area per luminaire



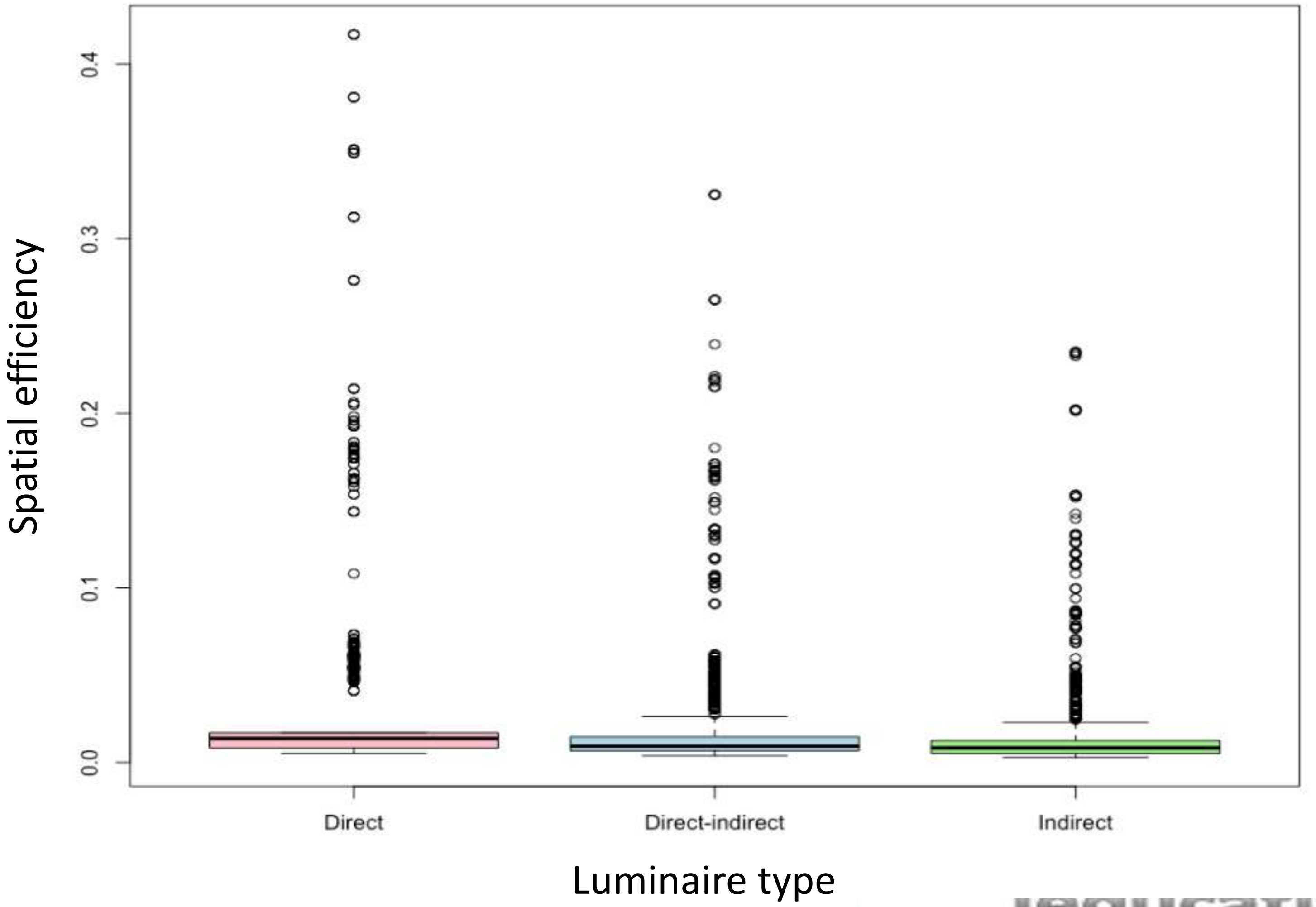
Spatial efficiency
Work plane level

Spatial efficiency on the work plane level by reflectance level



Spatial efficiency
Work plane level

Spatial efficiency on the work plane level by luminaire type



