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# Electrochromic / Tinted Glazing: Modelling the Illumination Spectrum

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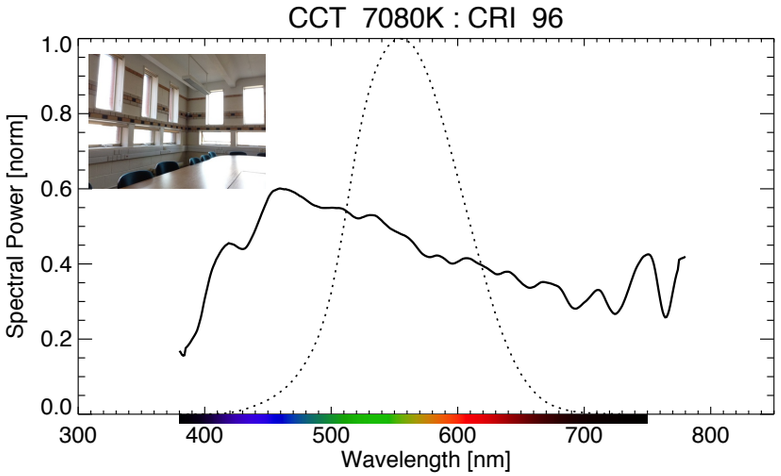
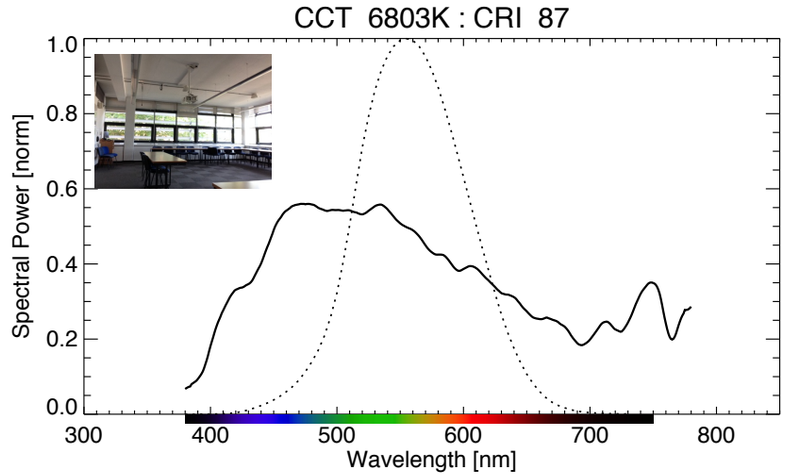
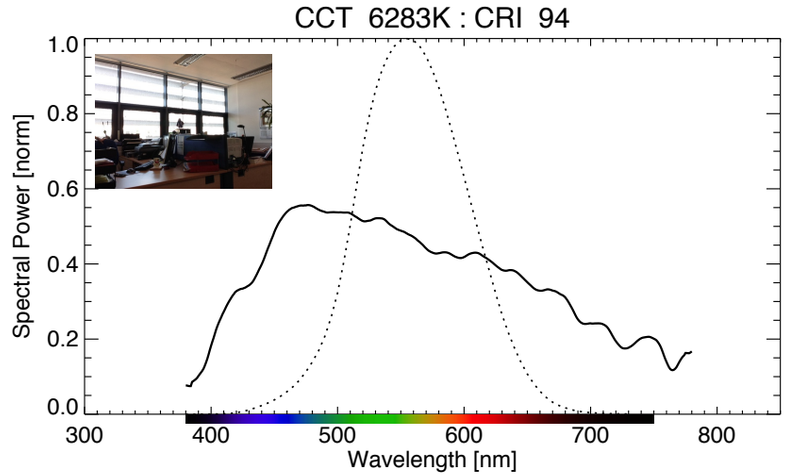
Centre of Excellence for Sustainable Building Design

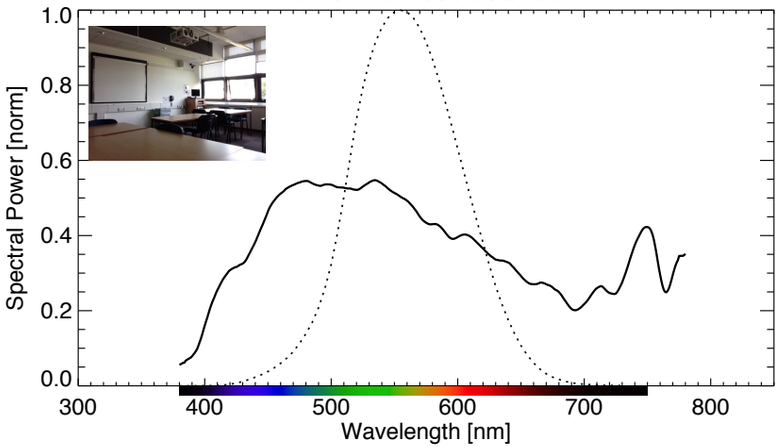
Loughborough University

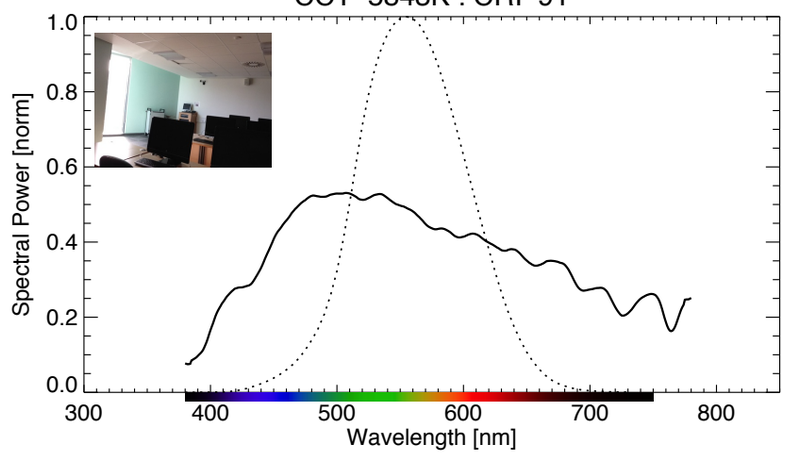
# Daylight illumination spectra

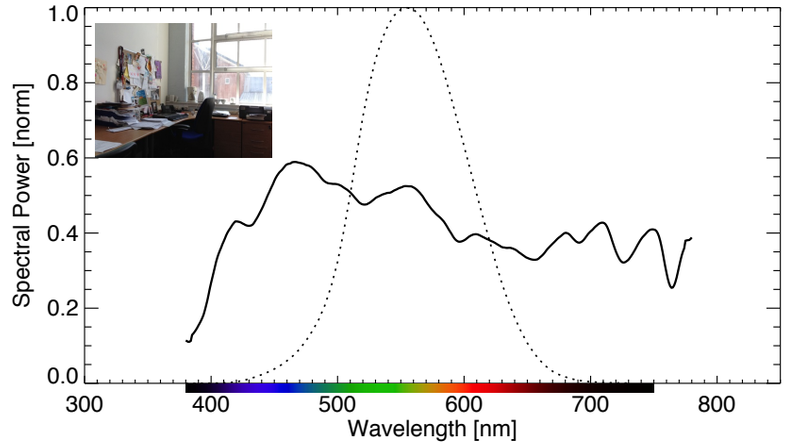

CCT 7080K : CRI 96
Spectral Power [norm]
Wavelength [nm]

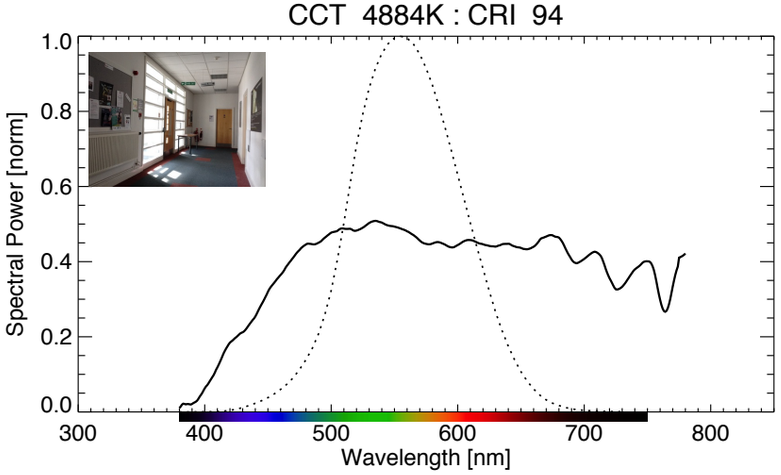

CCT 6803K : CRI 87
Spectral Power [norm]
Wavelength [nm]

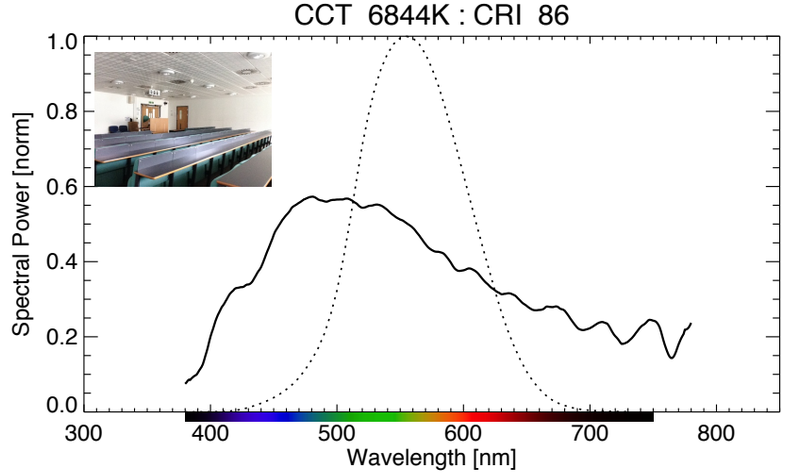

CCT 6283K : CRI 94
Spectral Power [norm]
Wavelength [nm]

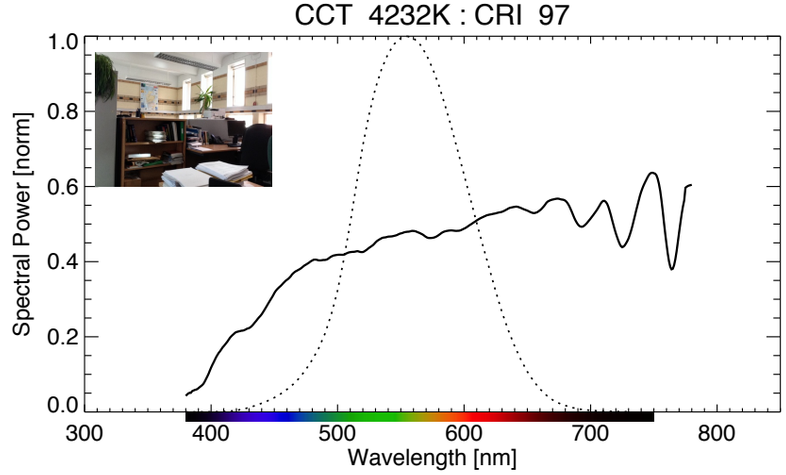

CCT 6468K : CRI 88
Spectral Power [norm]
Wavelength [nm]

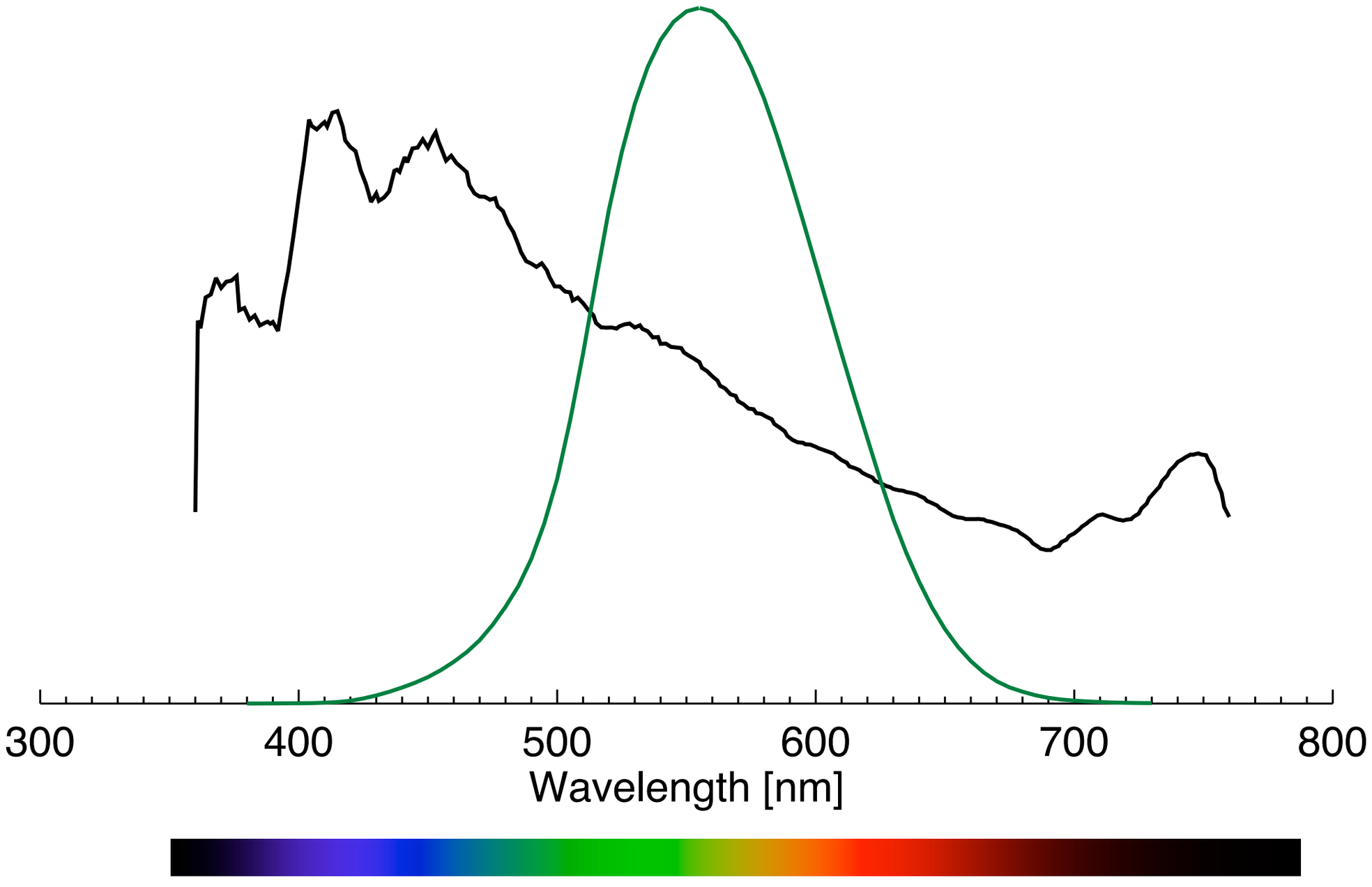

CCT 5843K : CRI 91
Spectral Power [norm]
Wavelength [nm]

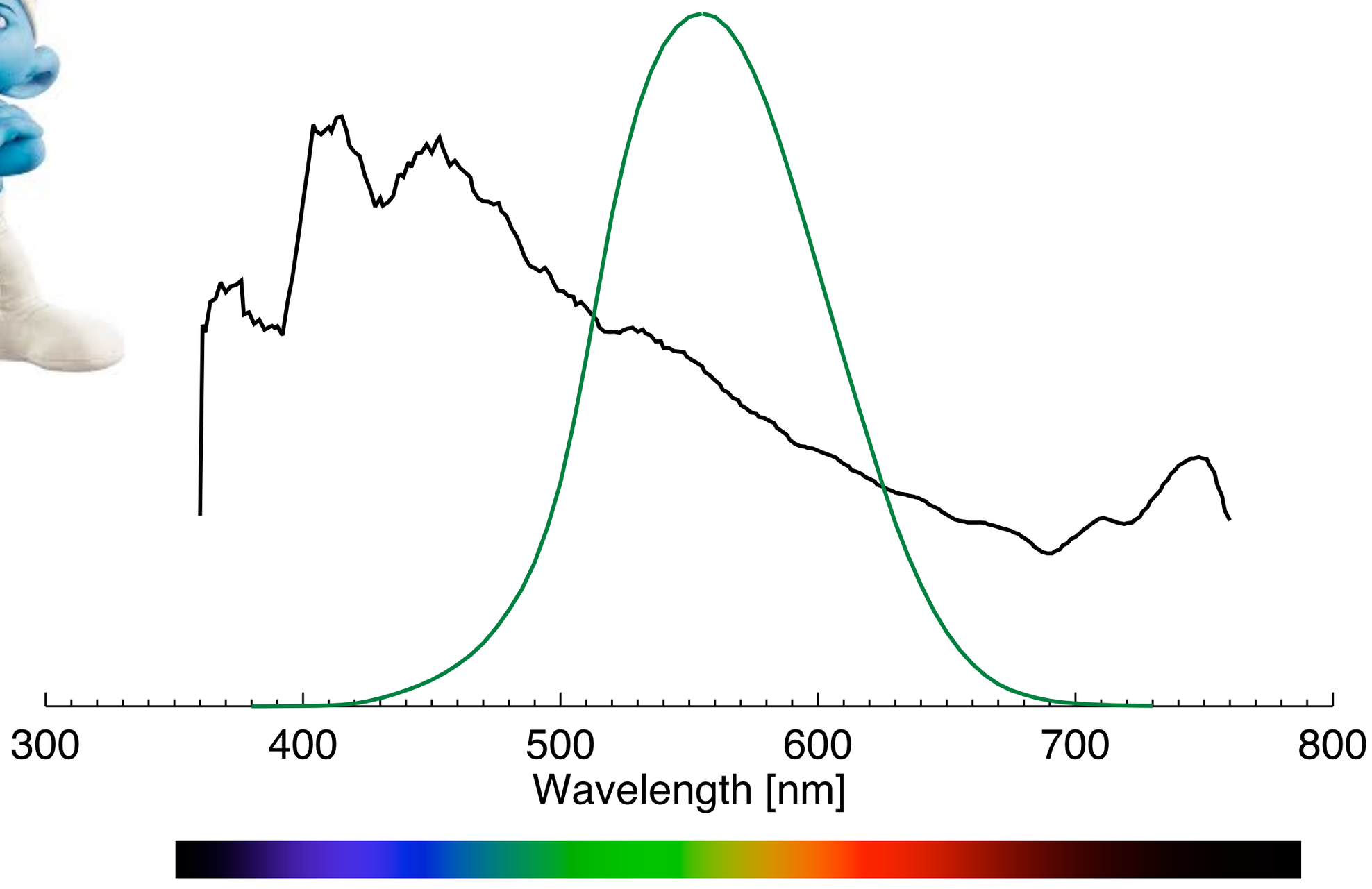

CCT 6843K : CRI 93
Spectral Power [norm]
Wavelength [nm]

