# 48-410 Acoustics and Lighting
# Fall 2008

**Monday, Wednesday, 12:30~13:20**
**DH A310 (lectures)**
**Hunt Lower Level (Software Sessions)**

## Lecture 4: Lighting Performance 2

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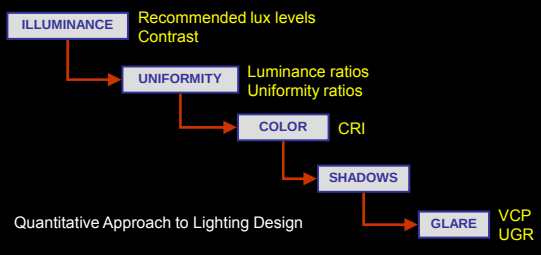
## *Class Plan*

- Uniformity metrics
- Luminance ratios
- Glare – VCP & UGR
- Daylight – Daylight Factor & Glazing Factors



## Recommended Illuminance Levels

| TASK REQUIREMENT | EXAMPLE | GUIDELINE ILLUMINANCE |
|---|---|---|
| General lighting Simple visual tasks | Access routes | 50 |
| | Staircases, corridors | 100 |
| | Bathrooms | 150 |
| | Foyers, lobbies | 200 |
| General Lighting Working spaces | Classrooms | 300 |
| | General Offices | 500 |
| | Drawing offices, studios | 700 |
| | Electronic Assembly | 1000 |
| Lighting for complicated visual tasks (small detail and low contrast) | Fine Work and Inspection | 1500 |
| | Assembly of minute mechanisms | 2000 |

| *Task requirements* | *Lux* | *Examples* |
|---|---|---|
| General awareness of space; perception of detail is unimportant | 50 | Access routes to service areas |
| Movement of people; recognition of detail for short periods; background lighting | 100 | Corridors, store rooms for large items, auditoria, bedrooms |
| Recognition of detail for short periods in areas where errors may be serious | 150 | Plant rooms, domestic bathrooms |
| Areas without difficult visual tasks but occupied for long periods; short-period tasks with moderate contrast or size of detail | 200 | General lighting in control booths, foyers, factory areas with automated processes |
| Tasks such as reading normal print (moderate contrast and size of detail) over long periods | 300 | Workshops for large items, general library areas, school classrooms, domestic kitchens |
| Tasks with some details of low contrast and moderate size | 500 | General offices, laboratories |
| Tasks with low contrast and small size | 700 | Drawing offices |
| Very small visual and low-contrast tasks | 1000 | Electronic assembly, tool rooms |
| Tasks with extremely small detail and low contrast | 1500 | Fine work and inspection |
| Tasks with exceptionally small detail and very low contrast | 2000 | Assembly of minute mechanisms |



## Contrast

Contrast describes the perceptible difference, and considers environmental adaptations

Contrast ratios, on the other hand, does not account for Weber's law, and simply describe the ratio between minimum and maximum luminances. (Not useful at extreme ranges)

### Weber Contrast

Contrast = Luminance Difference / Background Luminance $\frac{I - I_b}{I_b}$,

- Applicable when visual task is only a small portion of visual field

### Michelson Contrast

Contrast = Max Difference / 2 x Average Luminance $\frac{I_{max} - I_{min}}{I_{max} + I_{min}}$,

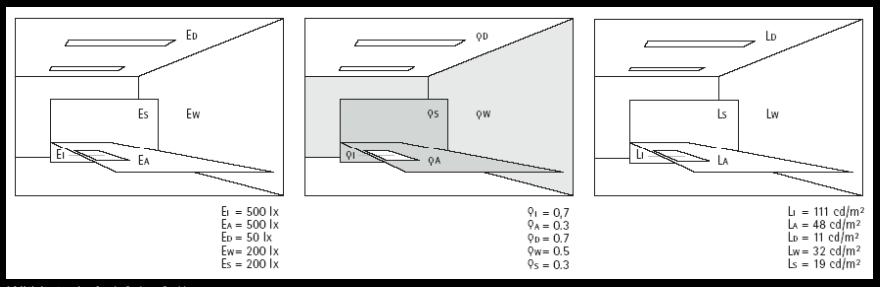
- Applicable when both bright and dark features take up similar fractions of area