Spatial efficiency

Based on the visual field angles

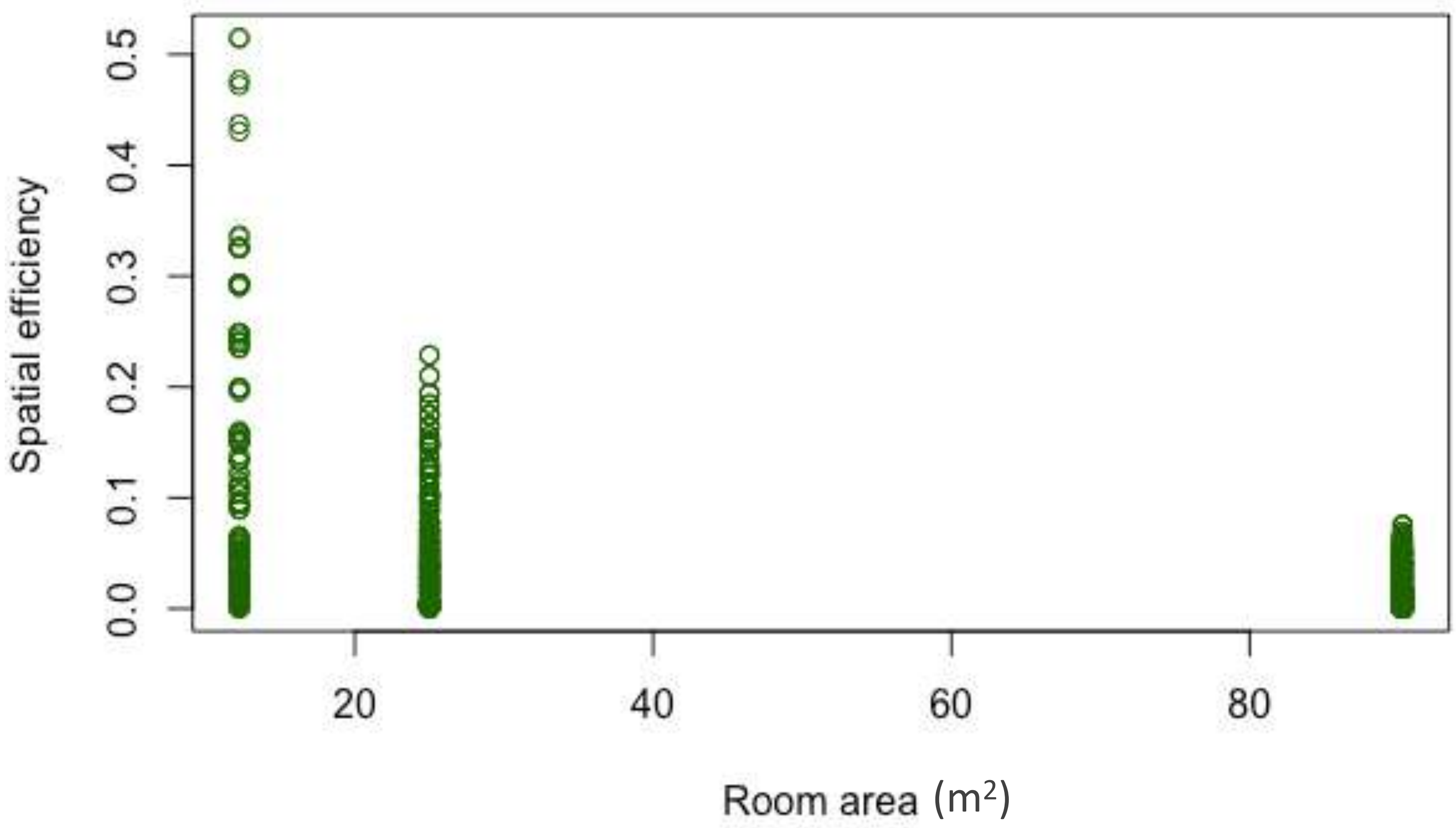
Descriptive statistics of spatial efficiency: a total of 54 room settings and 1944 distinct values for spatial efficiency.