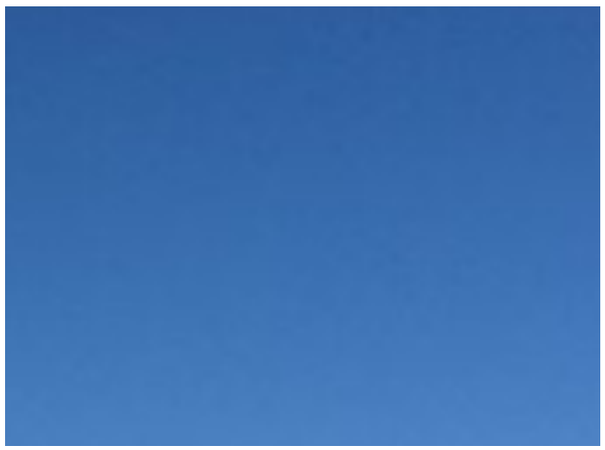

CCT 4884K : CRI 94
Spectral Power [norm]
Wavelength [nm]

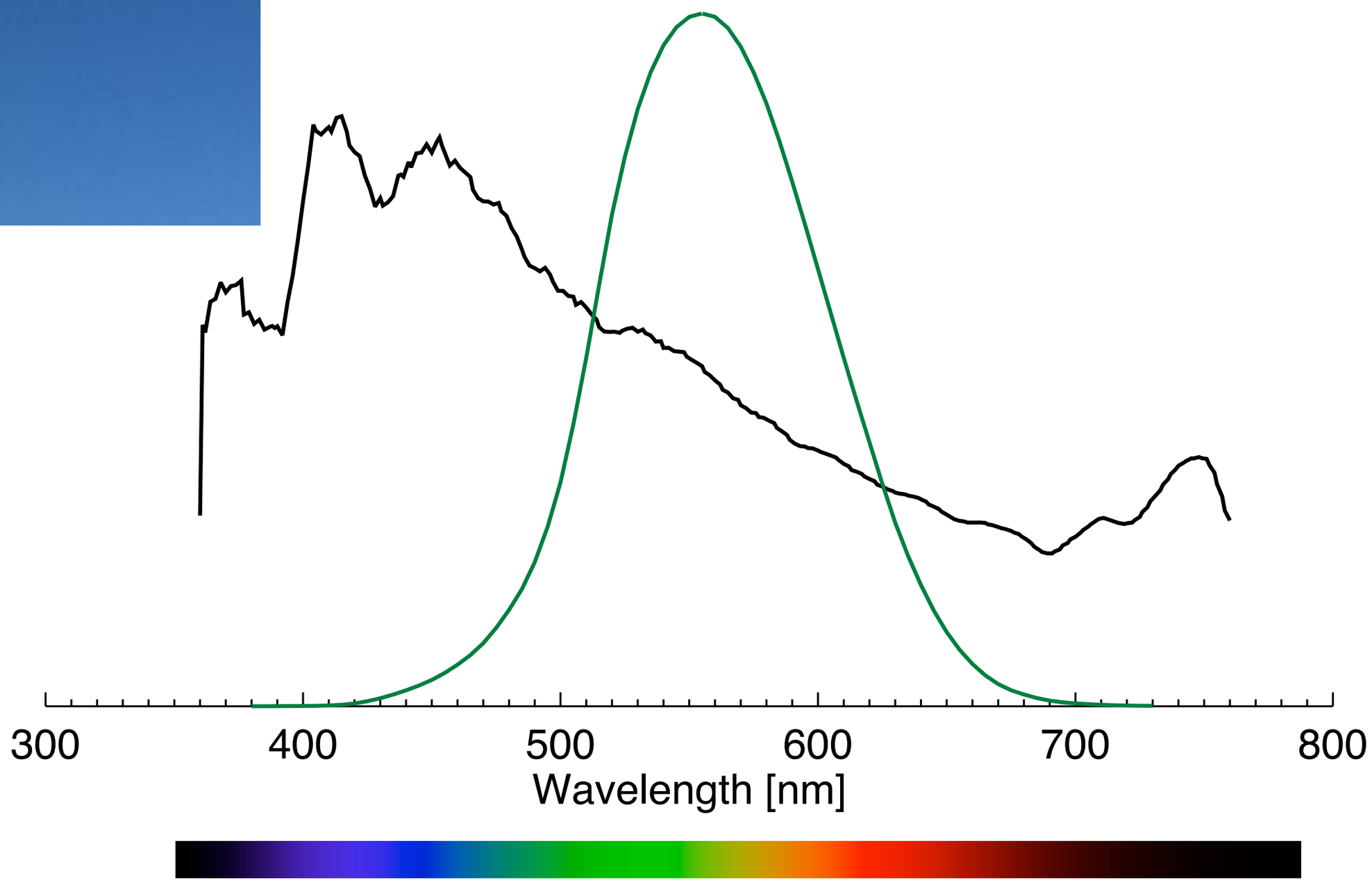

CCT 6844K : CRI 86
Spectral Power [norm]
Wavelength [nm]

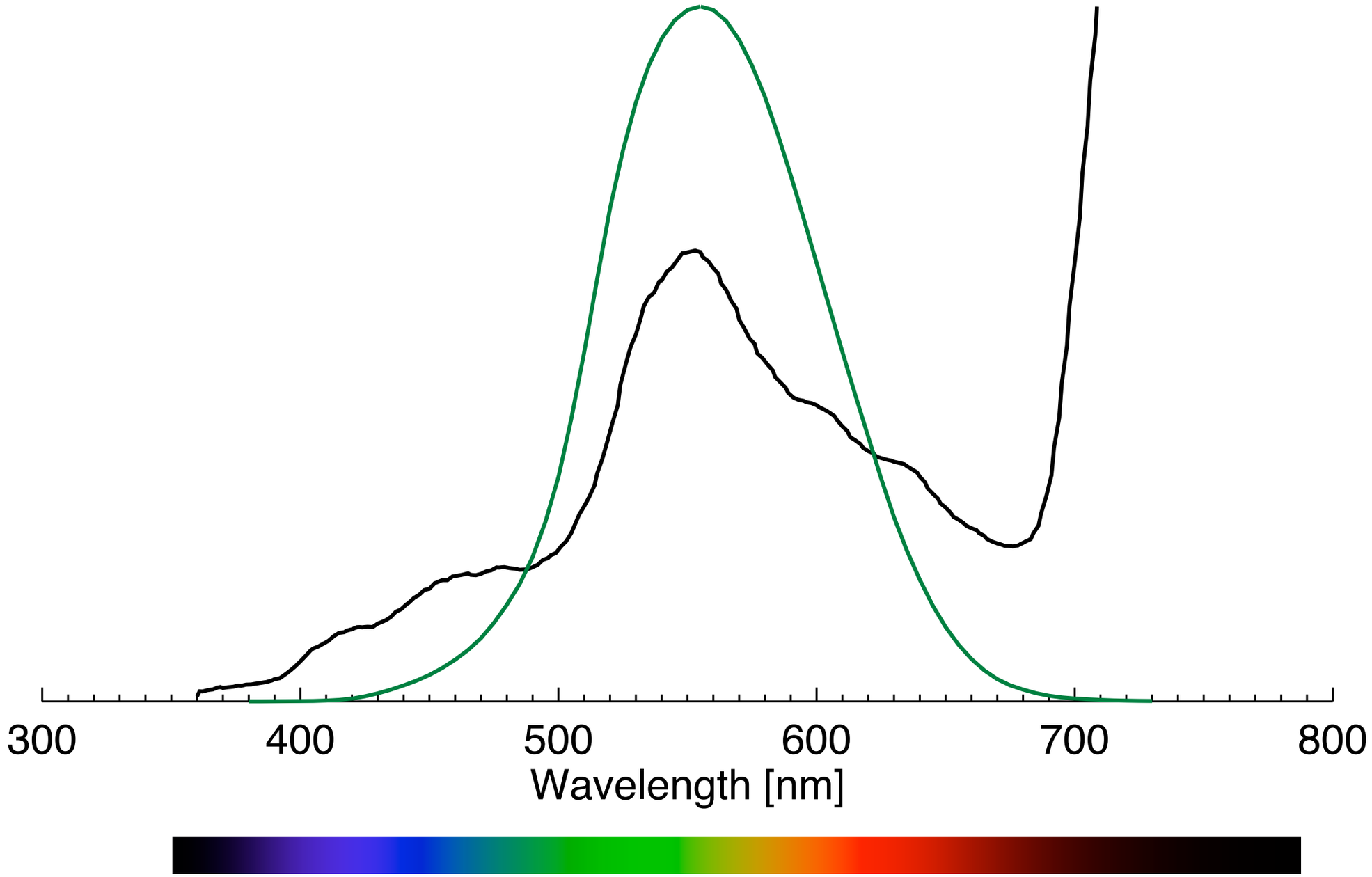

CCT 4232K : CRI 97
Spectral Power [norm]
Wavelength [nm]


300
400
500
600
700
800
Wavelength [nm]

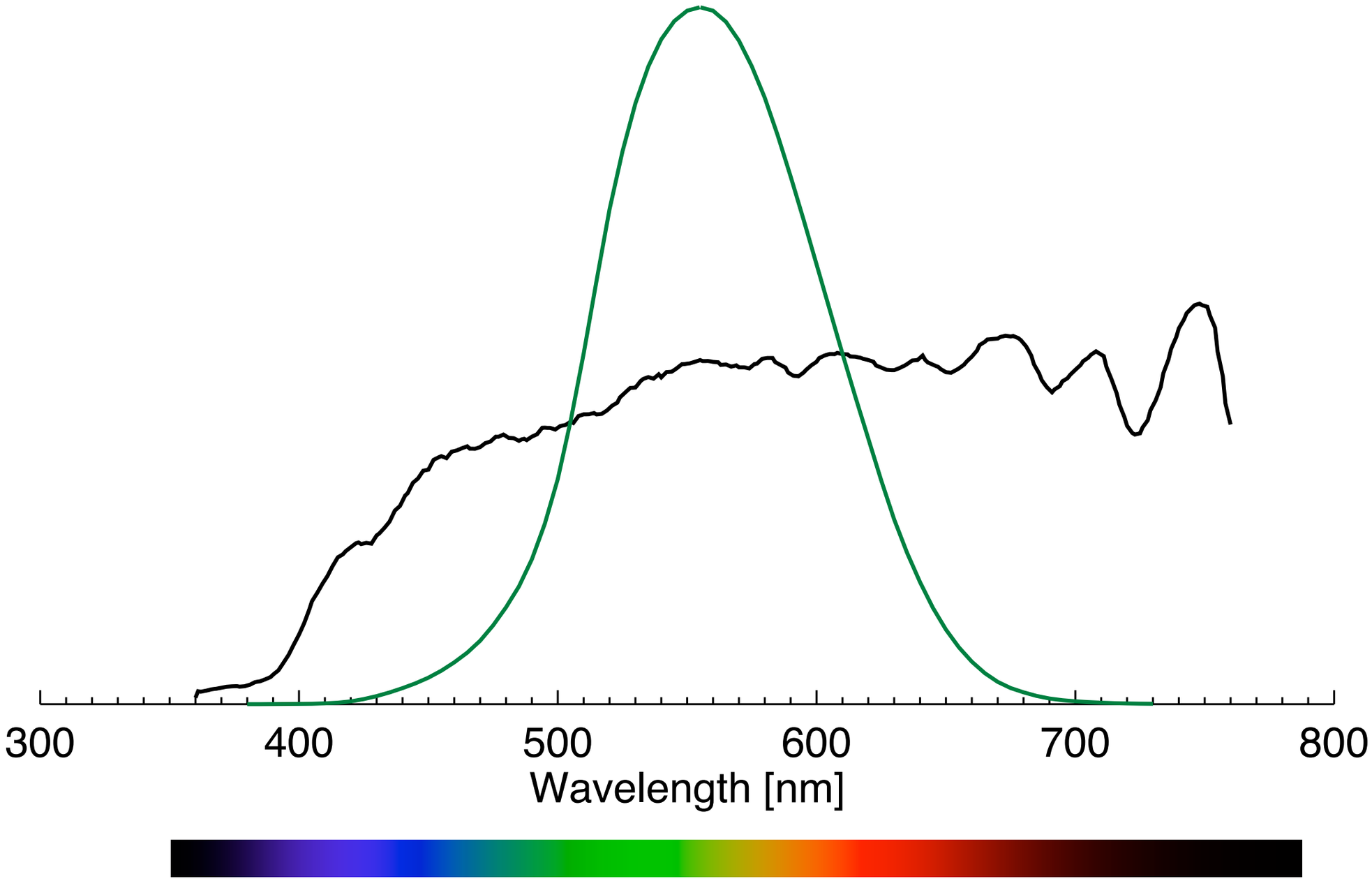

300
400
500
600
700
800
Wavelength [nm]

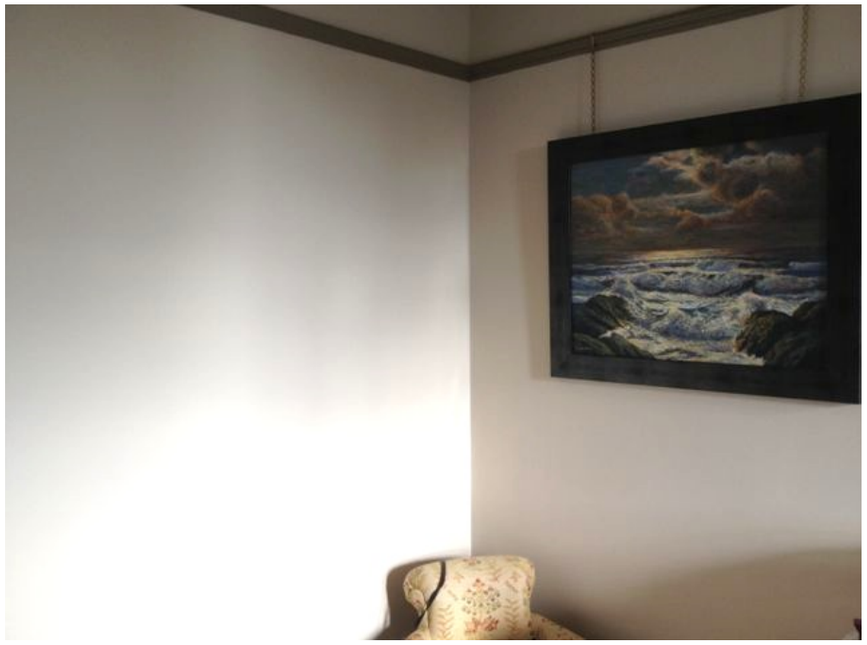



300
400
500
600
700
800
Wavelength [nm]

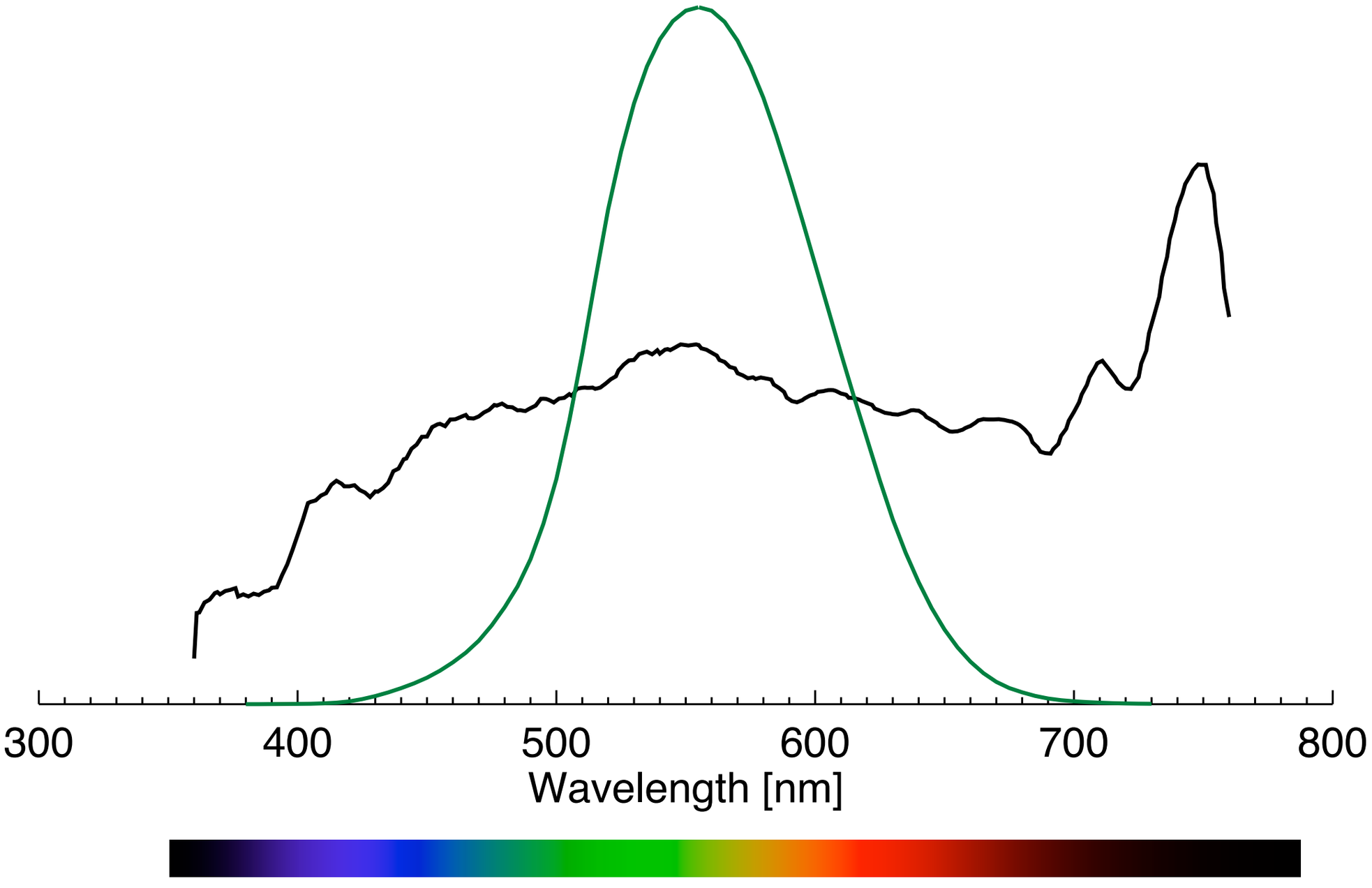

300
400
500
600
700
800
Wavelength [nm]

