

# **EFFECT OF SURFACE REFLECTANCE IN THE BUILT ENVIRONMENT ON CORNEAL SPECTRAL IRRADIANCE**

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# LIGHTING DESIGN SOFTWARE

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- Majority is Photometrically based
  - Surfaces characterized by net reflectance
  - Diffuse/specular reflectance characteristics
  - Computationally ~~efficient~~ fast (follow the lumens)
  - Well suited for estimating light levels

# LIGHTING DESIGN SOFTWARE

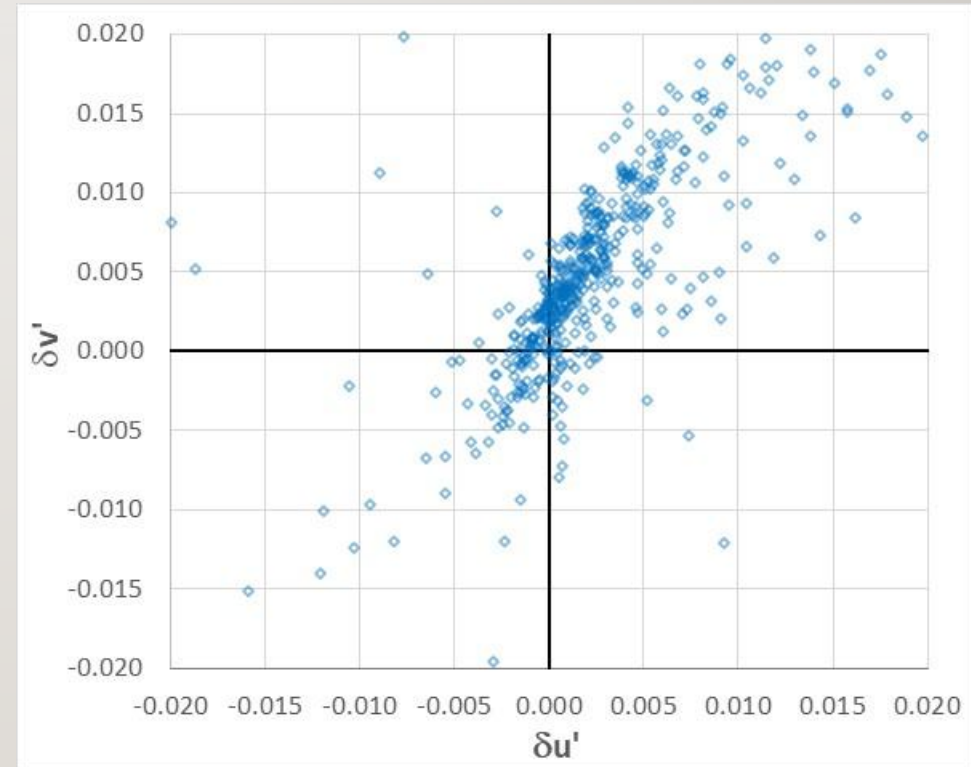
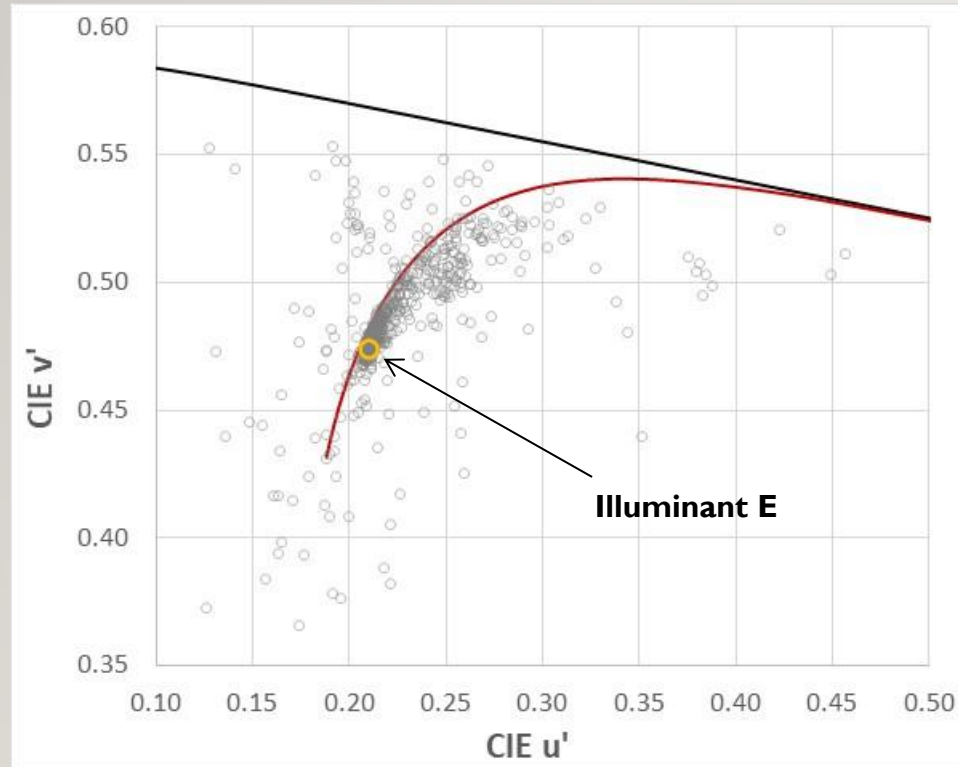