## Luminance Ratios

Appearance / Perception instead of simple illumination quantities
- Not only adequate lighting but also optical effect (human perception)

Brightness and Contrast ratios (basis of perception)
- Artificial & daylight have different effects (latter higher tolerance)
- Visual interest (higher tolerance)

Finer granularity of lighting planning for a space
- From single task in space to visual requirements in visual environment
- Zones
- Using ratios




Within task → 1:3 (or 3:1)
Task : Adjacent surround → 3:1 (or 3:1)
Task : Remote surfaces → 1:10 (or 10:1)



## Uniformity Ratios

Uniformity describes the spatial distribution of light. Varying illumination on visual objects within a visual field causes different luminance levels, which results in both adaptations in our visual systems as well as variations in contrast levels in the visual task.

Variations can improve visual performance such as pattern recognition, or be detrimental such as being distracting when driving at night

Uniformity metrics assess the distribution of light according specific concerns

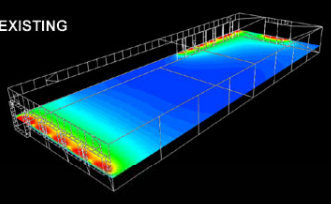
IESNA Uniformity Ratio for roadways $U = \frac{E_{avg}}{E_{\min}}$

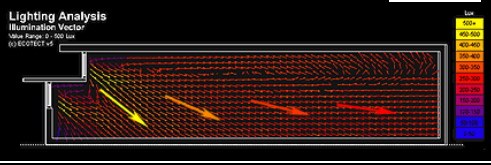
IESNA Uniformity Ratio for parking $U = \frac{E_{\max}}{E_{\min}}$

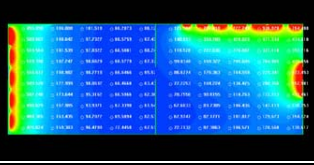
CIE Uniformity Ratio $U = \frac{E_{\min}}{E_{avg}}$

General lighting scheme should be better than 0.6 or 0.8

EXISTING





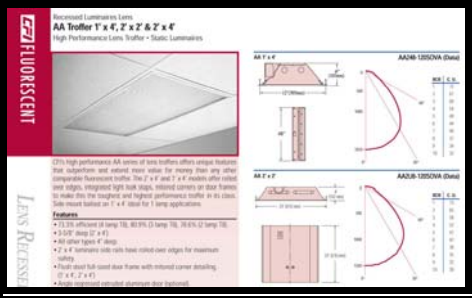
## Visual Comfort Probability (VCP)

Visual Comfort Probability (VCP) predicts if a lighting system would have direct glare problems. VCP estimates the percentage of people that would accept a lighting arrangement as visually comfortable.

Variables include –
- Field of view
- Luminaire mounting height, size, luminance
- Room Size
- Surface reflectance

Threshold evaluation based on Borderline of Comfort and Discomfort (BCD)
Formulated empirically (differences <5 not significant), applicable to "standard layouts"

Manufacturers use VCP formulas and standard conditions to produce tabular estimates of the level of discomfort glare produced by a regular array of their luminaires for a range of standard interiors




| Reference Data | |
|---|---|
| Efficiency | 70.7% |
| Spacing Ratio | 1.3 |
| **Electronic Ballast** | |
| Input Watts (120V) | 60.0W |
| Ballast Factor | .88 |

| Application Data* | | | |
|---|---|---|---|
| Luminaire Spacing | FC | VCP | W/Sq Ft |
| 50' x 70' x 8.5' Space | | | |
| 8' x 8' (64 sq ft/luminaire) | 52 | 59 | .9 |
| 8' x 10' (80 sq ft/luminaire) | 42 | 59 | .8 |
| 12' x 16' x 8.5' Space | | | |
| 6' x 8' (48 sq ft/luminaire) | 45 | 84 | 1.3 |



## CIE Unified Glare Rating (UGR)

The UGR scale is an *interval scale* where the differences between numbers represent the perceptible differences in psychological value. Only differences are meaningful, the value assigned to the lowest value is arbitrary.