	Radiant flux (W)	**Spatial efficiency**
N	1944	1944
Mean	3.17	0.03
SD	4.12	0.05
Median	1.49	0.01
Min	0.01	0.00
Max	22.67	0.51
Range	22.66	0.51
SE	0.09	0.00

Spatial efficiency

Based on the visual field angles

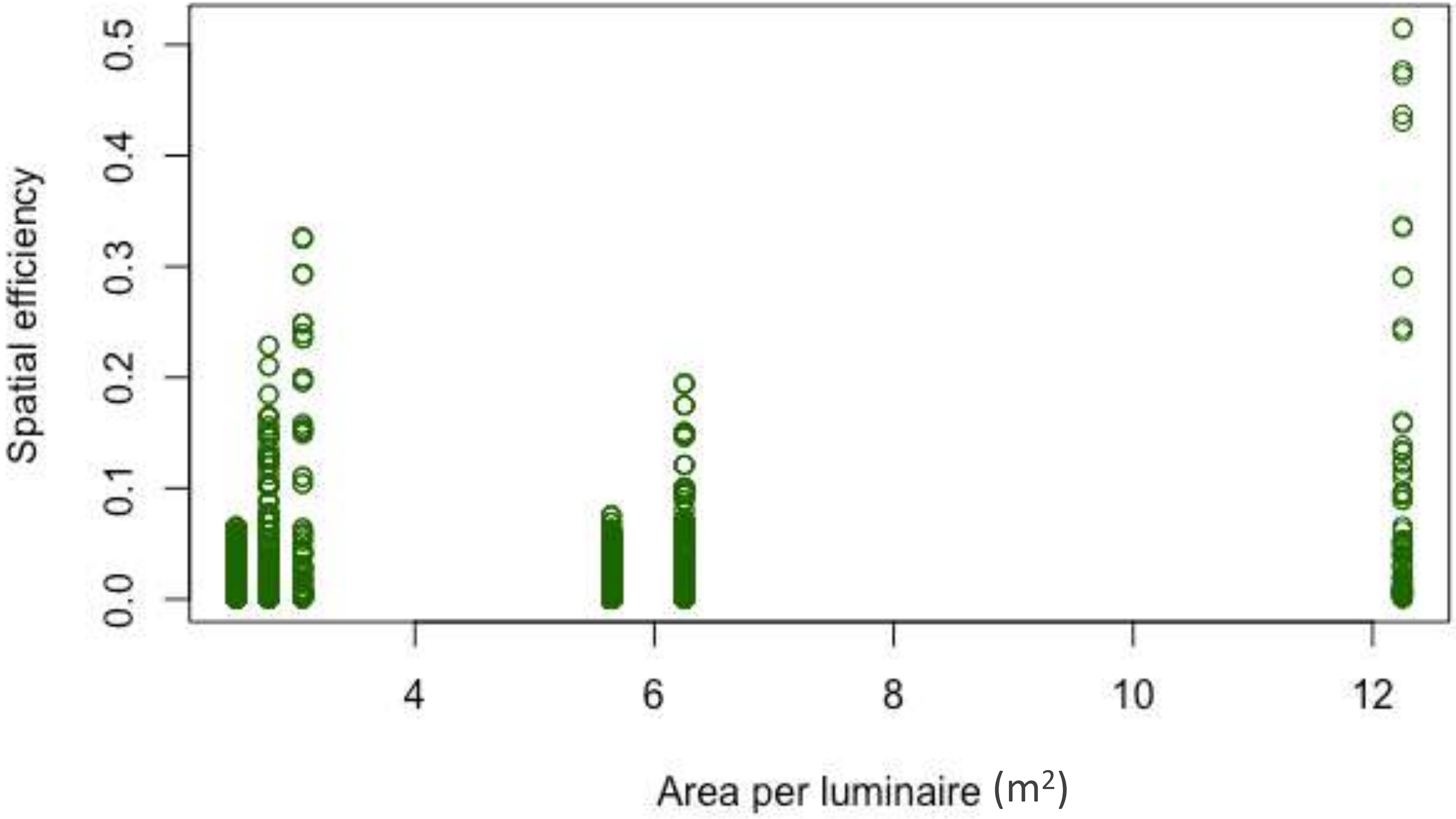
Spatial efficiency based on the visual field angles by room area