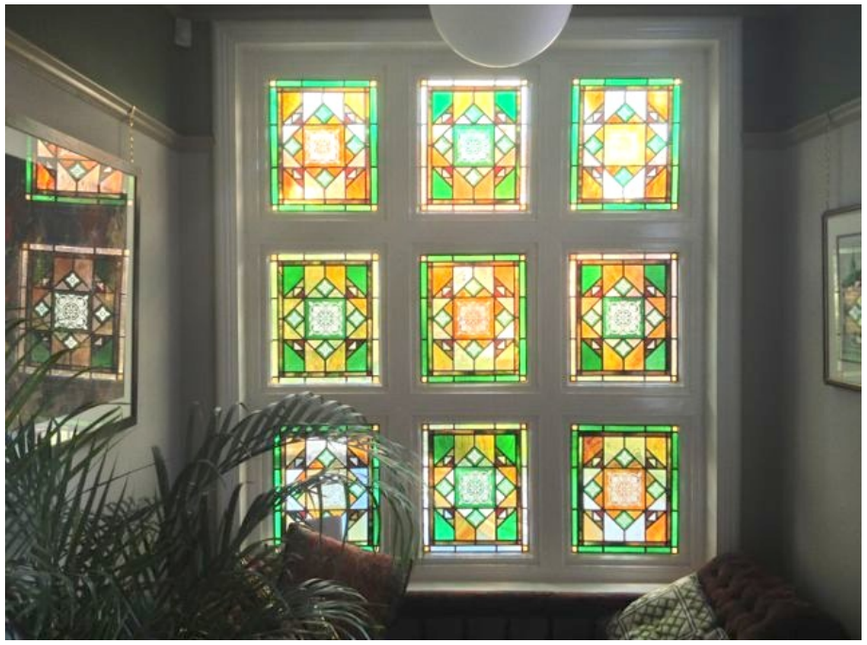

300
400
500
600
700
800
Wavelength [nm]


300
400
500
600
700
800
Wavelength [nm]



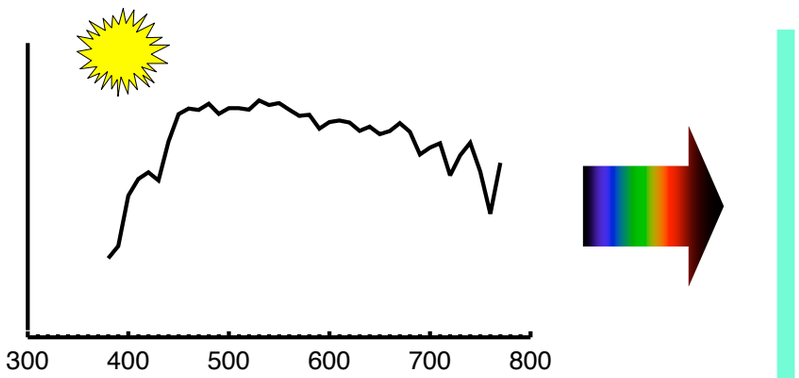

300
400
500
600
700
800
Wavelength [nm]


300
400
500
600
700
800
Wavelength [nm]

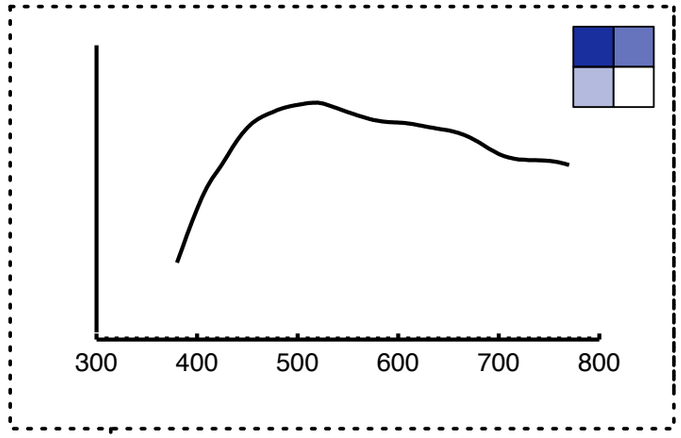



300
400
500
600
700
800
Wavelength [nm]

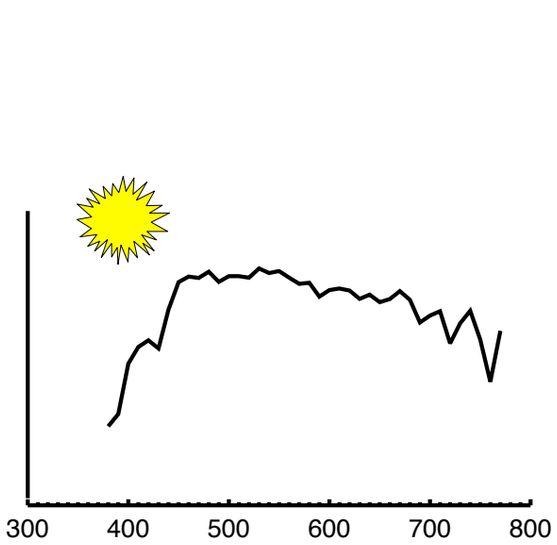
# Transformations of daylight



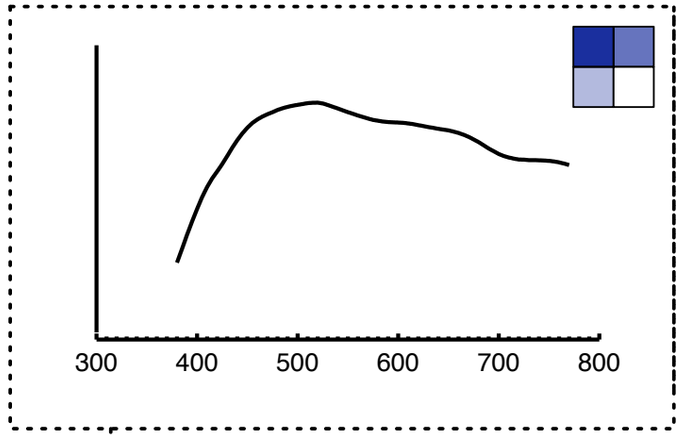

**SPD of light incident on the window**



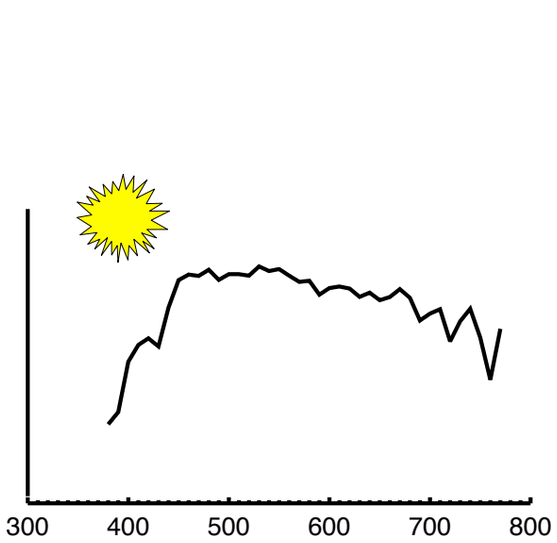

**Spectral transmittance of the glazing panels**



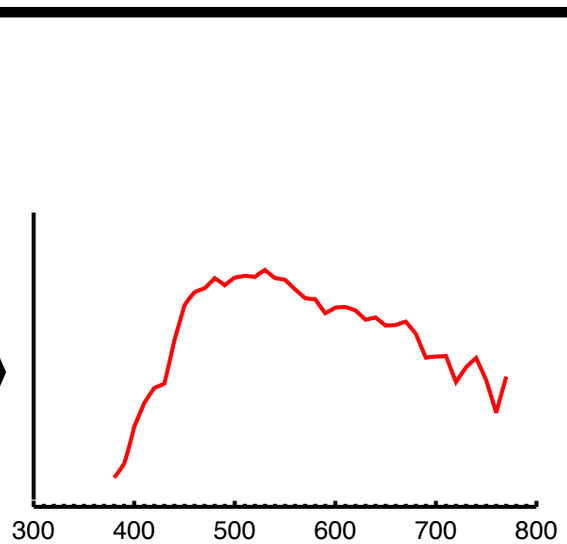

**SPD of light incident on the window**



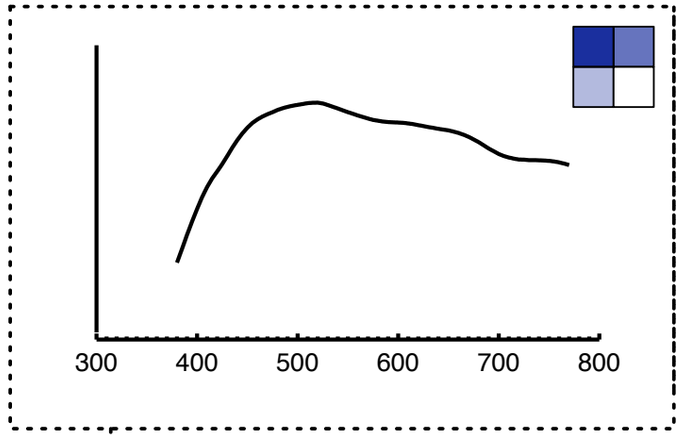

**Spectral transmittance of the glazing panels**



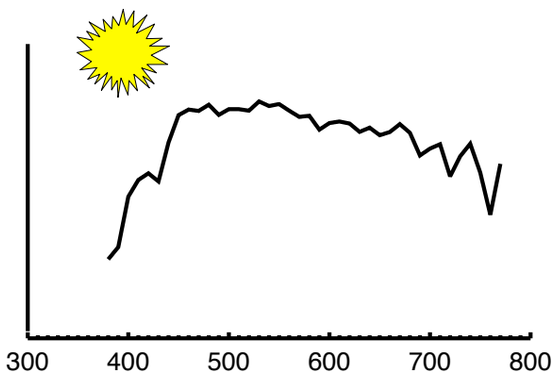

**SPD of light incident on the window**



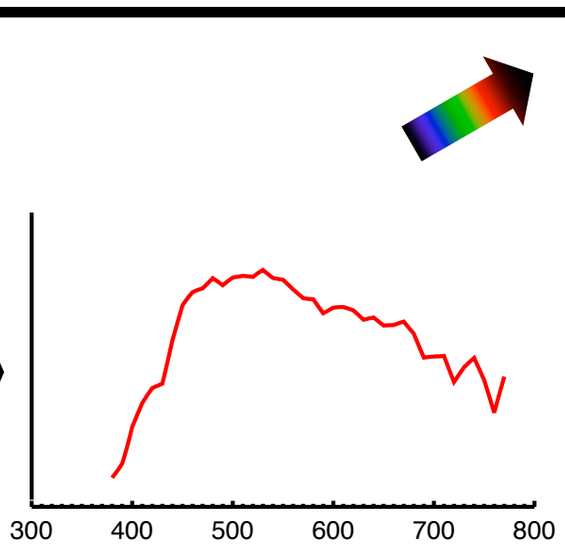

**SPD of light entering the space**



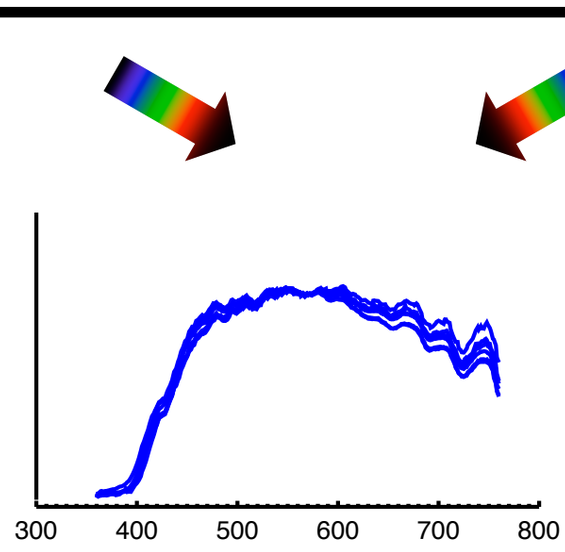

**Spectral transmittance of the glazing panels**



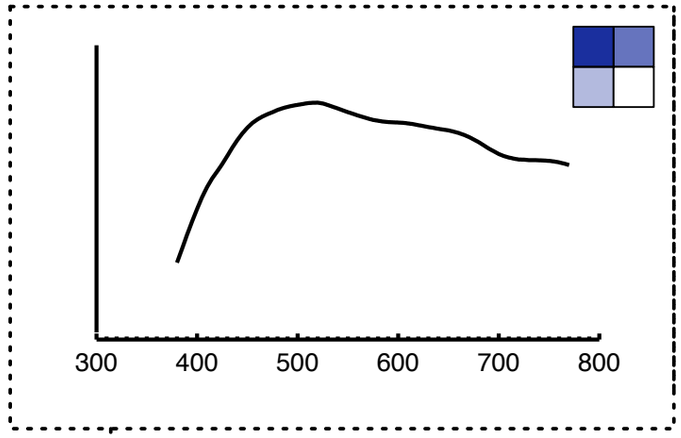

**SPD of light incident on the window**



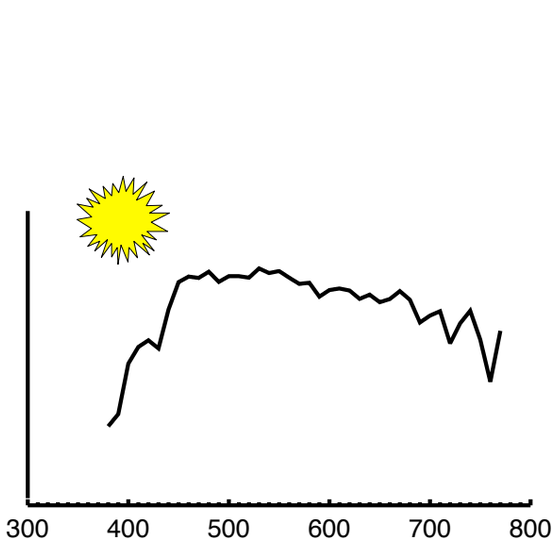

**SPD of light entering the space**



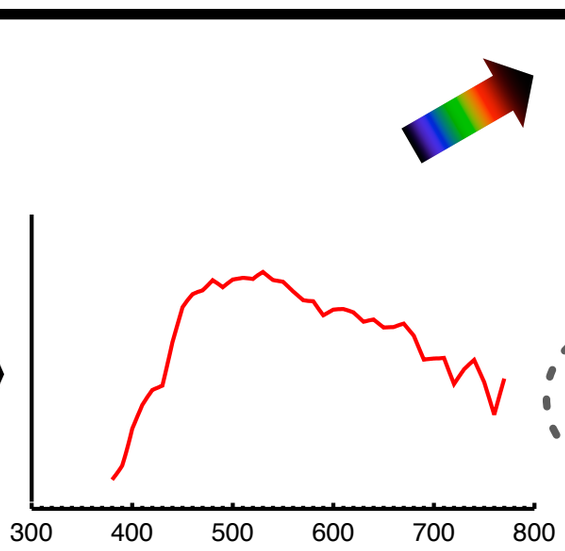

**SPD of light recieved at points in the space**




**Spectral transmittance of the glazing panels**




**SPD of light incident on the window**




**SPD of light entering the space**

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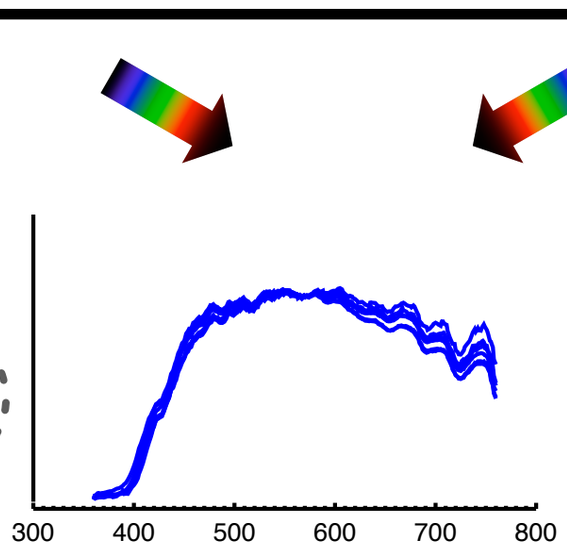