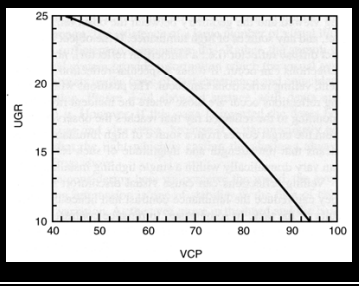
It is limited to direct sources within the 0.0003~0.1 steradians range

One glare rating unit is the least detectable step and three glare rating units is an acceptable step in terms of glare criteria.

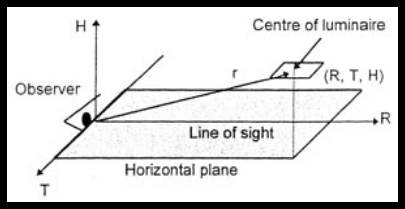
The practical range is 10-30 with most systems producing values in that range. It is sufficient to characterize systems with UGR below 10 as simply UGR<10.

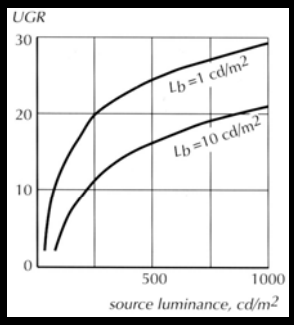
| Working area | Maximum allowed UGR |
|---|---|
| Drawing rooms | 16 |
| *Offices* | *19* |
| Industrial work, fine | 22 |
| Industrial work, medium | 25 |
| Industrial work, coarse | 28 |

**Recommended limiting glare indeces**



## CIE Unified Glare Rating (UGR)




$$UGR = 8 \log \left[ \frac{0.25}{L_b} \Sigma \frac{L^2 \omega}{p^2} \right]$$

L – Luminance of glare source
$L_b$ – Luminance of background to the source
ω – Solid angle subtended by glare source (size)
p – Position index

| Zone | Region | UGR |
|---|---|---|
| Discomfort Zone | Intolerable | >28 |
| | Just Intolerable | 28 |
| | Uncomfortable | 25 |
| | Just Uncomfortable | 22 |
| Comfort Zone | Acceptable | 19 |
| | Just Acceptable | 16 |
| | Noticeable | 13 |
| | Just Perceptible | 10 |



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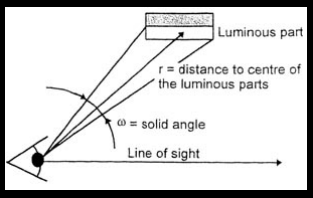
$$UGR = 8 \log \left[ \frac{0.25}{L_b} \Sigma \frac{L^2 \omega}{p^2} \right]$$




$L_b$ – Luminance of background to the source

Defined as the uniform luminance of the whole surroundings which produces the same illuminance on a vertical plane at the observer's eye as the visual field under consideration excluding the glare sources

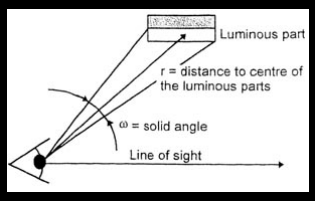
Thus, if given the indirect illuminance $E_i$ at the eye of the observer, $L_b = E_i / \pi$

Alternatively, computational methods can be used to determine the luminance on surfaces within the visual filed, then the illuminance at the observer's eye, and finally $L_b$