Spatial efficiency

Based on the visual field angles

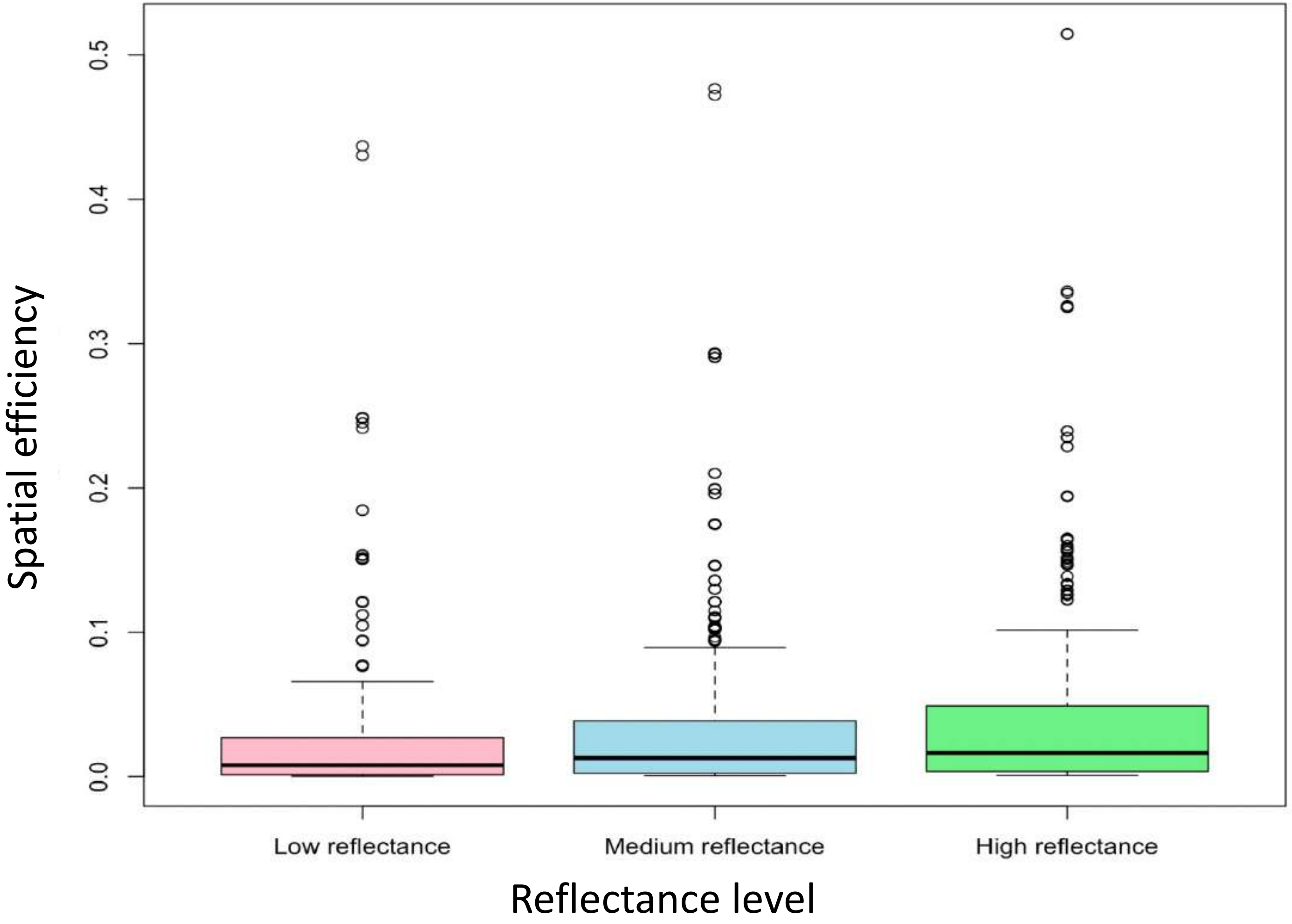
Spatial efficiency based on the visual field angles by area per luminaire