Software



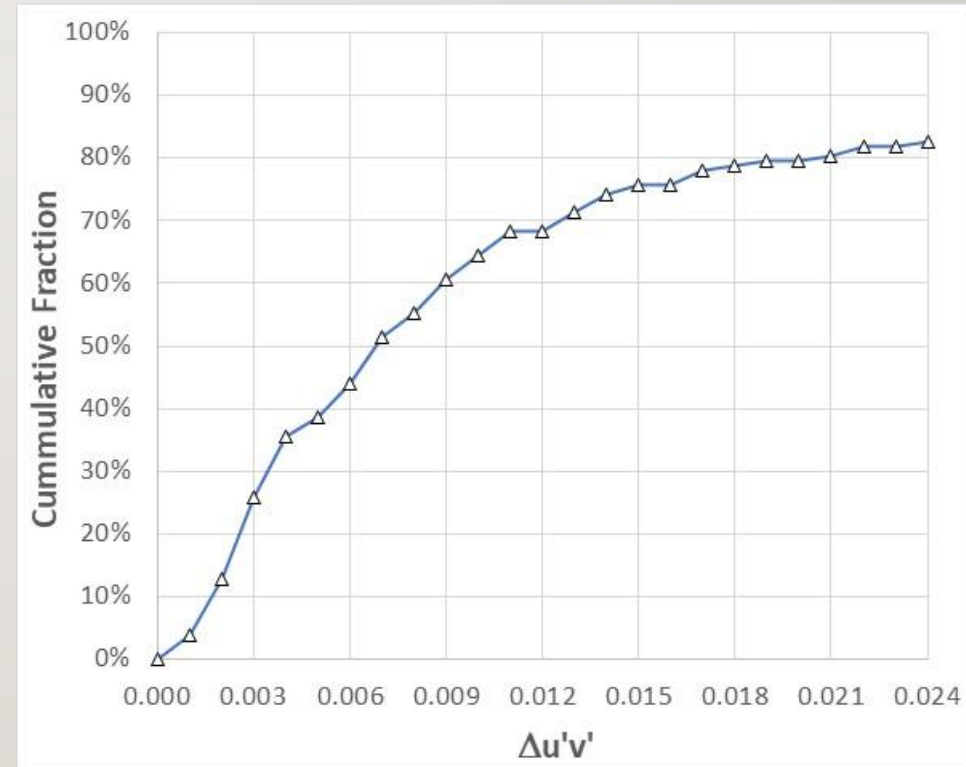
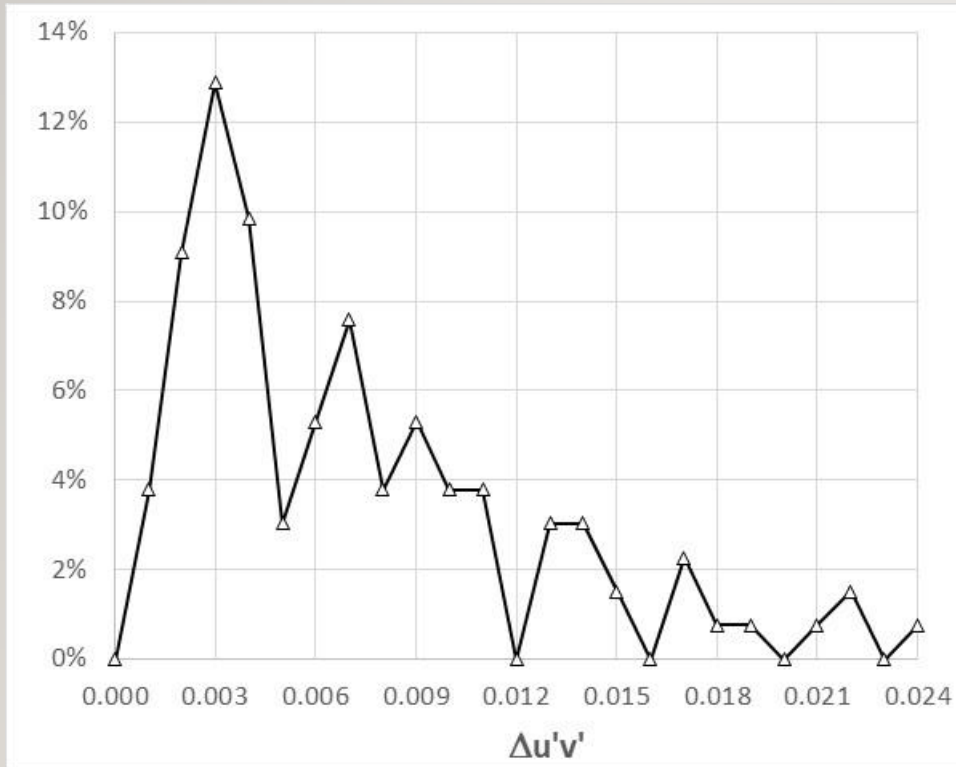
Human eye