The UGR is relatively insensitive to errors in $L_b$, an error of +33% in $L_b$ will result in an error of the UGR of 1 unit

## CIE Unified Glare Rating (UGR)

$$UGR = 8 \log \left[ \frac{0.25}{L_b} \sum \frac{L^2 \omega}{p^2} \right]$$




L – Luminaire (Glare) Luminance

Generally derived from the luminous intensity I of the luminaire in the direction of the observer, and the projected area $A_{proj}$ of the luminaire, $L = I / A_{proj}$

ω – Solid angle subtended by glare source

The solid angle subtended by the luminaire can be derived from the projected area Ap of the luminaire and the distance r from the center of the luminaire to the observer, $\omega = Ap / r2$

p – Position index

Derived empirically, the position index accounts for variations in sensitivity related to the position of the glare source in the field of vision.

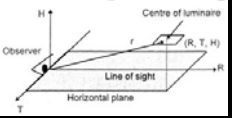
Given the same luminance and displacement from the center of the visual field, discomfort from glare on the horizontal axis is more pronounced than the vertical axis.



## CIE Unified Glare Rating (UGR)

| T/R \ H/R | 0,00 | 0,10 | 0,20 | 0,30 | 0,40 | 0,50 | 0,60 | 0,70 | 0,80 | 0,90 | 1,00 | 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | 1,60 | 1,70 | 1,80 | 1,90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,00 | 1,00 | 1,26 | 1,53 | 1,90 | 2,35 | 2,86 | 3,50 | 4,20 | 5,00 | 6,00 | 7,00 | 8,10 | 9,25 | 10,35 | 11,70 | 13,15 | 14,70 | 16,20 | - | - |
| 0,10 | 1,05 | 1,22 | 1,46 | 1,80 | 2,20 | 2,75 | 3,40 | 4,10 | 4,80 | 5,80 | 6,80 | 8,00 | 9,10 | 10,30 | 11,60 | 13,00 | 14,60 | 16,10 | - | - |
| 0,20 | 1,12 | 1,30 | 1,50 | 1,80 | 2,20 | 2,66 | 3,18 | 3,88 | 4,60 | 5,50 | 6,50 | 7,60 | 8,75 | 9,85 | 11,20 | 12,70 | 14,00 | 15,70 | - | - |
| 0,30 | 1,22 | 1,38 | 1,60 | 1,87 | 2,25 | 2,70 | 3,25 | 3,90 | 4,60 | 5,45 | 6,45 | 7,40 | 8,40 | 9,50 | 10,85 | 12,10 | 13,70 | 15,00 | - | - |
| 0,40 | 1,32 | 1,47 | 1,70 | 1,96 | 2,35 | 2,80 | 3,30 | 3,90 | 4,60 | 5,40 | 6,40 | 7,30 | 8,30 | 9,40 | 10,60 | 11,90 | 13,20 | 14,60 | 16,00 | - |
| 0,50 | 1,43 | 1,60 | 1,82 | 2,10 | 2,48 | 2,91 | 3,40 | 3,98 | 4,70 | 5,50 | 6,40 | 7,30 | 8,30 | 9,40 | 10,50 | 11,75 | 13,00 | 14,40 | 15,70 | - |