Spatial efficiency

Based on the visual field angles

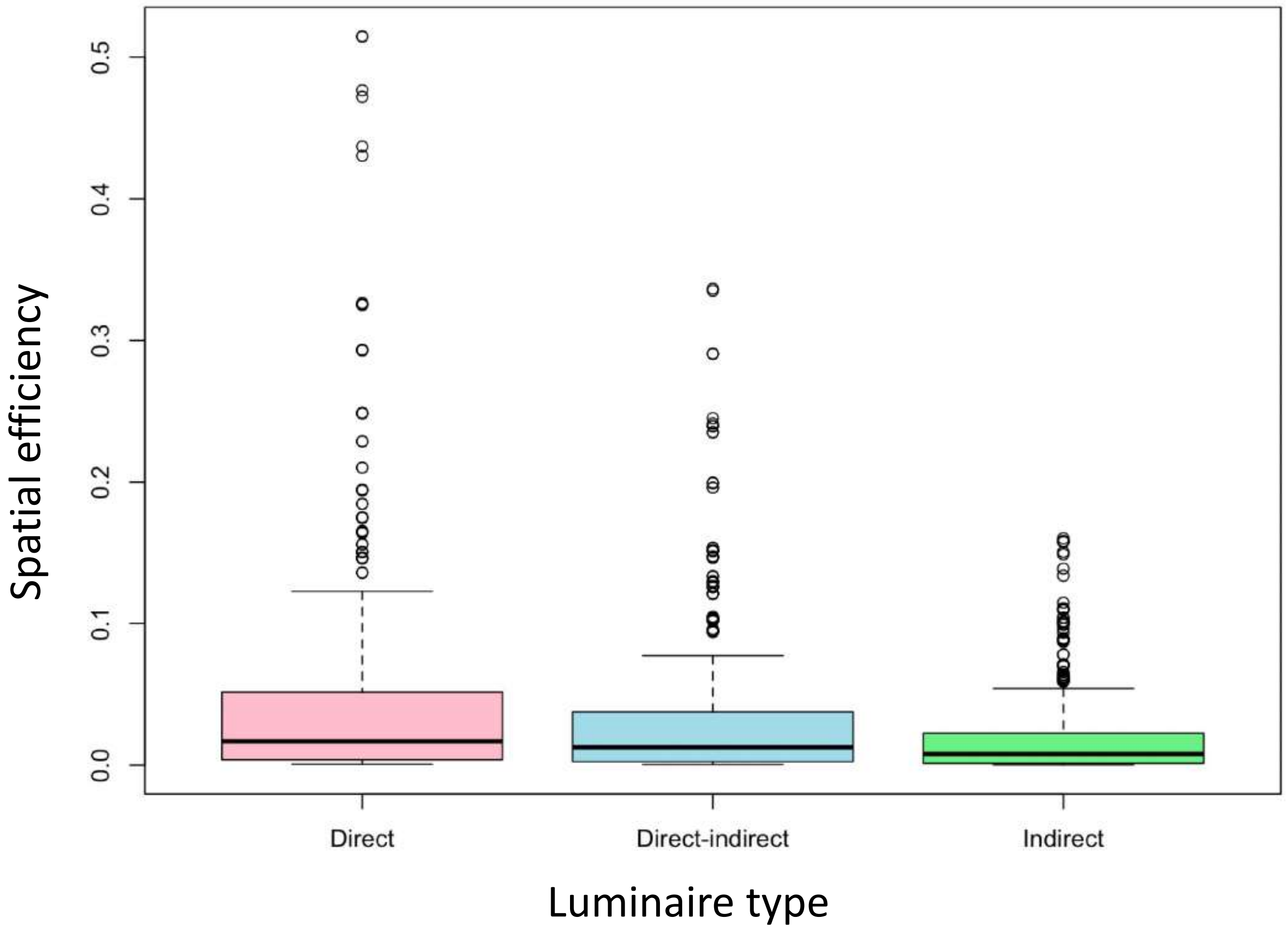
Spatial efficiency based on the visual field angles by reflectance level