# FIRST SURFACE SPECTRAL REFLECTANCE\*



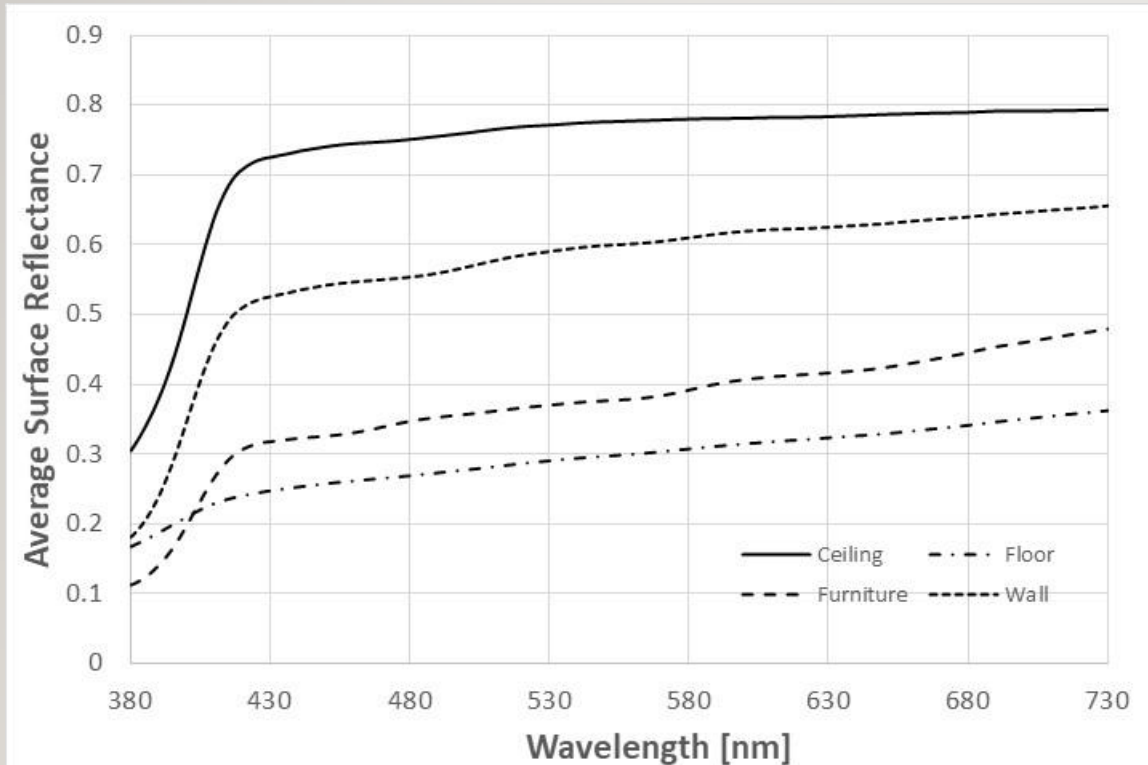
\* JA Jakubiec (2016). Building a database of opaque materials for lighting simulation. In *PLEA 2016–Cities, Buildings, People: Towards Regenerative Environments, Proceedings of the 32nd International Conference on Passive and Low Energy Architecture*.

# WALL SPECTRAL REFLECTANCE – CHROMATICITY SHIFT



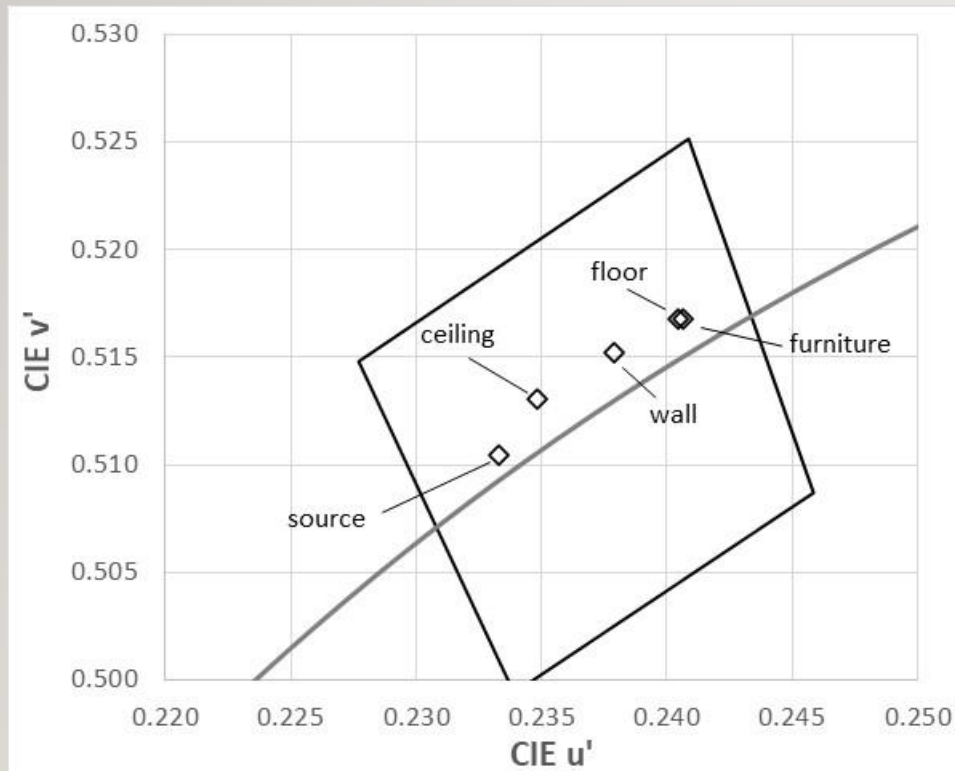
~75% of first reflections from walls result in  $\Delta u'v' \geq 0.003$