**SPD of light recieved at points in the space**

# Hypothesis

The dynamic control of daylight is the

*"Holy Grail of the fenestration industry"*

Steve Selkowitz, Lawrence Berkeley national Laboratory, CA, USA

1998

**Image from Monty Python and the Holy Grail**

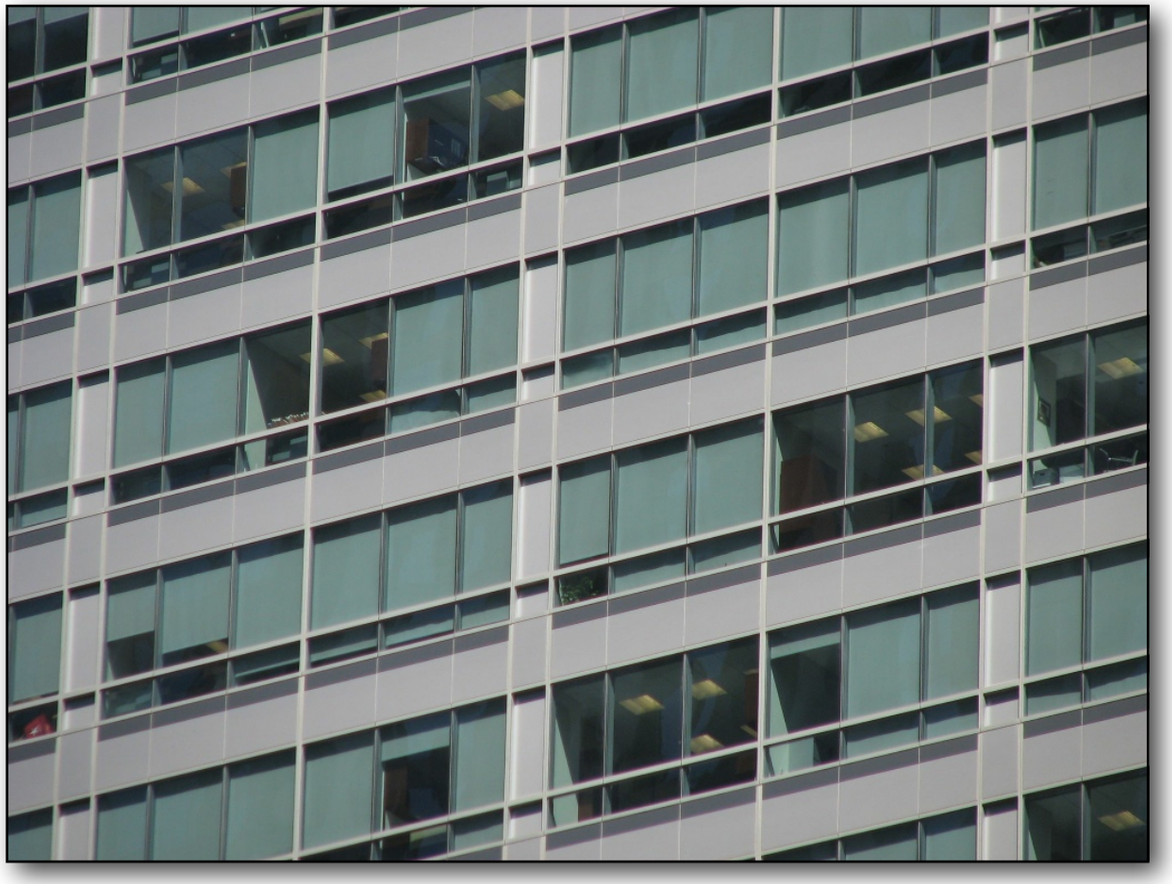

Image SAGE Electrochromics

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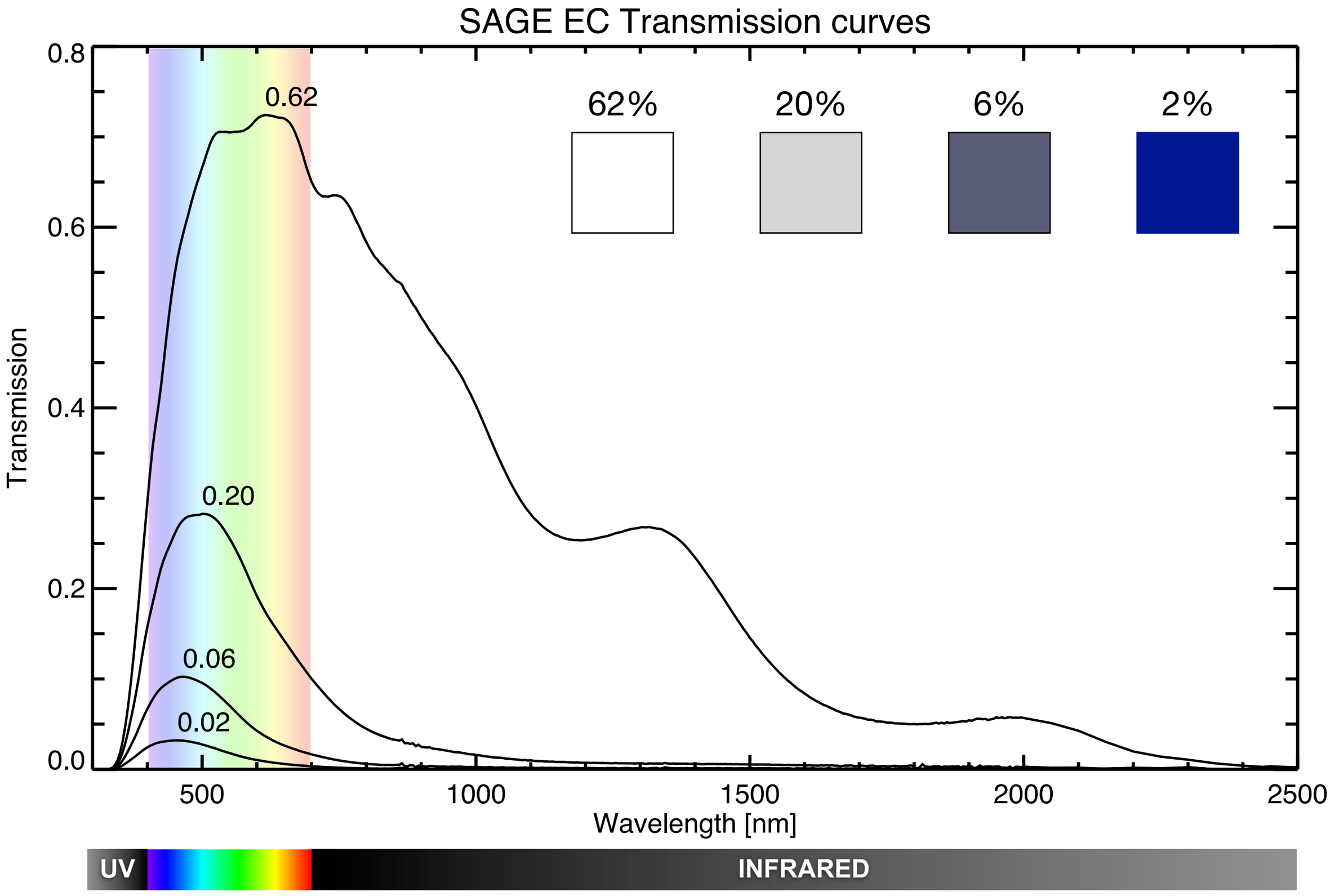
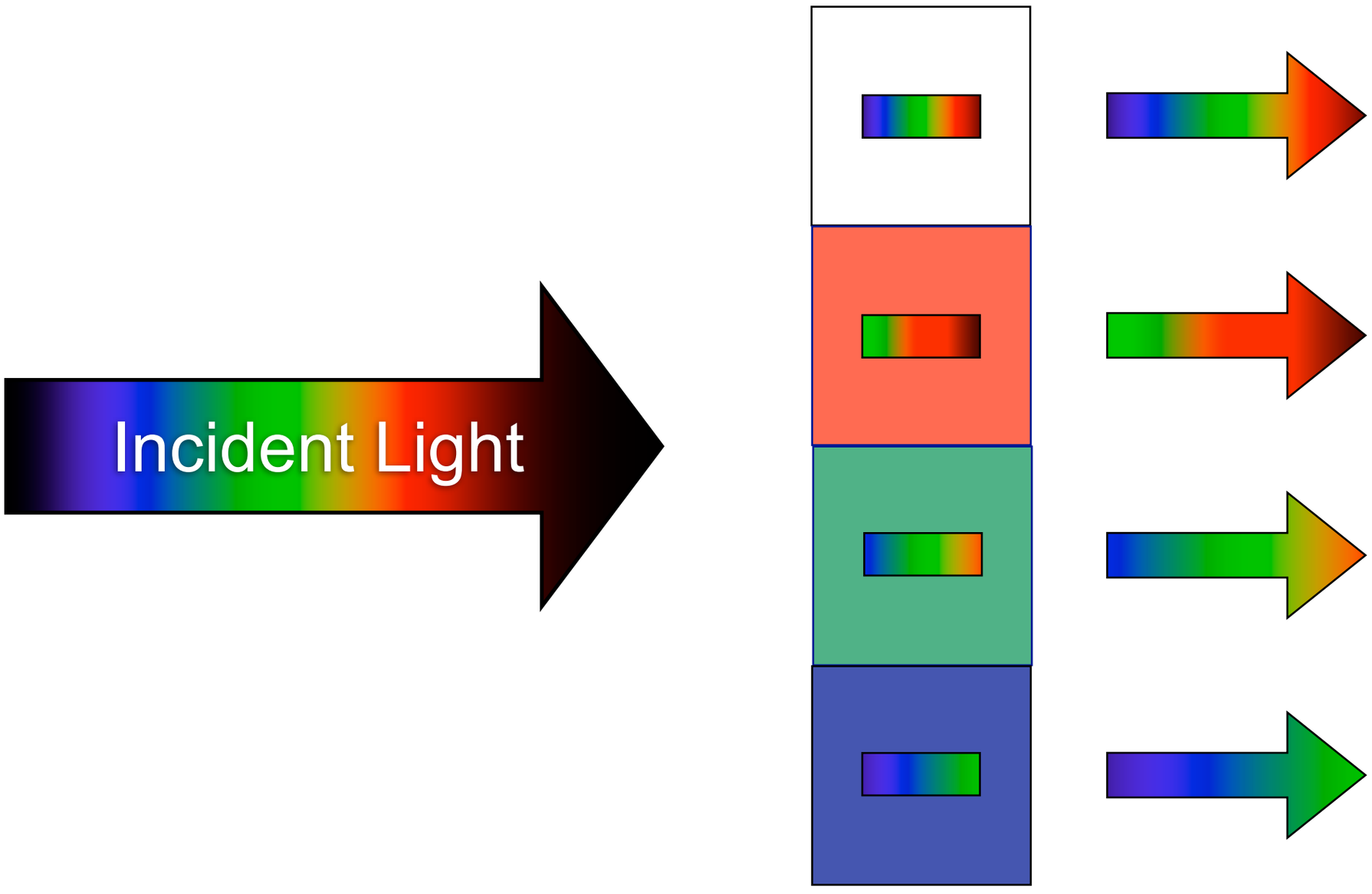
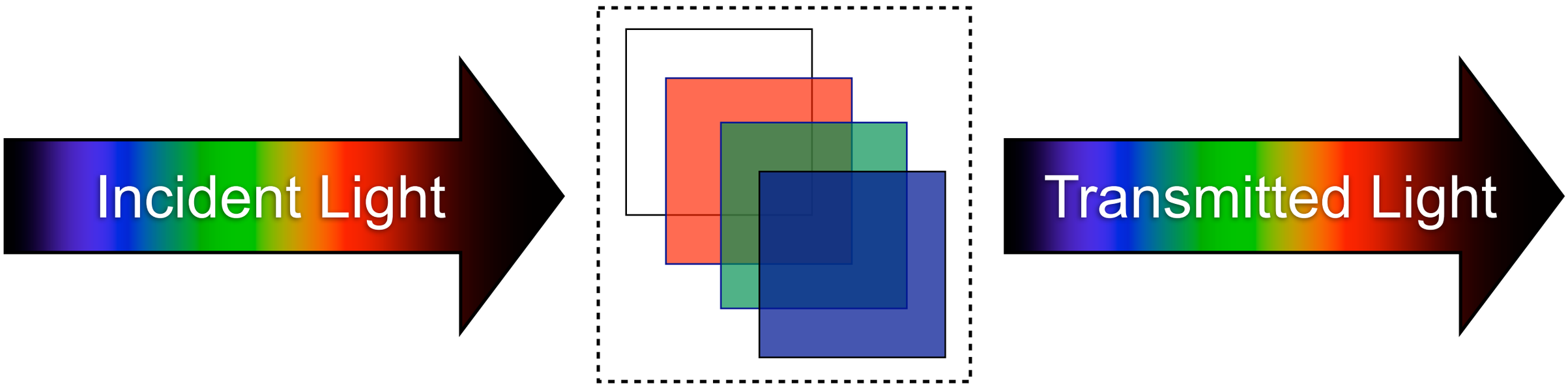

SAGE EC Transmission curves
62%
20%
6%
2%
0.62
0.20
0.06
0.02
0.8
0.6
0.4
0.2
0.0
Transmission
500
1000
1500
2000
2500
Wavelength [nm]
UV
INFRARED

?

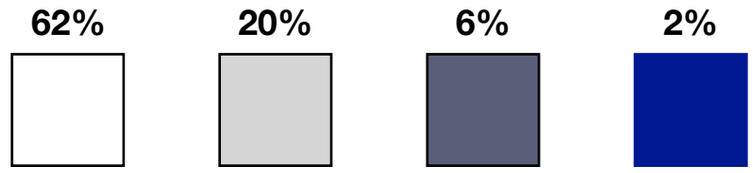
# Arbitrary combinations of clear / tinted glass



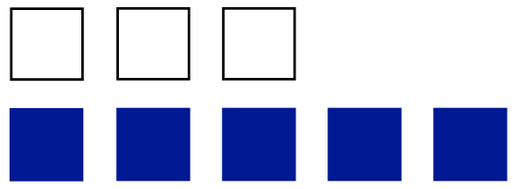
# Create a spectral transmission model for the combination



$$
\begin{aligned}
\mathbf{V} &= \begin{bmatrix} V_a & V_b & V_c & V_d \end{bmatrix} \\
&= \begin{bmatrix} 0.62 & 0.20 & 0.06 & 0.02 \end{bmatrix}
\end{aligned}
$$




$$
\begin{aligned}
\mathbf{R} &= \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix} \\
&= \begin{bmatrix} 3 & 0 & 0 & 5 \end{bmatrix}
\end{aligned}
$$



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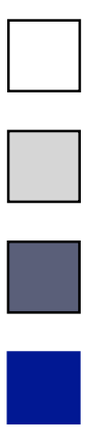
$$
V_R = \frac{\begin{bmatrix} V_a & V_b & V_c & V_d \end{bmatrix} \cdot \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix}^\top}{(N_a + N_b + N_c + N_d)}
$$

$$
V_R = \frac{\mathbf{V} \cdot \mathbf{R}^\top}{\sum \mathbf{R}}
$$

Vector of transmission values [300nm - 2,500nm] for EC glazing in one state of tint

$$\mathbf{T_a} = \begin{bmatrix} t_{a_1} & t_{a_2} & \cdots & t_{a_m} \end{bmatrix}$$

Matrix of transmission values for EC glazing in four states of tint



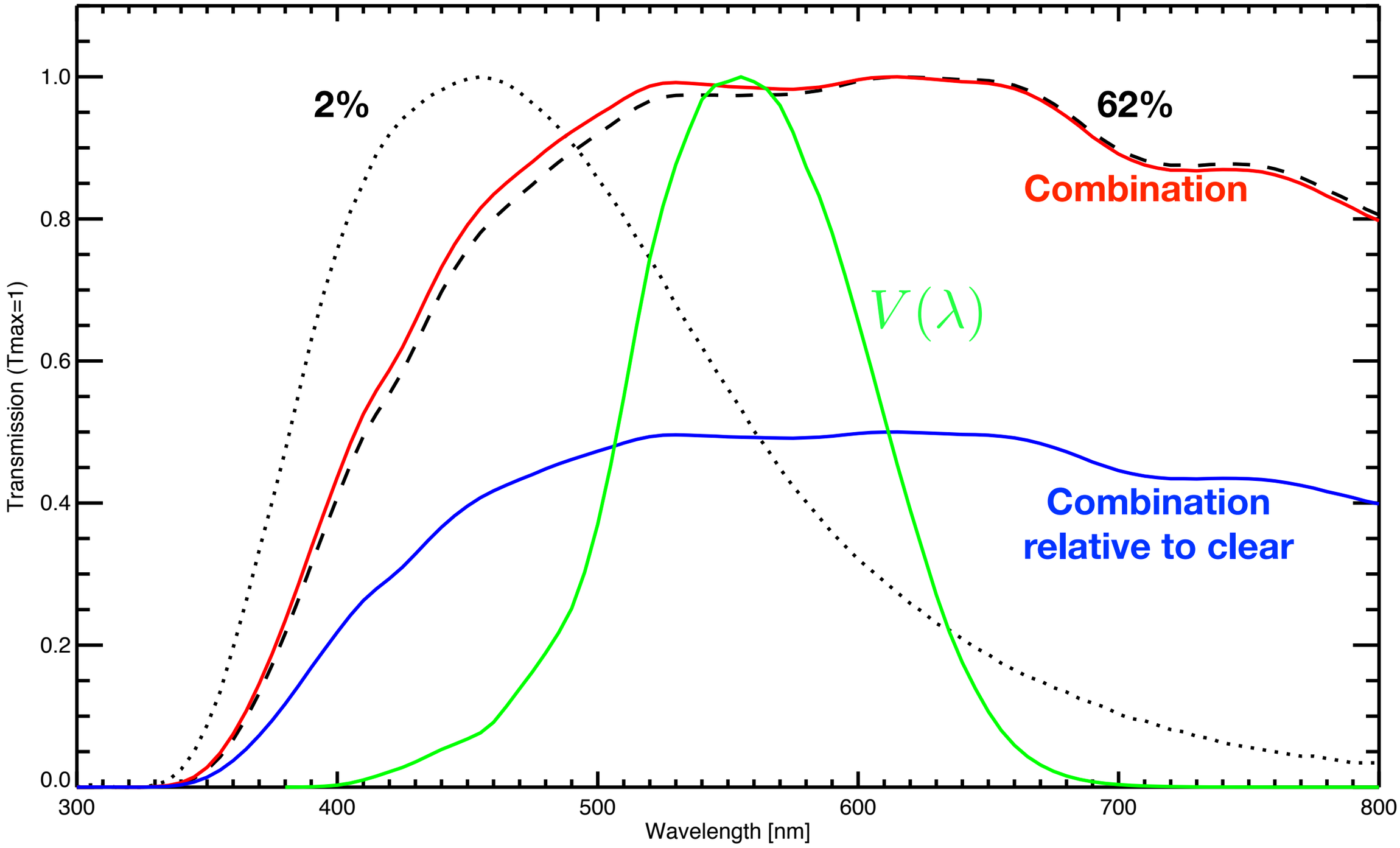
$$\begin{bmatrix} \mathbf{T}_a \\ \mathbf{T}_b \\ \mathbf{T}_c \\ \mathbf{T}_d \end{bmatrix} = \begin{bmatrix} t_{a_1} & t_{a_2} & \cdots & t_{a_m} \\ t_{b_1} & t_{b_2} & \cdots & t_{b_m} \\ t_{c_1} & t_{c_2} & \cdots & t_{c_m} \\ t_{d_1} & t_{d_2} & \cdots & t_{d_m} \end{bmatrix}$$

For any arbitrary combination $\mathbf{R}$ of EC glazing in tint states $a$, $b$, $c$ and $d$, the effective spectral transmission curve for the ensemble is:

$$\mathbf{T_R} = \frac{\mathbf{R} \cdot \begin{bmatrix} \mathbf{T}_a & \mathbf{T}_b & \mathbf{T}_c & \mathbf{T}_d \end{bmatrix}^\top}{\sum \mathbf{R}}$$

$$\mathbf{T_R} = \begin{bmatrix} t_{R_1} & t_{R_2} & \cdots & t_{R_m} \end{bmatrix}$$