Spatial efficiency

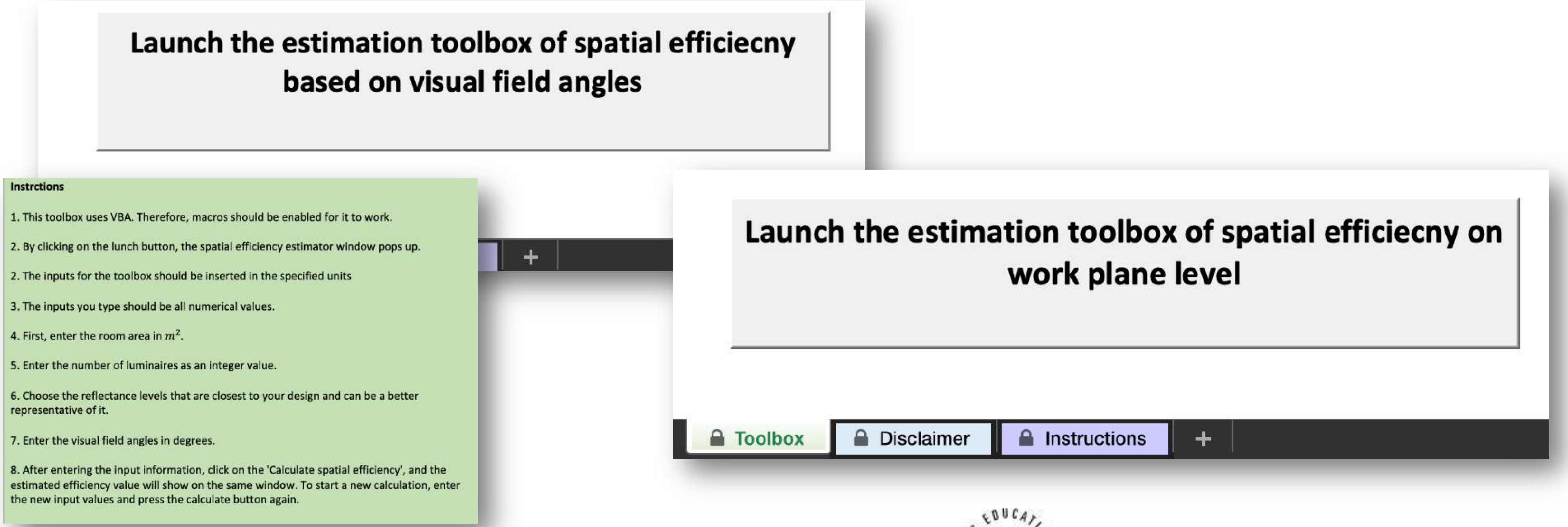
Based on the visual field angles

Spatial efficiency based on the visual field angles by luminaire distribution type



The spatial efficiency toolbox

Based on regression model



Instrctions

1. This toolbox uses VBA. Therefore, macros should be enabled for it to work.

2. By clicking on the lunch button, the spatial efficiency estimator window pops up.

2. The inputs for the toolbox should be inserted in the specified units

3. The inputs you type should be all numerical values.

4. First, enter the room area in m^2.

5. Enter the number of luminaires as an integer value.

6. Choose the reflectance levels that are closest to your design and can be a better representative of it.

7. Enter the visual field angles in degrees.

8. After entering the input information, click on the 'Calculate spatial efficiency', and the estimated efficiency value will show on the same window. To start a new calculation, enter the new input values and press the calculate button again.

Next Steps

	Luminaire efficiency $\eta_{luminaire}$	Spatial efficiency $\eta_{spatial}$	Visual sensitivity S_{visual}
Version 1: Near-term Low complexity	• Radiant efficiency • Light output ratio	• Proportion of emitted light directed to areas within occupants' visual fields • Proportion of emitted light directed to task area(s)	• Spectral luminous efficiency (V_λ)
Version 2: Medium-term Moderate complexity	All of the above +		
	• Efficiency changes as a function of operating time		• Effect of contrast on perceived brightness
Version 3: Long-term High complexity	All of the above +		
	• Control system efficiency • Efficiency changes from altered conditions (e.g., temperature)	• Spatially dynamic lighting (e.g., gaze-dependent lighting)	• State of visual adaptation • Occupant age • Sensitivity as a function of location within visual field

This is next.

Summary

Spatial efficiency

On work plane level

Precise: Using Radiance &
ALFA Solemma

Approximate: The spatial
efficiency toolbox

Based on visual field angles

Precise: Using Radiance

Approximate: The spatial
efficiency toolbox

The first step in developing a computational method for LAE

Conclusions

- Lighting design is multifaceted.
- Luminous efficacy alone is not perfect or enough.
- The necessity of a holistic approach in lighting efficiency measures.
- Future work will advance the LAE to be more comprehensive.
- The LAE spreadsheet toolboxes and step-step guidelines will be released.
- New research is demanded to build upon the LAE framework.

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Questions?

Special thanks to Dr. Richard Mistrick, Dr. Jennifer Valcin, George Zhu, and Greg Ward.

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This concludes The American Institute of Architects Continuing Education Systems Course

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