# AVERAGE SPECTRAL REFLECTANCE



- Ceilings can be argued to be approximately achromatic, some shift towards longer wavelengths
- Designs often incorporate a “color scheme”
- Chromatic shifts will increase with degree of interaction (number of reflections)

# AVERAGE SPECTRAL REFLECTANCE



- Chromatic nature of surfaces loosely correlates with height
  - Ceiling  $\Delta u'v'$ : 0.00305
  - Walls  $\Delta u'v'$ : 0.00666
  - Floors  $\Delta u'v'$ : 0.00959
  - Furniture  $\Delta u'v'$ : 0.00977

# IMPORTANCE OF SPECTRAL CONTENT AT CORNEA

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The built environment is rarely monochromatic

- Surface reflections modify relative spectral power distribution
- Cannot assume that corneal spectral power distribution = luminaire spectral power distribution

Directly impacts chromatic adaption

- Color rendering

Photobiological effects

- Pupillary response/Visual acuity
- Circadian effects



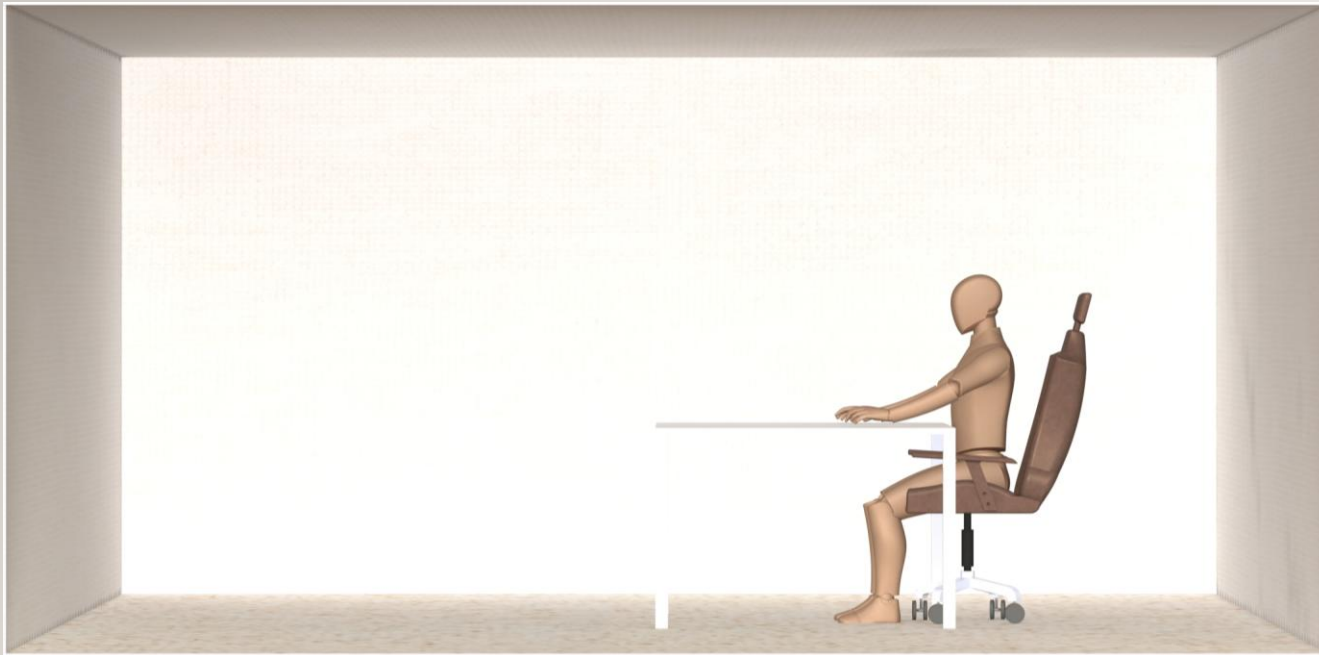
# RAY TRACE SOFTWARE

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- Radiometric or Photometric Basis
- Spectral capability (source, surface/material properties)
- High spatial accuracy ( $< 1 \mu\text{m}$ )
- Analysis Capabilities
  - Ray history - full path data for each ray
  - Path sorting – series of surface interactions for light incident on a surface (by source)
  - Summary of flux reaching surface (irradiance) by unique path
- Computationally intensive (CPU load, memory requirements)