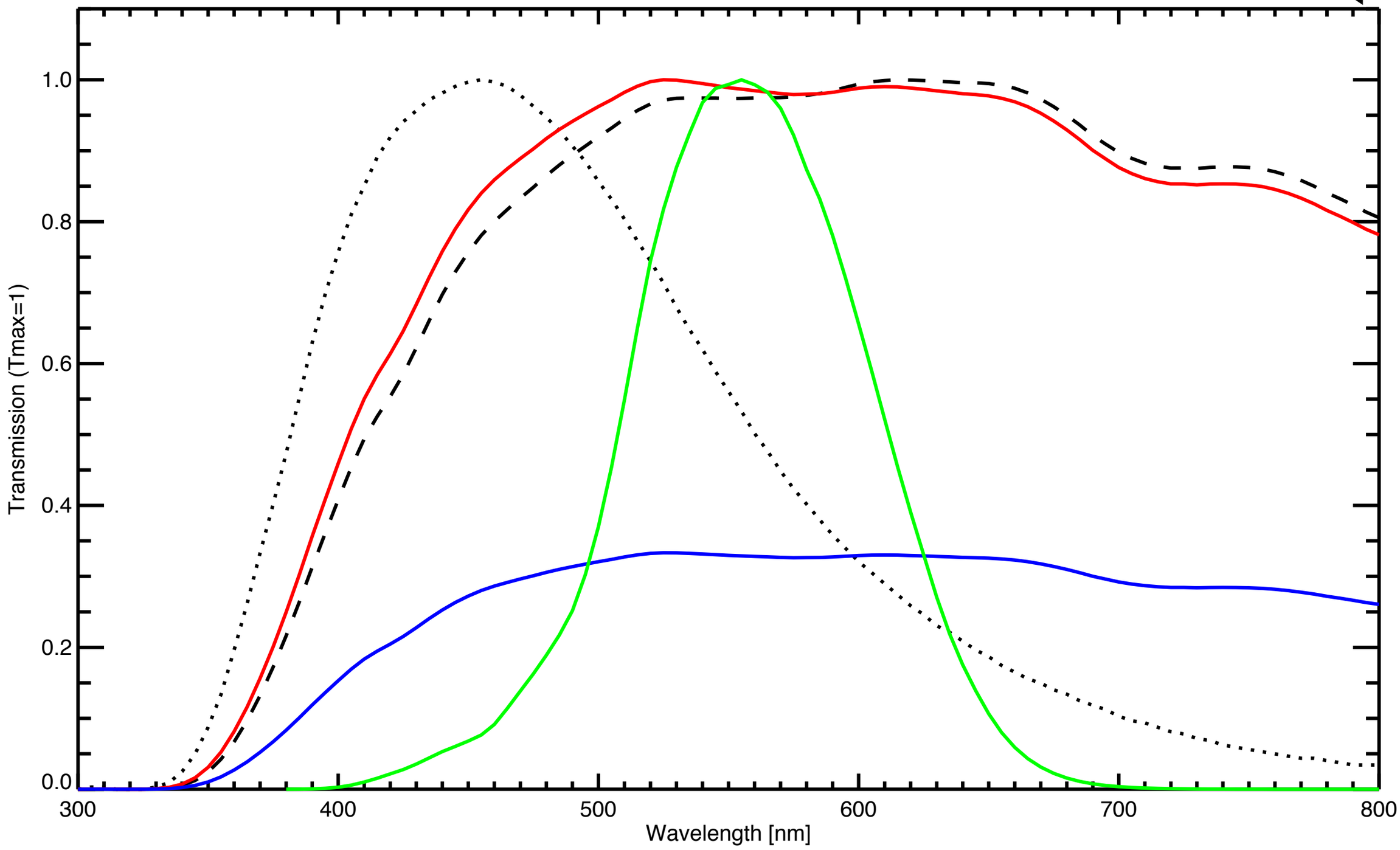
Effective transmission of ensemble = 0.320 : % of transmitted light from clear state = 96%
T_vis [ 0.62 0.20 0.06 0.02] in ratio [ 1 0 0 1]




62%

2%

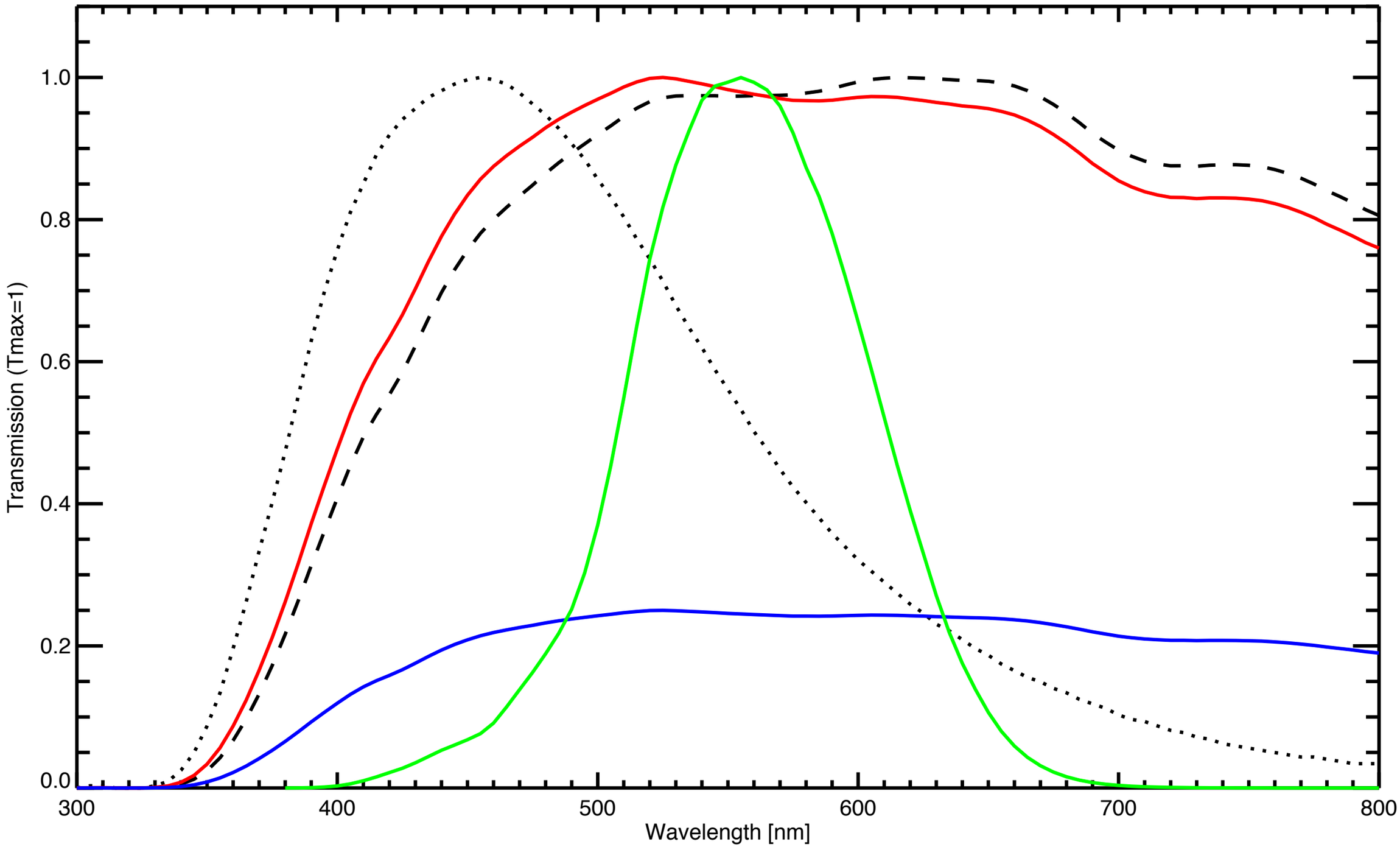
Effective transmission of ensemble = 0.220 : % of transmitted light from clear state = 93%
T_vis [ 0.62 0.20 0.06 0.02] in ratio [ 1 0 0 2]

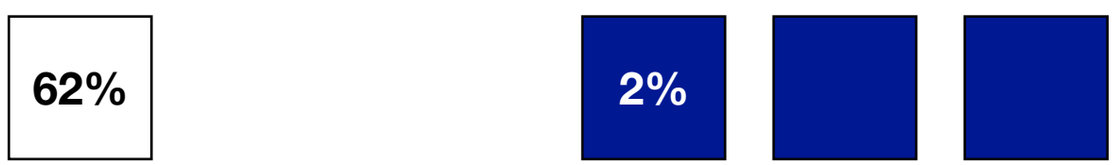



62%

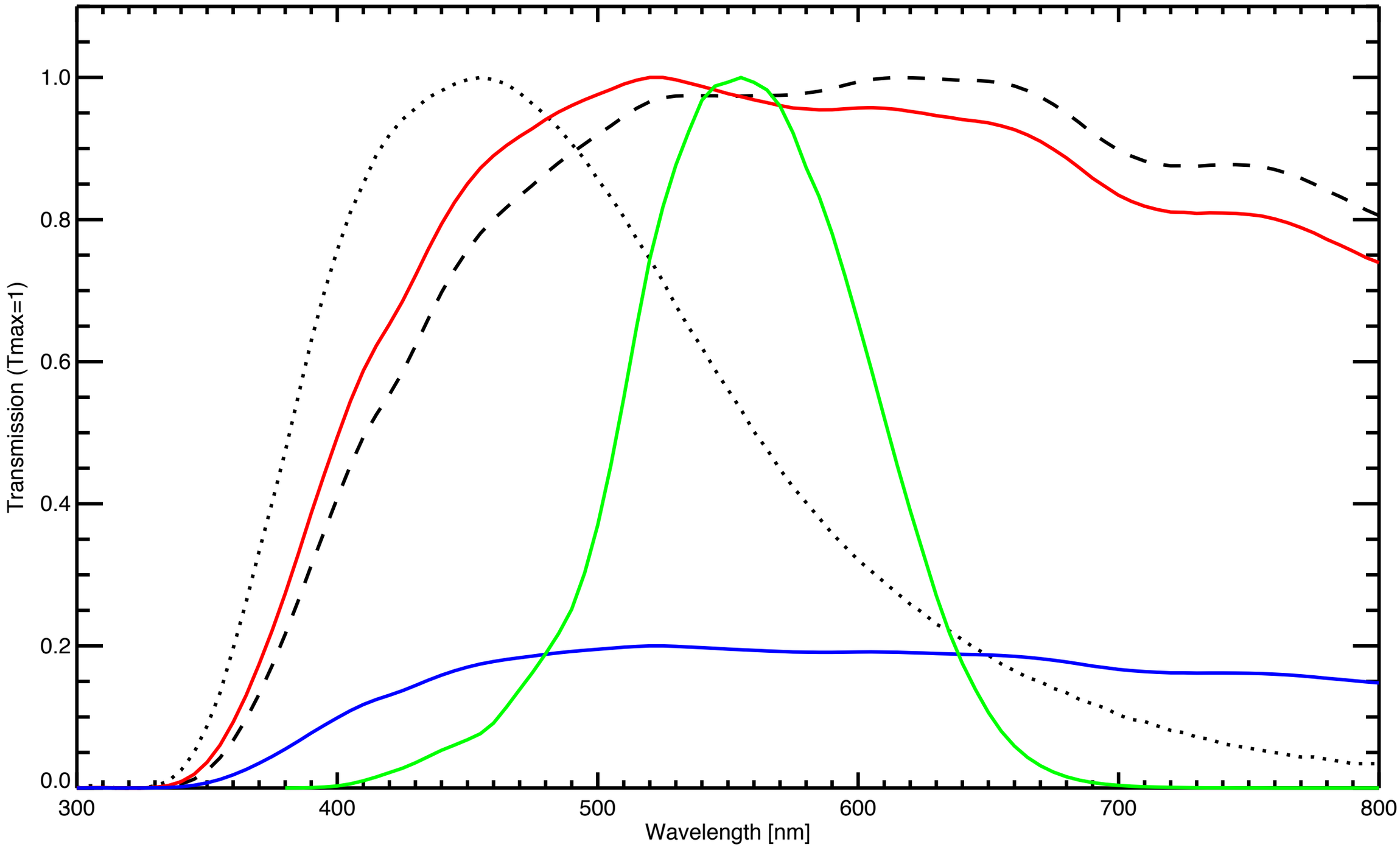
2%

Effective transmission of ensemble = 0.170  :  % of transmitted light from clear state =  91%
T_vis [  0.62  0.20  0.06  0.02]  in ratio [  1  0  0  3]

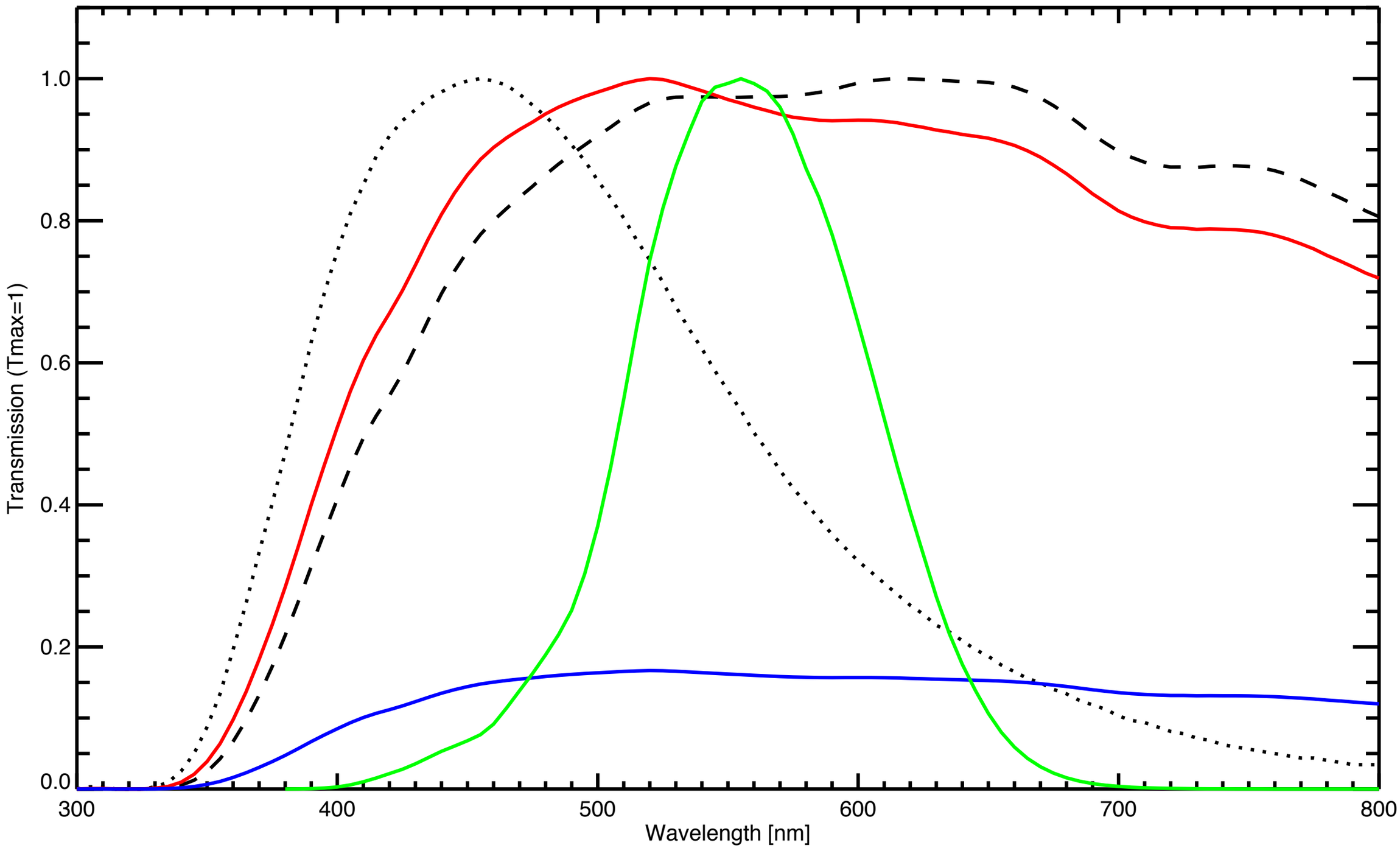


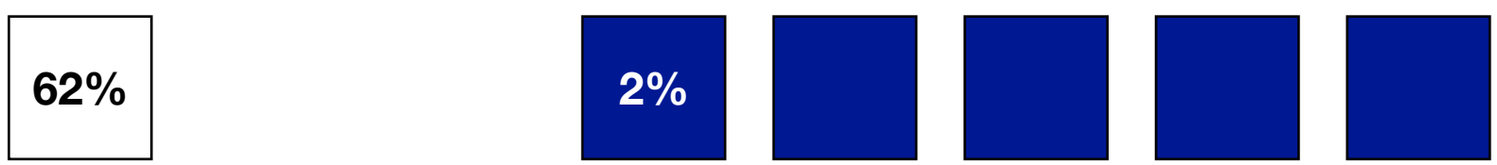



Effective transmission of ensemble = 0.140  :  % of transmitted light from clear state =  88%
T_vis [  0.62  0.20  0.06  0.02]  in ratio [  1  0  0  4]

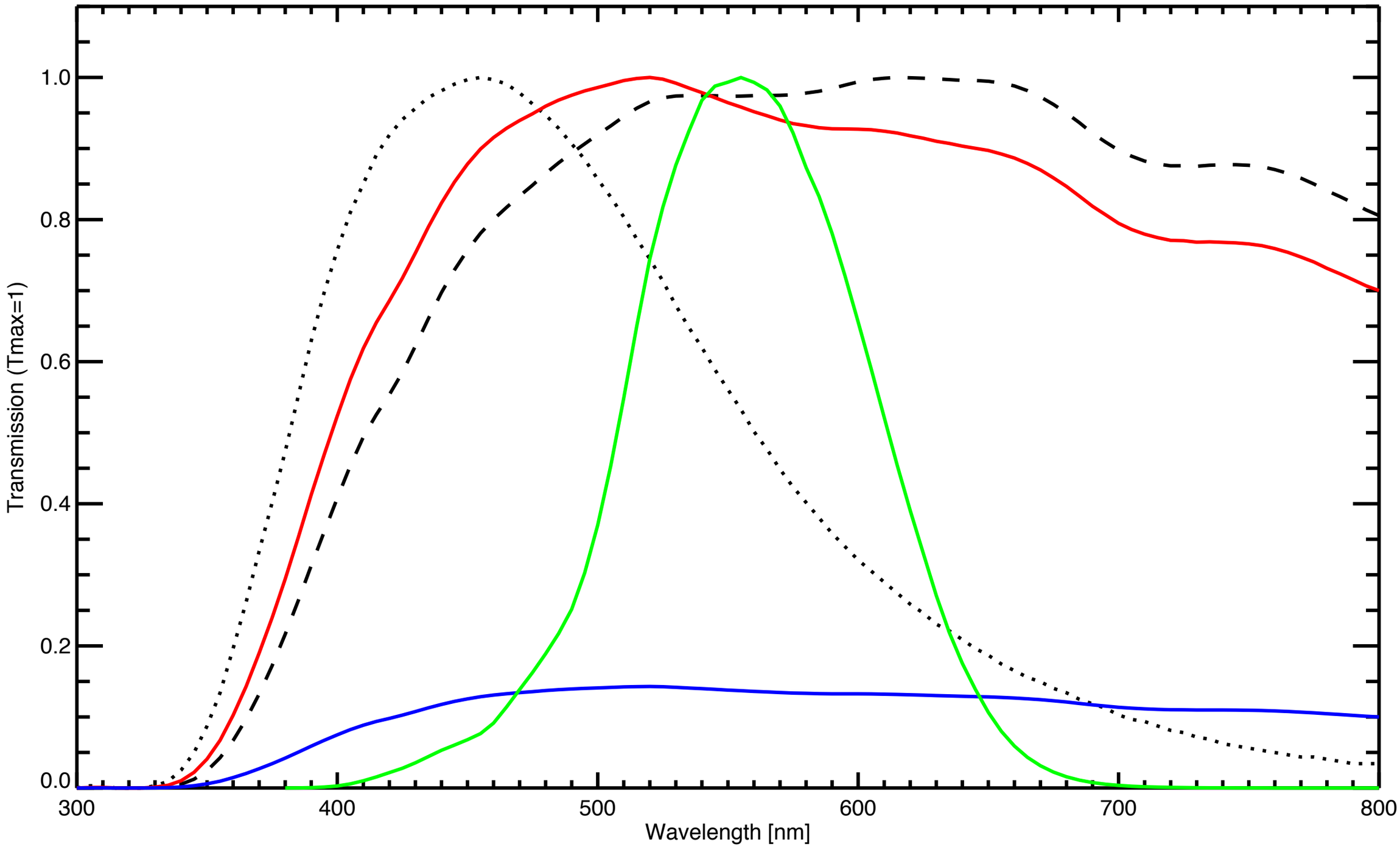


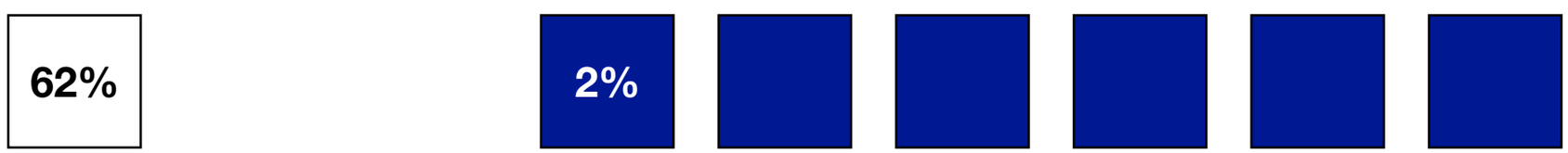

Effective transmission of ensemble = 0.120  :  % of transmitted light from clear state =  86%
T_vis [  0.62  0.20  0.06  0.02]  in ratio [  1  0  0  5]