# EVALUATION METHOD

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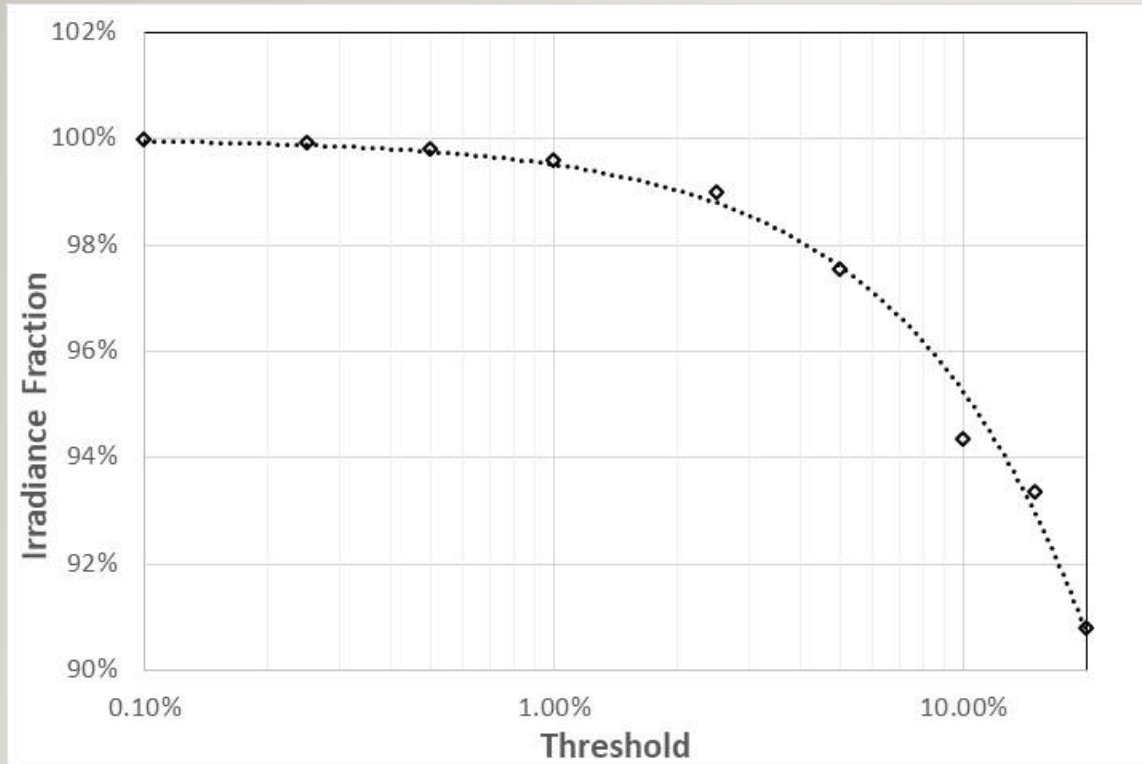


\*Chair and mannequin for reference only

CAD Model → Import to TracePro 7.4

- 2'x4' Troffer
- Parallel orientation
- Lambertian Emission
- 4000 lumens
- 100kk initial rays

# THRESHOLD VS IRRADIANCE/ILLUMINANCE ERROR



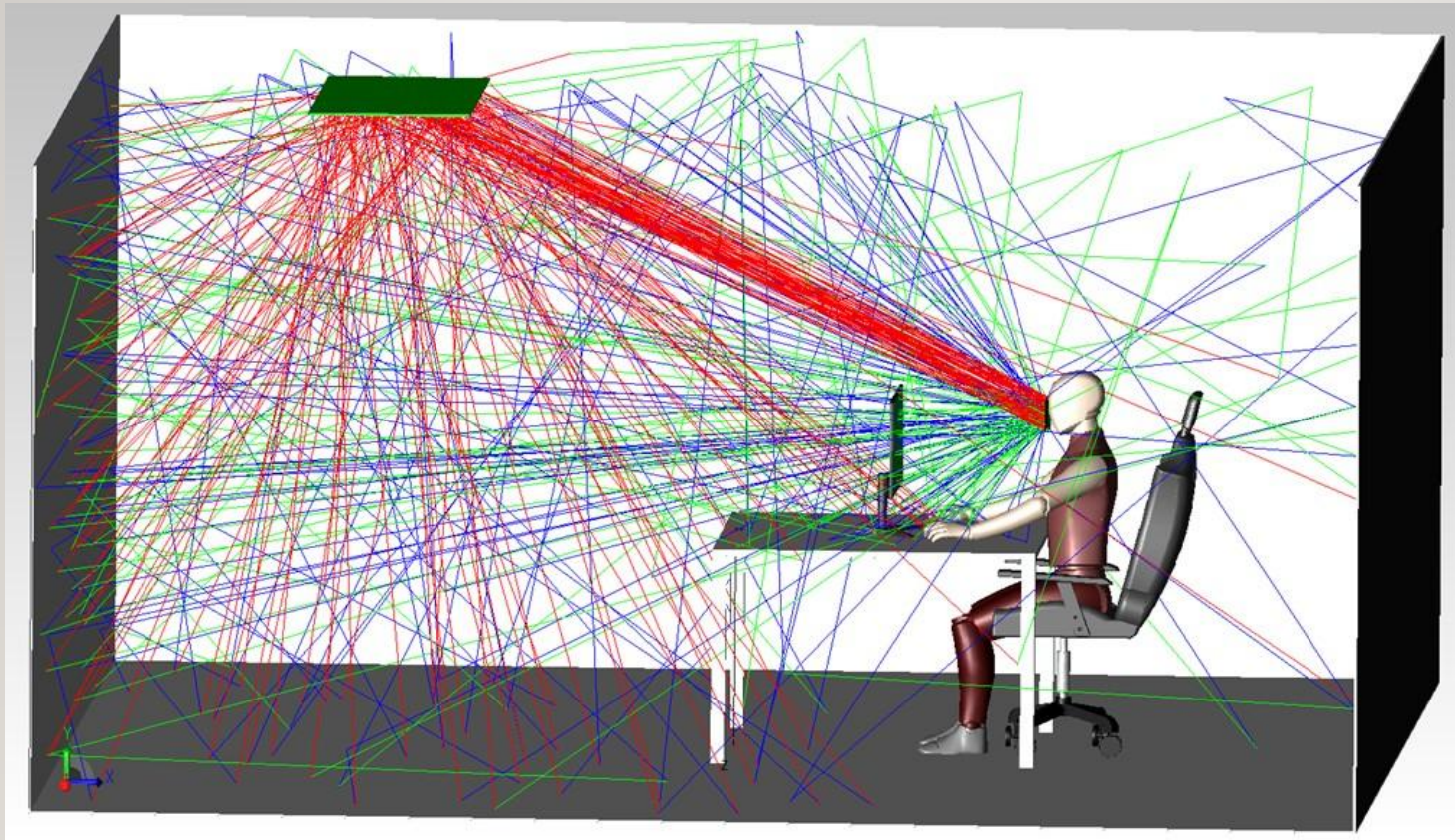
Photometric and Ray Trace software both use a threshold (minimum intensity for propagation)

Lower threshold increases accuracy, but adds time/computation expense

- Study threshold = 2.5%
- ~1% underestimation
- File size >130 GB

Approximation: missed light = threshold/2

# RAY ANALYSIS



- Ray energy coded by color
- All primary room surfaces interact to some extent

# RAY PATH DATA

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- Even summary data is a large file ( $\gg 1,000$  unique paths)
- Top 40 paths  $> 95\%$  of total irradiance
- 40 unique paths  $\rightarrow$  14 equivalent paths
  - Surfaces with same property
  - Sequence invariance (order of interactions does not change result)
- Equivalent paths used to create reflectance model

# EXAMPLE RAY PATH DATA

Ray Path	Source	No. Rays	Incident Flux	% of Total	Path Type	No.	Intercept Type	Surface
⊖ 1	2x4 troffer/>>>> Emitter	32690	1.96139999999879	62.10	Specular	1	Emitted	>>> Emitter
						2	At Surface	<<< Eye zone
⊖ 2	2x4 troffer/>>>> Emitter	10132	0.30395999999997	9.62	Single Surf Scat	1	Emitted	>>> Emitter
						2	RandRefl	# Desk surface
						3	At Surface	<<< Eye zone
⊖ 3	2x4 troffer/>>>> Emitter	9724	0.291719999999998	9.24	Single Surf Scat	1	Emitted	>>> Emitter
						2	RandRefl	Front Wall
						3	At Surface	<<< Eye zone
⊖ 4	2x4 troffer/>>>> Emitter	2135	0.0640500000000019	2.03	Single Surf Scat	1	Emitted	>>> Emitter
						2	RandRefl	Right Wall
						3	At Surface	<<< Eye zone
⊖ 5	2x4 troffer/>>>> Emitter	2078	0.0623400000000018	1.97	Single Surf Scat	1	Emitted	>>> Emitter
						2	RandRefl	Left Wall
						3	At Surface	<<< Eye zone
⊖ 6	2x4 troffer/>>>> Emitter	5453	0.0523487999999945	1.66	Multiple Surf Scat			

- All walls have same surface properties ∴ equivalent

# ANALYSIS

#	Path	Fraction	Cumulative
1	Direct	62.024%	62.024%
2	1 Wall	13.333%	75.358%
3	Desk	9.603%	84.961%
4	Ceiling + Wall	3.266%	88.227%
5	Floor + Ceiling	1.661%	89.888%
6	2 Wall	1.478%	91.366%
7	Floor + Wall	1.125%	92.491%
8	Ceiling + Desk	0.854%	93.345%
9	Wall + Ceiling + Desk	0.647%	93.993%
10	Floor	0.597%	94.589%
11	2 Wall + Ceiling	0.430%	95.020%
12	Wall + Desk	0.412%	95.432%
13	Wall + Floor + Ceiling	0.400%	95.832%
14	Floor + Ceiling + Desk	0.387%	96.219%