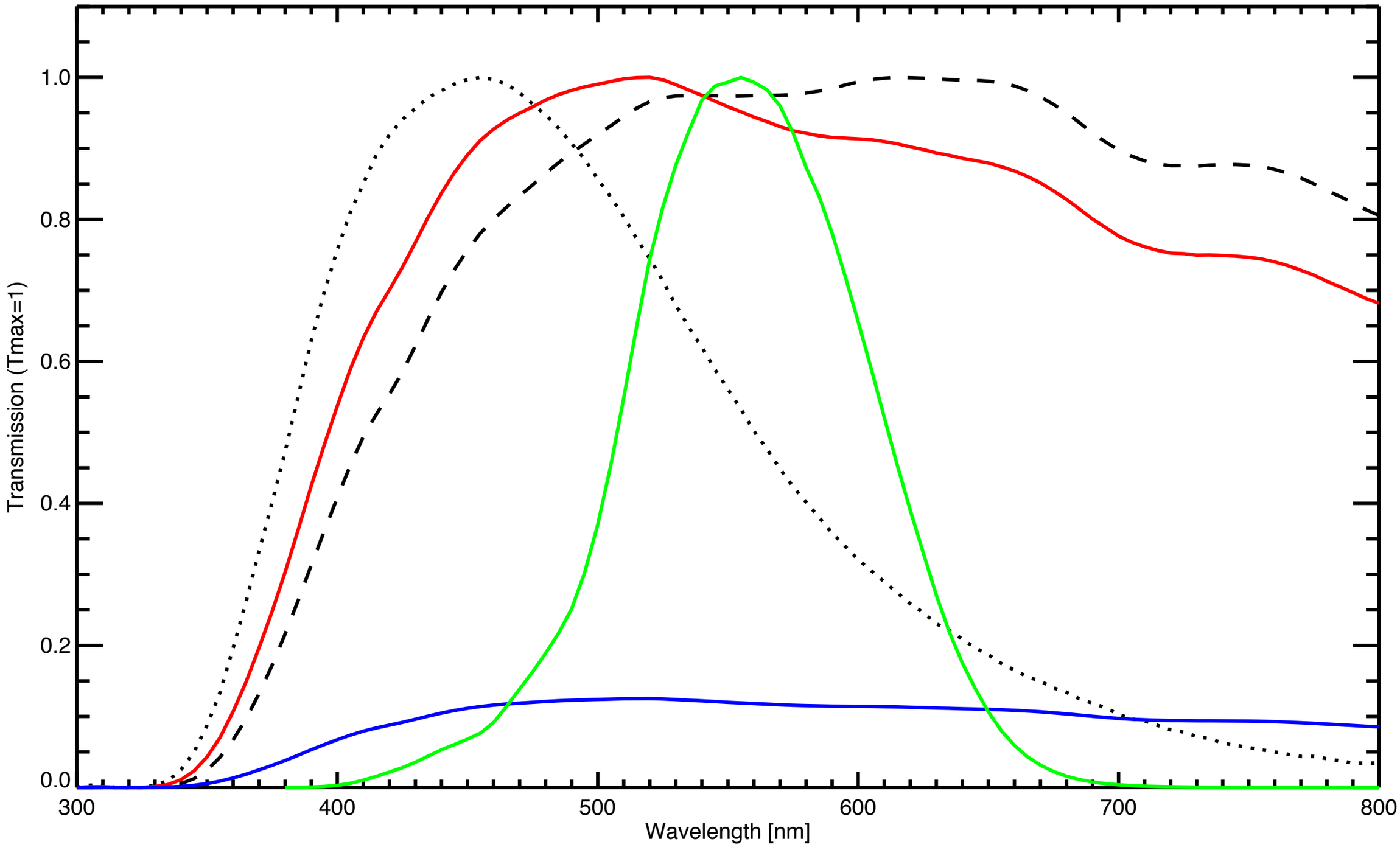



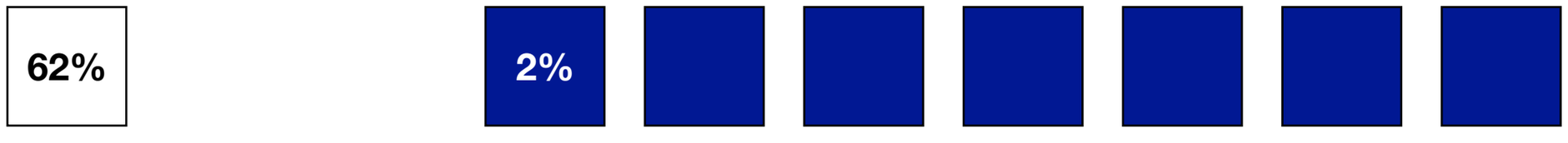
Effective transmission of ensemble = 0.106  :  % of transmitted light from clear state =  83%
T_vis [  0.62  0.20  0.06  0.02]  in ratio [  1  0  0  6]



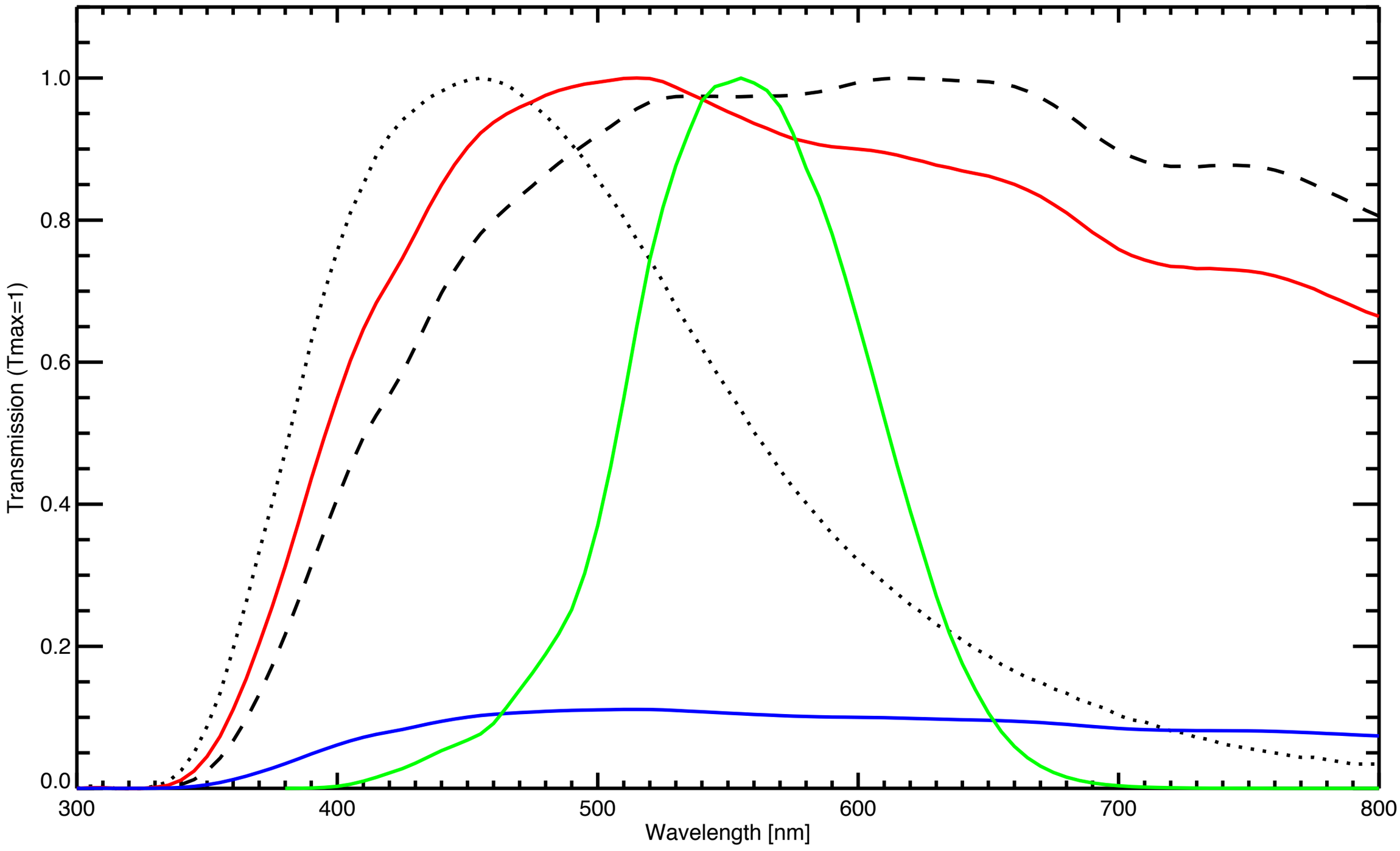



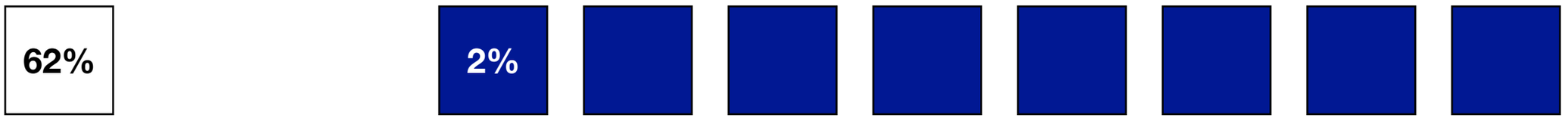
Effective transmission of ensemble = 0.095 : % of transmitted light from clear state = 81%
T_vis [ 0.62 0.20 0.06 0.02] in ratio [ 1 0 0 7]

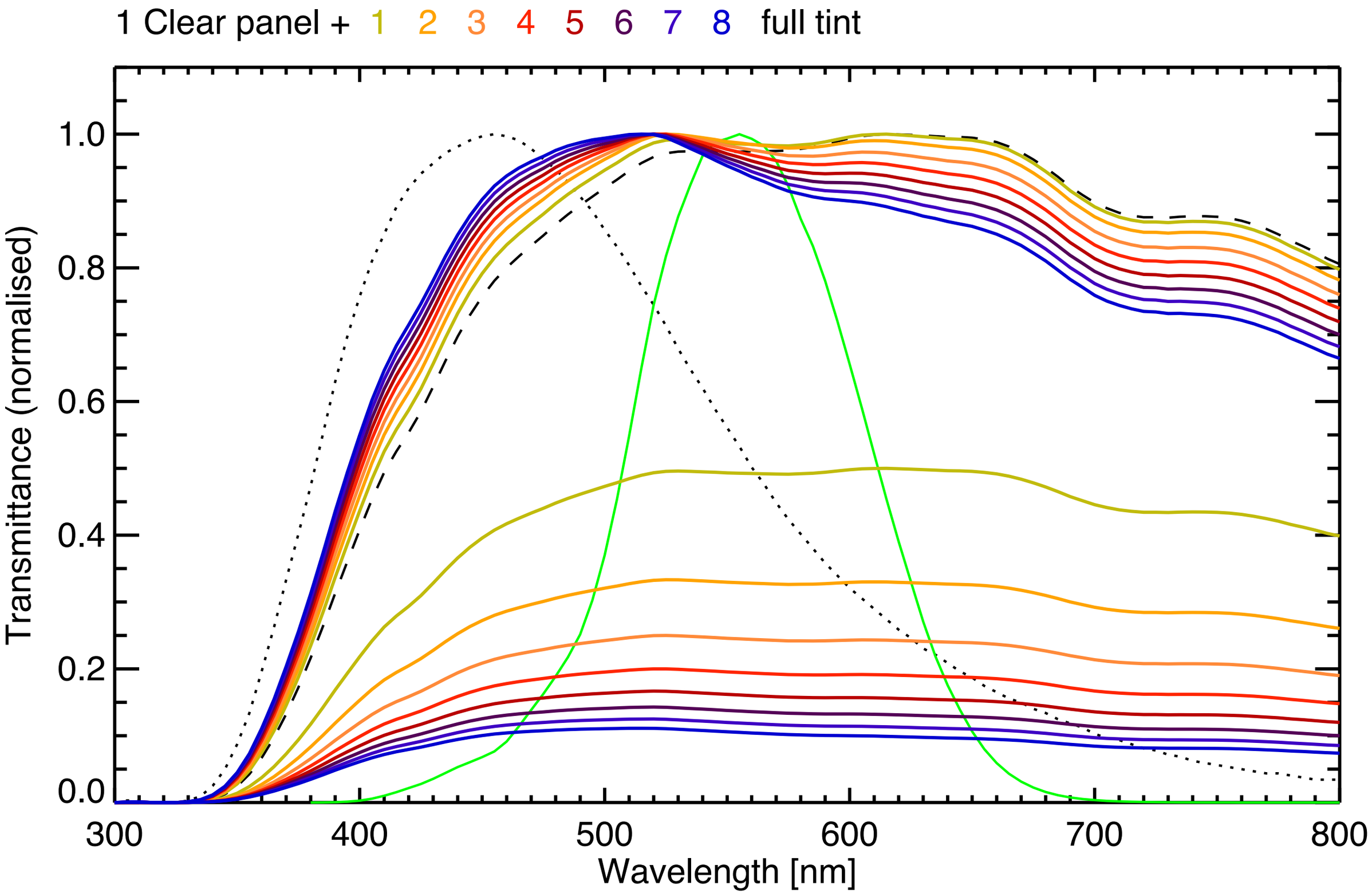


Effective transmission of ensemble = 0.087  :  % of transmitted light from clear state =  79%
T_vis [  0.62  0.20  0.06  0.02]  in ratio [  1  0  0  8]

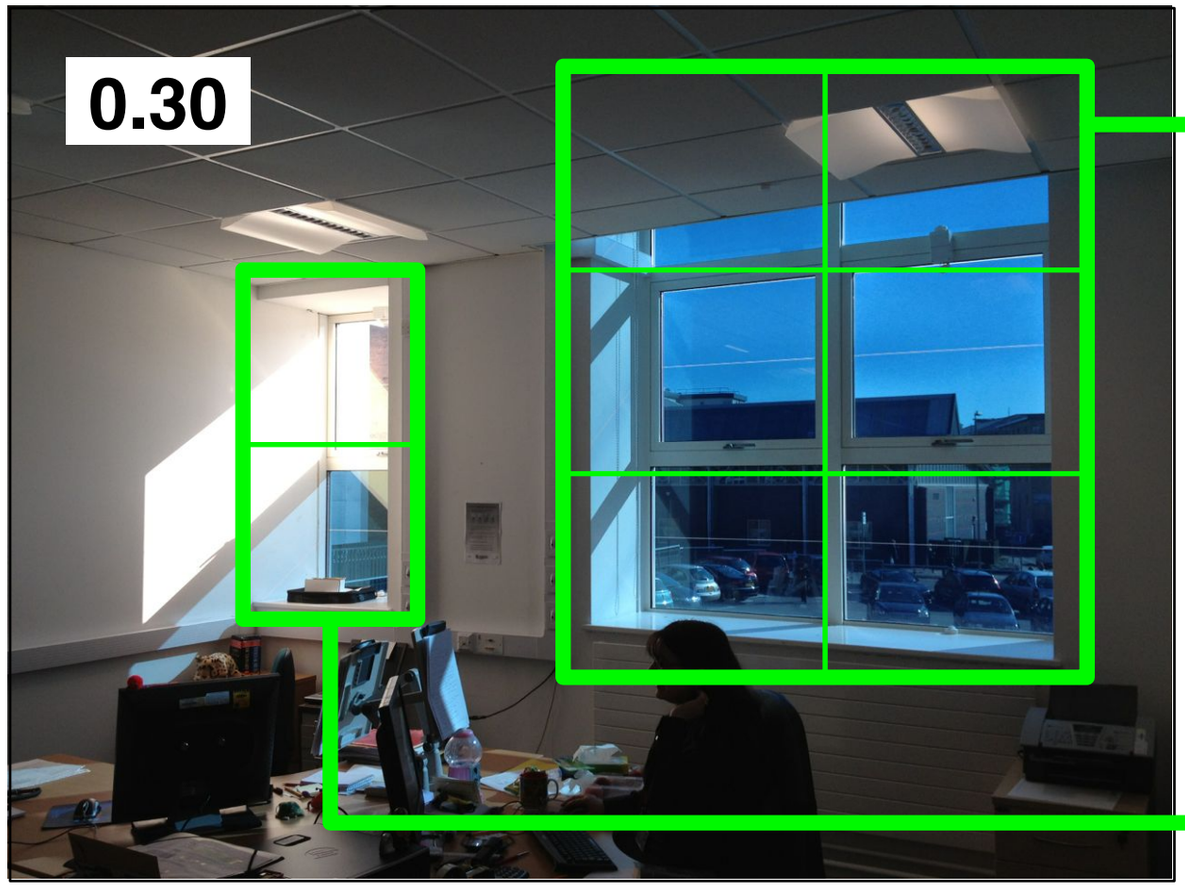



1 Clear panel + 1 2 3 4 5 6 7 8 full tint
Transmittance (normalised)
1.0
0.8
0.6
0.4
0.2
0.0
300
400
500
600
700
800
Wavelength [nm]