## Corneal Irradiance

- >21% depends on wall interactions
- ~12% from work surface interactions (highly variable surface)
- 7-8% from ceiling interactions
- ~4% from floor interactions

# ANALYSIS

Source/Path	Contribution	Surface Interactions	Fraction	Cummulative
Direct	62.024%	0	62.024%	62.024%
1 Wall	13.333%	1	23.533%	85.557%
Desk	9.603%			
Floor	0.597%			
Ceiling + Wall	3.266%	2	8.797%	94.355%
Floor + Ceiling	1.661%			
2 Wall	1.478%			
Floor + Wall	1.125%			
Ceiling + Desk	0.854%			
Wall + Desk	0.412%			
Wall + Ceiling + Desk	0.647%	3	1.864%	96.219%
2 Wall + Ceiling	0.430%			
Wall + Floor + Ceiling	0.400%			
Floor + Ceiling + Desk	0.387%			

## Corneal Irradiance

- Direct + Primary + Secondary interactions account for majority of corneal irradiance
- Tertiary + higher interactions are minor component of corneal irradiance
- Chromaticity shift increases with each interaction

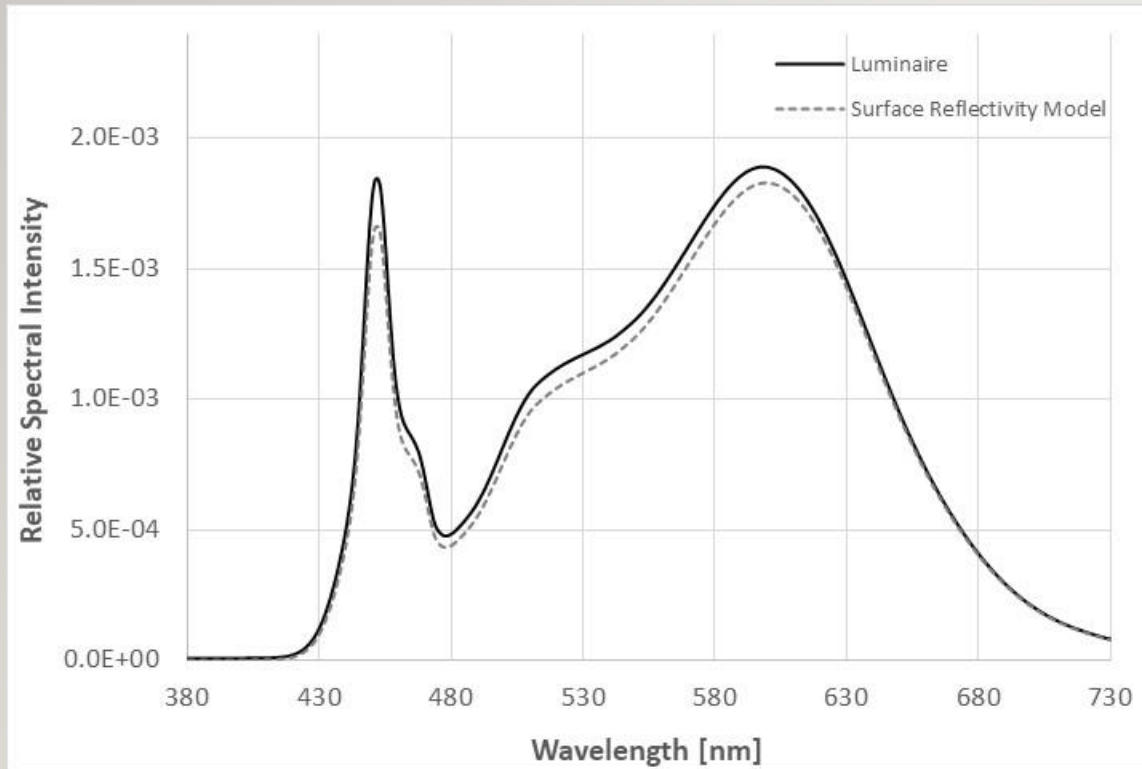
# ANALYSIS

Source/Path	Contribution	Surface Interactions	Fraction	Cummulative	$\Delta u'v'$
Direct	62.024%	0	62.024%	62.024%	0.00000
1 Wall	13.333%	1	23.533%	85.557%	0.00664
Desk	9.603%				0.00976
Floor	0.597%				0.00958
Ceiling + Wall	3.266%	2	8.797%	94.355%	0.00941
Floor + Ceiling	1.661%				0.01226
2 Wall	1.478%				0.01293
Floor + Wall	1.125%				0.01578
Ceiling + Desk	0.854%				0.01243
Wall + Desk	0.412%				0.01598
Wall + Ceiling + Desk	0.647%	3	1.864%	96.219%	0.01847
2 Wall + Ceiling	0.430%				0.01549
Wall + Floor + Ceiling	0.400%				0.01828
Floor + Ceiling + Desk	0.387%				0.02128