# Validation Scenario:

# The De Montfort EC Office Study


0.30

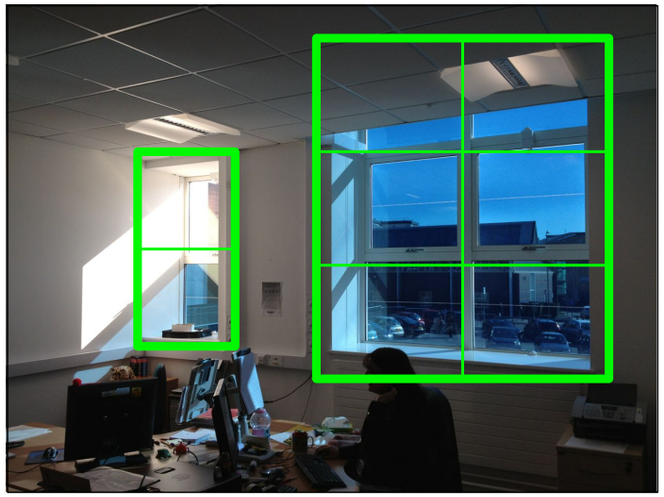

0.30
0.29

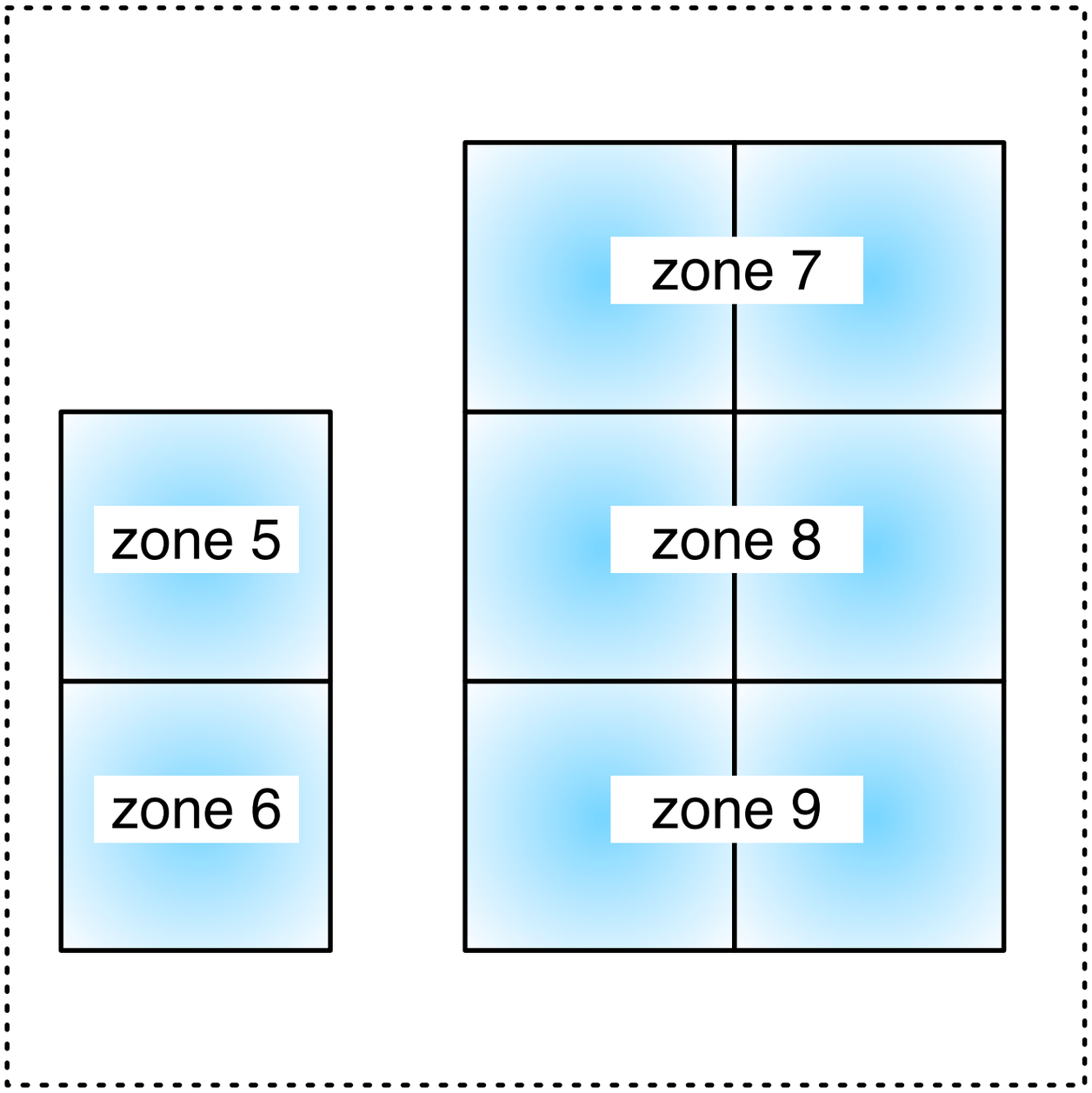
# Methodology

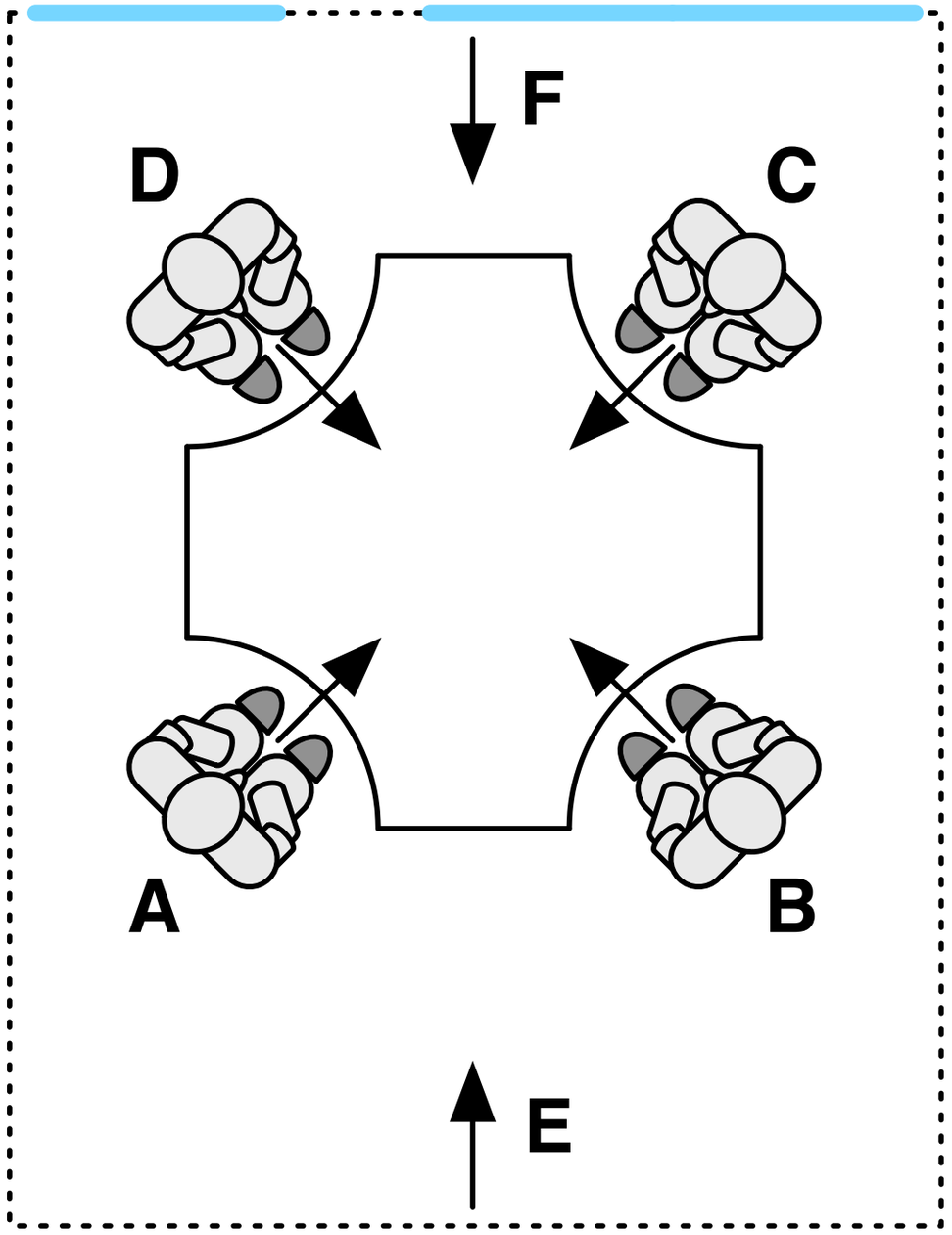
Compare predicted spectrum with measurements of the daylight spectrum taken at six points in a room with EC glazing for various combinations of tint state.

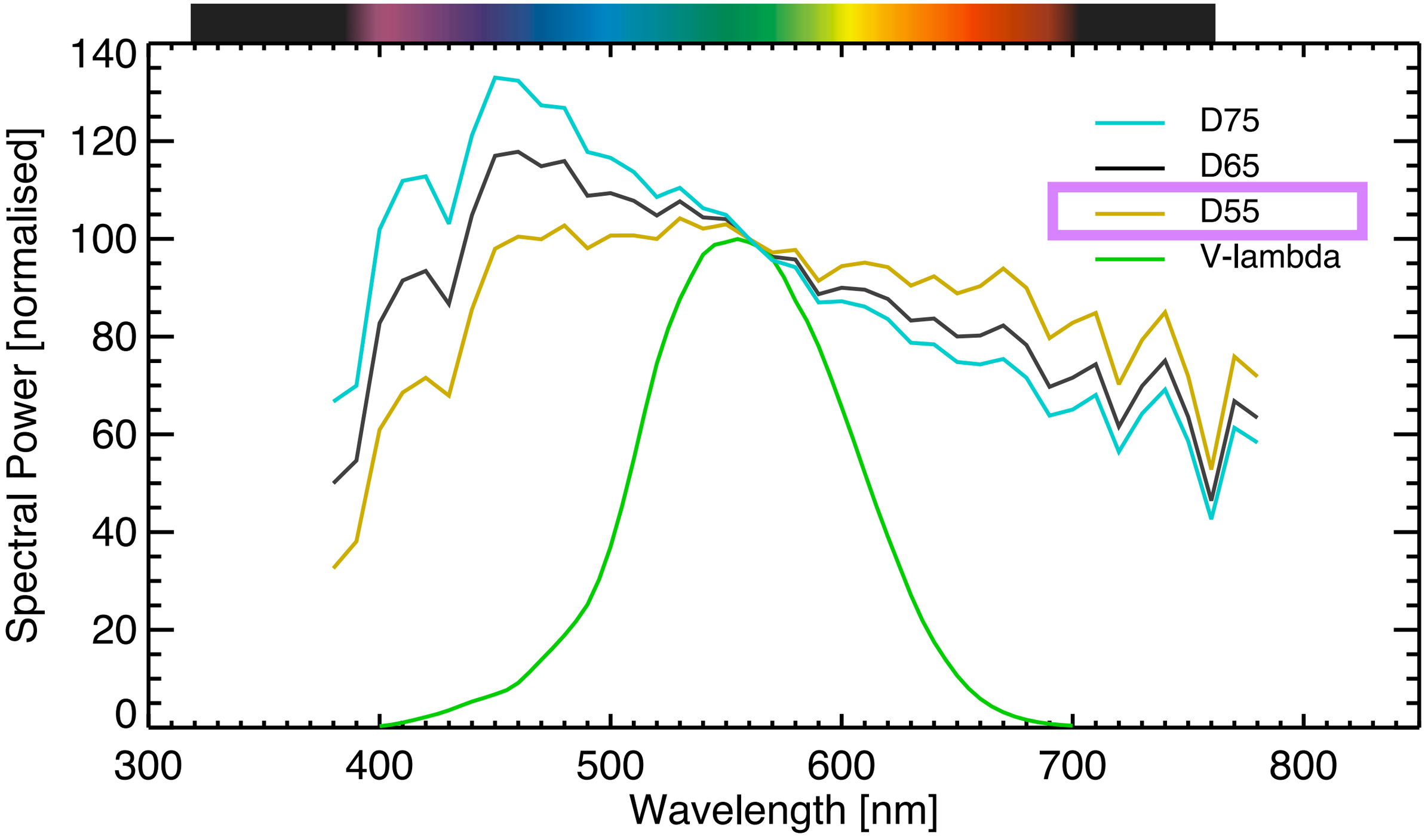
Measurements taken under sunny conditions.

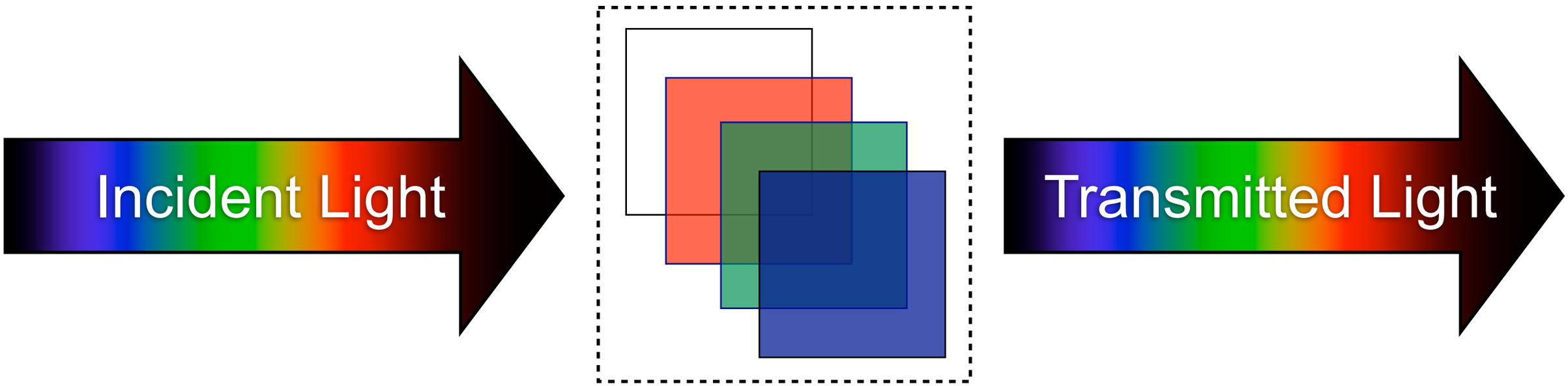
Spectra normalised to the same effective lux value.




zone 7
zone 5
zone 8
zone 6
zone 9


F
D
C
A
B
E


140
120
100
80
60
40
20
0
Spectral Power [normalised]
300
400
500
600
700
800
Wavelength [nm]
D75
D65
D55
V-lambda




$$\mathbf{D_{55}} \circ \mathbf{T_R} = \text{Illumination spectrum}$$

≠

R = [ 3 0 0 5]

Theory [D55]

Measured

$r_{mean}$ = 0.980

$T_{vis}$ = 0.25 : $P_{clear}$ = 94%

$CCT_{mean}$ = 4970K : $CRI_{mean}$ = 93

41-441

Spectral power [normalised]

1.5

1.0

0.5

0.0

300

400

500

600

700

800

Wavelength [nm]

R = [ 1 0 0 7]

Theory [D55]

Measured

$r_{mean}$ = 0.906

$T_{vis}$ = 0.09 : $P_{clear}$ = 81%

$CCT_{mean}$ = 4800K : $CRI_{mean}$ = 94

41-444

Spectral power [normalised]

1.5

1.0

0.5

0.0

300 400 500 600 700 800

Wavelength [nm]

R = [ 3 5 0 0]

Theory [D55]

Measured

$r_{mean}$ = 0.972

$T_{vis}$ = 0.36 : $P_{clear}$ = 65%

$CCT_{mean}$ = 5211K : $CRI_{mean}$ = 92

21-221

Spectral power [normalised]

1.5

1.0

0.5

0.0

300

400

500

600

700

800

Wavelength [nm]

R = [ 3 0 5 0]

Theory [D55]

Measured

$r_{mean}$ = 0.977

$T_{vis}$ = 0.27 : $P_{clear}$ = 86%

$CCT_{mean}$ = 5243K : $CRI_{mean}$ = 93

31-331

Spectral power [normalised]

1.5

1.0

0.5

0.0

300 400 500 600 700 800

Wavelength [nm]

R = [ 0 3 0 5]

Theory [D55]

Measured

$r_{mean}$ = 0.971

$T_{vis}$ = 0.09 : $P_{clear}$ = 0%

$CCT_{mean}$ = 6845K : $CRI_{mean}$ = 87

42-442

Spectral power [normalised]

1.5

1.0

0.5

0.0

300 400 500 600 700 800

Wavelength [nm]

R = [ 0 0 3 5]

Theory [D55]

Measured

$r_{mean}$ = 0.974

$T_{vis}$ = 0.03 : $P_{clear}$ = 0%

$CCT_{mean}$ = 11557K : $CRI_{mean}$ = 84

43-443

Spectral power [normalised]

1.5

1.0

0.5

0.0

300

400

500

600

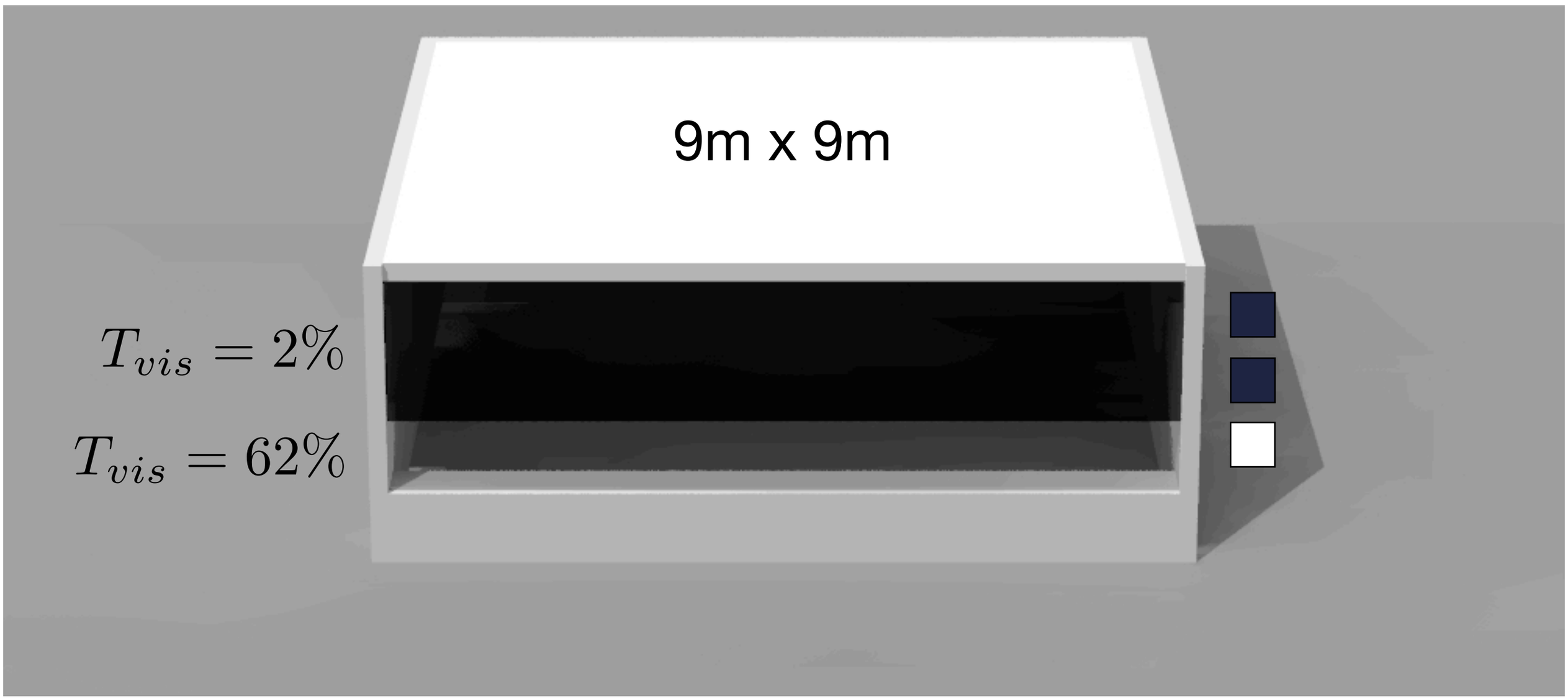
700

800

Wavelength [nm]

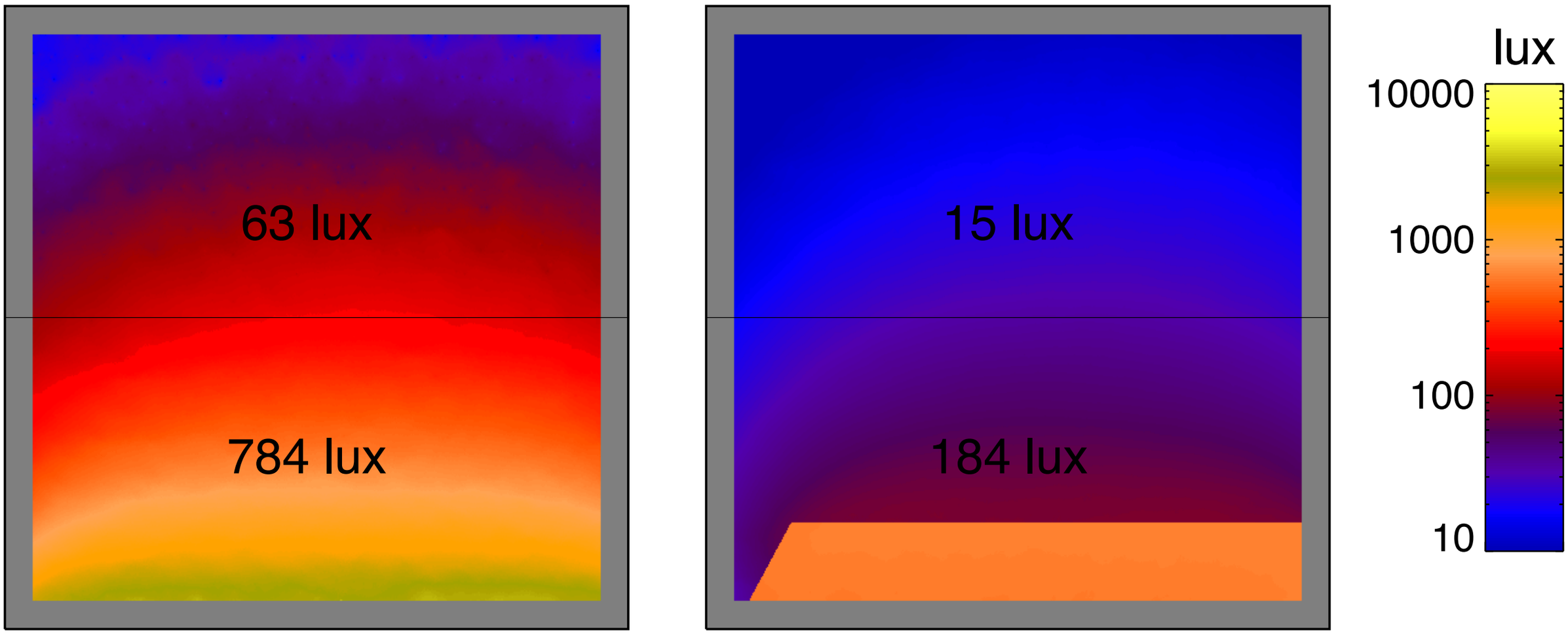
| $\mathbf{R}$ $[N_{62}\ N_{20}\ N_{06}\ N_{02}]$ | Measured $CCT_{mean}$ | Measured $CRI_{mean}$ | $r_{mean}$ $D_{55}$ $(D_{65}, D_{75})$ |
|---|---|---|---|
| $[3\quad 5\quad 0\quad 0]$ | 5211 K | 92 | 0.972 (0.875, 0.760) |
| $[3\quad 0\quad 5\quad 0]$ | 5243 K | 93 | 0.977 (0.902, 0.782) |
| $[3\quad 0\quad 0\quad 5]$ | 4970 K | 93 | 0.980 (0.919, 0.794) |
| $[1\quad 0\quad 0\quad 7]$ | 4800 K | 94 | 0.906 (0.700, 0.514) |
| $[0\quad 3\quad 0\quad 5]$ | 6845 K | 87 | 0.971 (0.917, 0.862) |
| $[0\quad 0\quad 3\quad 5]$ | 11557 K | 84 | 0.974 (0.947, 0.916) |

Wot, no
*Radiance*?


9m x 9m
$T_{vis} = 2\%$
$T_{vis} = 62\%$

$T_{vis} = 62\%$

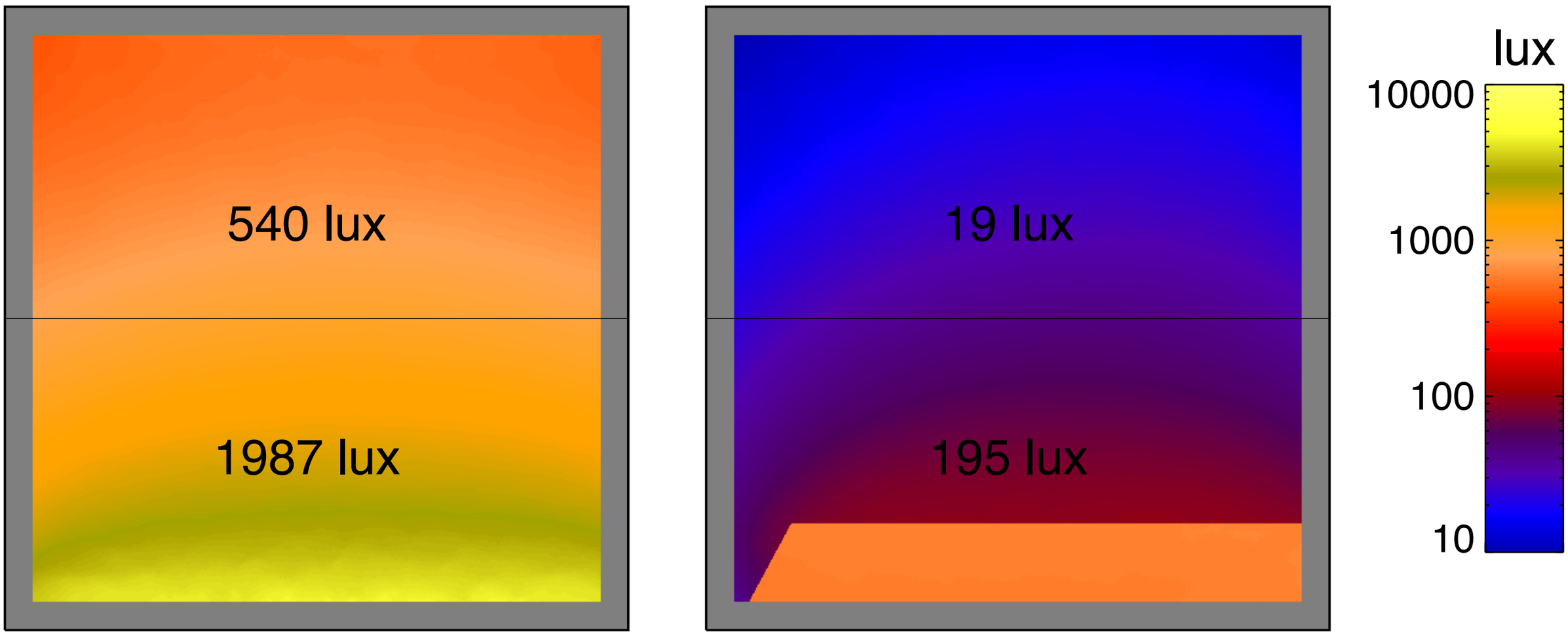
$T_{vis} = 2\%$




ab 1

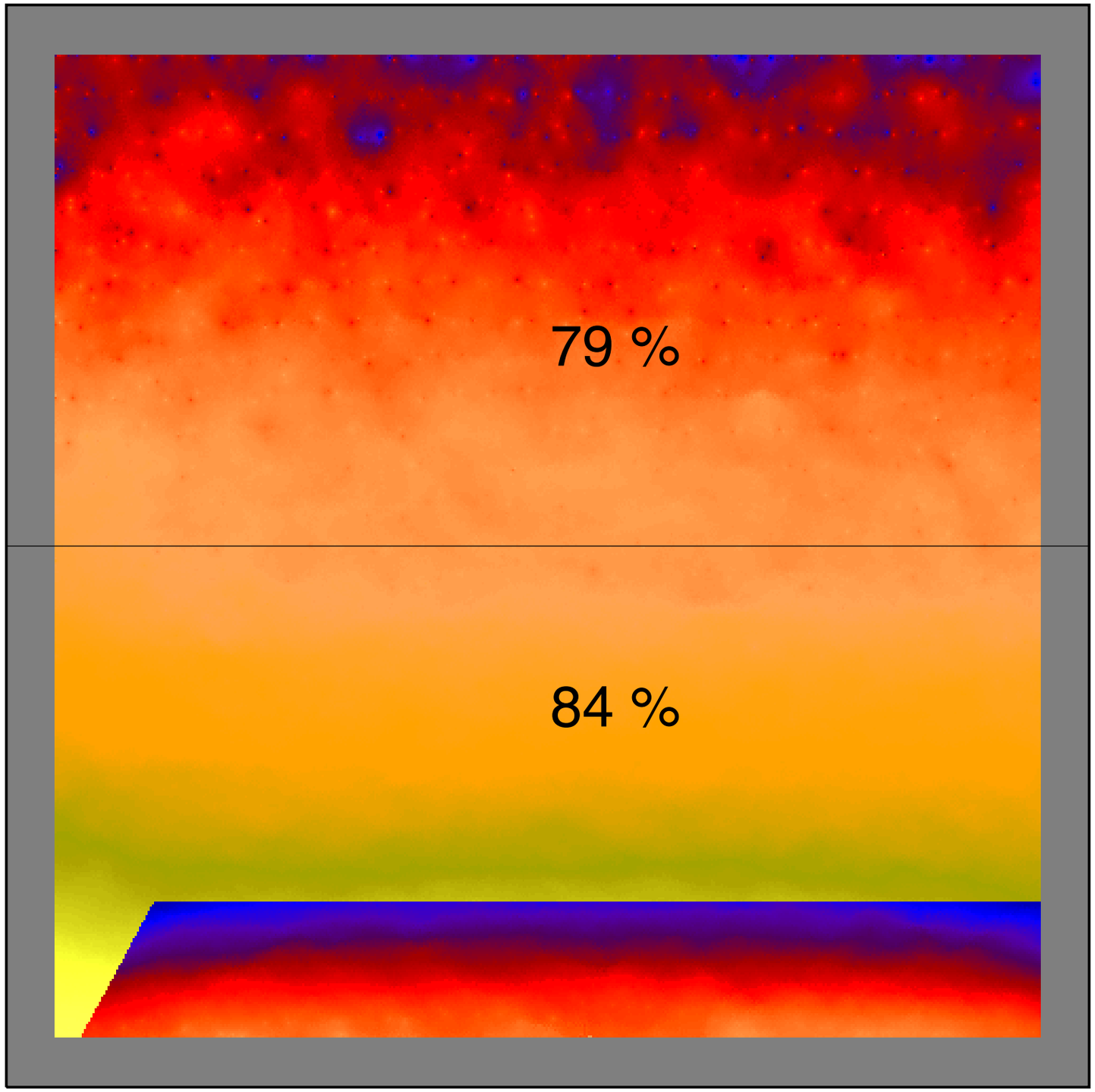
$T_{vis} = 62\%$

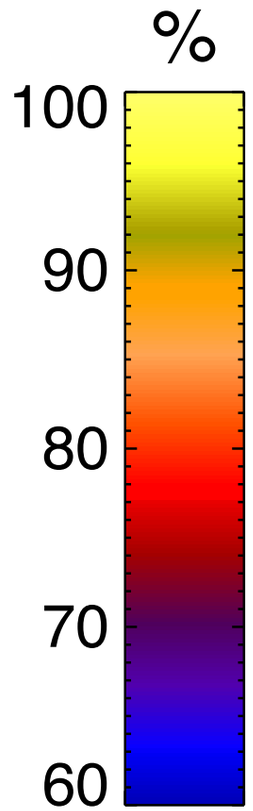
$T_{vis} = 2\%$




ab 7

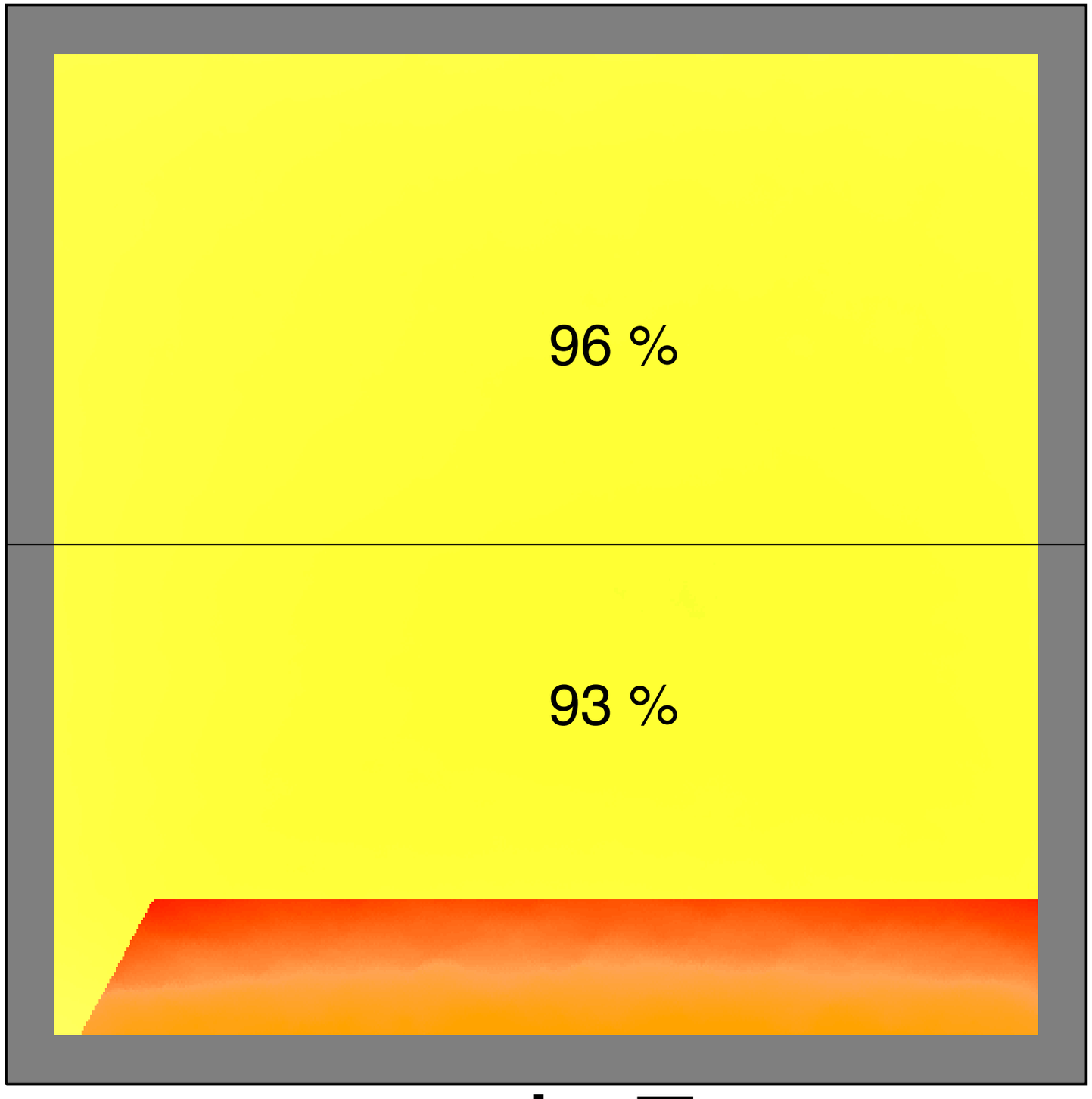
# % contribution from clear state



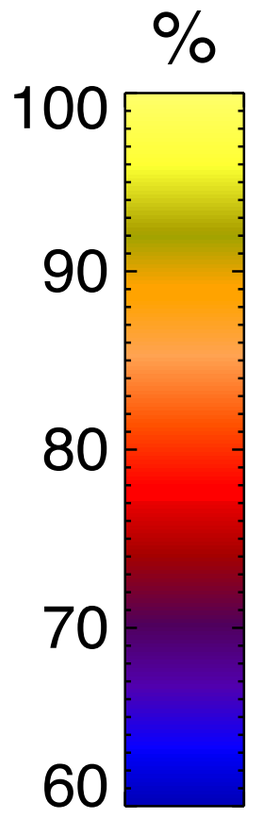




ab 1

# % contribution from clear state




ab 7



SAGE White Paper: *“How to Maintain Neutral Daylight Illumination with SageGlass Electrochromic Glazing”*

*Neutral daylight illumination with variable transmission glass: Theory and validation.* J. Mardaljevic, R. Kelly Waskett, and B. Painter. Accepted for publication in Lighting Research and Technology.

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