## Average Chromaticity Shift

- Primary  $\Delta u'v' = 0.00866$
- Secondary  $\Delta u'v' = 0.01313$
- Tertiary  $\Delta u'v' = 0.01838$

# SUMMARY



$$\Delta u'v' = 0.00341$$

- Interactions with surfaces in the build environment can significantly shift spectrum incident at the cornea relative to luminaire emission
- Nominal effect expected  $\Delta u'v' > 0.0030$
- Magnitude of effect depends on “strength” of chromatic surfaces
- CCT for color rendering will differ from that of luminaire

# OTHER FACTORS

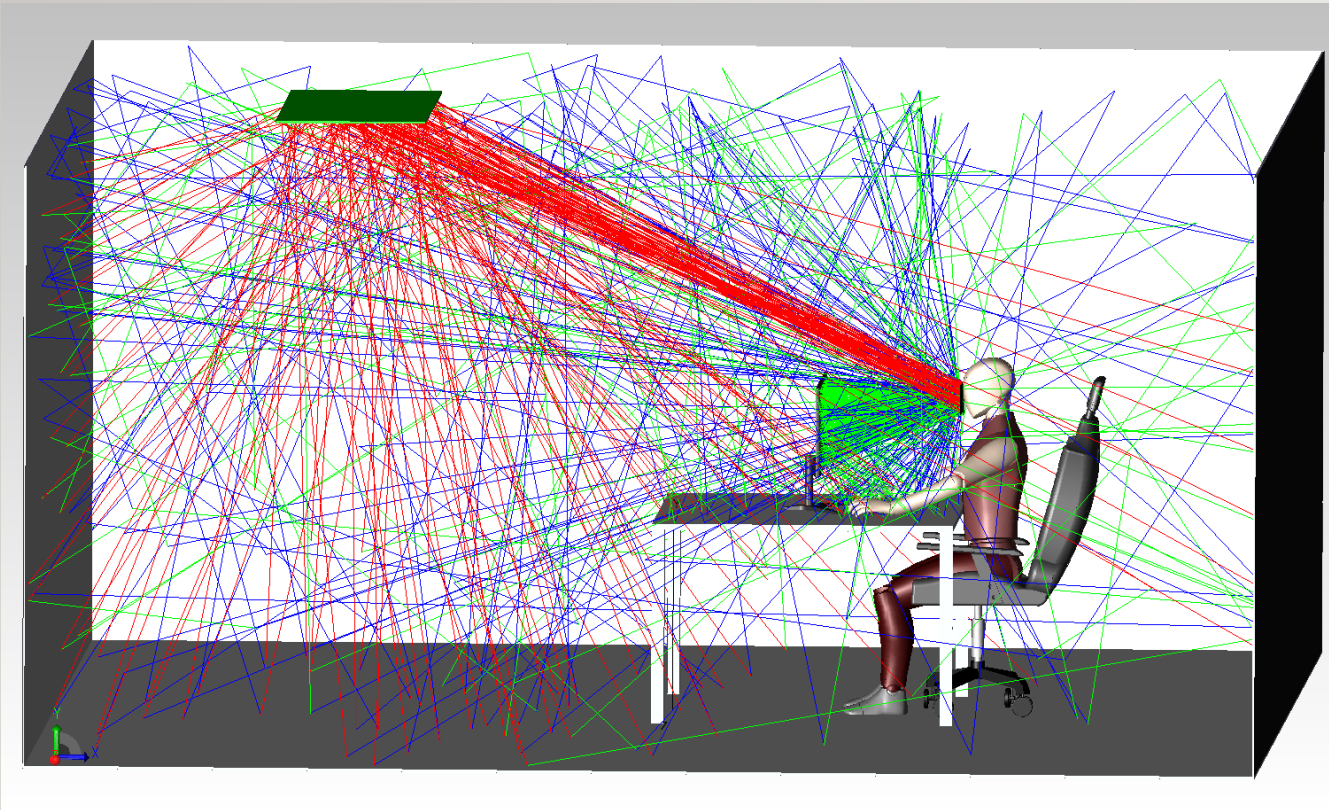
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- Contributions from emissive displays
- Displays are prevalent in office environments
- Displays occupy a significant fraction of the visual field

# OTHER FACTORS

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- Corneal irradiance can be dominated by emissions from display
- 27", 300 nit display >60% of corneal irradiance
- Larger, brighter displays or dual displays will have proportionally larger impact

# CONCLUSIONS

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- Spectral power distributions at the cornea are significantly impacted by interactions with surfaces in the built environment
- Effective CCT for color rendering will differ from that of luminaire(s)
- Surface interactions should be accounted for (uncertainty?)
- Impact on corneal irradiance varies with location and design (luminaires, subject position)
- Corneal irradiance can easily be dominated by even modest displays