| 0,60 | 1,55 | 1,72 | 1,98 | 2,30 | 2,65 | 3,10 | 3,60 | 4,10 | 4,80 | 5,50 | 6,40 | 7,35 | 8,40 | 9,40 | 10,50 | 11,70 | 13,00 | 14,10 | 15,40 | - |
| 0,70 | 1,70 | 1,88 | 2,12 | 2,48 | 2,87 | 3,30 | 3,78 | 4,30 | 4,88 | 5,60 | 6,50 | 7,40 | 8,50 | 9,50 | 10,50 | 11,70 | 12,85 | 14,00 | 15,20 | - |
| 0,80 | 1,82 | 2,00 | 2,32 | 2,70 | 3,08 | 3,50 | 3,92 | 4,50 | 5,10 | 5,75 | 6,60 | 7,50 | 8,60 | 9,50 | 10,60 | 11,75 | 12,80 | 14,00 | 15,10 | - |
| 0,90 | 1,95 | 2,20 | 2,54 | 2,90 | 3,30 | 3,70 | 4,20 | 4,75 | 5,30 | 6,00 | 6,75 | 7,70 | 8,70 | 9,65 | 10,75 | 11,80 | 12,90 | 14,00 | 15,00 | 16,00 |
| 1,00 | 2,11 | 2,40 | 2,75 | 3,10 | 3,50 | 3,91 | 4,40 | 5,00 | 5,60 | 6,20 | 7,00 | 7,90 | 8,80 | 9,75 | 10,80 | 11,90 | 12,95 | 14,00 | 15,00 | 16,00 |
| 1,10 | 2,30 | 2,55 | 2,92 | 3,30 | 3,72 | 4,20 | 4,70 | 5,25 | 5,80 | 6,55 | 7,20 | 8,15 | 9,00 | 9,90 | 10,95 | 12,00 | 13,00 | 14,00 | 15,00 | 16,00 |
| 1,20 | 2,40 | 2,75 | 3,12 | 3,50 | 3,90 | 4,35 | 4,85 | 5,50 | 6,05 | 6,70 | 7,50 | 8,30 | 9,20 | 10,00 | 11,02 | 12,10 | 13,10 | 14,00 | 15,00 | 16,00 |
| 1,30 | 2,55 | 2,90 | 3,30 | 3,70 | 4,20 | 4,65 | 5,20 | 5,70 | 6,30 | 7,00 | 7,70 | 8,55 | 9,35 | 10,20 | 11,20 | 12,25 | 13,20 | 14,00 | 15,00 | 16,00 |
| 1,40 | 2,70 | 3,10 | 3,50 | 3,90 | 4,35 | 4,85 | 5,35 | 5,85 | 6,50 | 7,25 | 8,00 | 8,70 | 9,50 | 10,40 | 11,40 | 12,40 | 13,25 | 14,05 | 15,00 | 16,00 |
| 1,50 | 2,85 | 3,15 | 3,65 | 4,10 | 4,55 | 5,00 | 5,50 | 6,20 | 6,80 | 7,50 | 8,20 | 8,85 | 9,70 | 10,55 | 11,50 | 12,50 | 13,30 | 14,05 | 15,02 | 16,00 |
| 1,60 | 2,95 | 3,40 | 3,80 | 4,25 | 4,75 | 5,20 | 5,75 | 6,30 | 7,00 | 7,65 | 8,40 | 9,00 | 9,80 | 10,80 | 11,75 | 12,60 | 13,40 | 14,20 | 15,10 | 16,00 |
| 1,70 | 3,10 | 3,55 | 4,00 | 4,50 | 4,90 | 5,40 | 5,95 | 6,50 | 7,20 | 7,80 | 8,50 | 9,20 | 10,00 | 10,85 | 11,85 | 12,75 | 13,45 | 14,20 | 15,10 | 16,00 |
| 1,80 | 3,25 | 3,70 | 4,20 | 4,65 | 5,10 | 5,60 | 6,10 | 6,75 | 7,40 | 8,00 | 8,65 | 9,35 | 10,10 | 11,00 | 11,90 | 12,80 | 13,50 | 14,20 | 15,10 | 16,00 |
| 1,90 | 3,43 | 3,86 | 4,30 | 4,75 | 5,20 | 5,70 | 6,30 | 6,90 | 7,50 | 8,17 | 8,80 | 9,50 | 10,20 | 11,00 | 12,00 | 12,82 | 13,55 | 14,20 | 15,10 | 16,00 |
| 2,00 | 3,50 | 4,00 | 4,50 | 4,90 | 5,35 | 5,80 | 6,40 | 7,10 | 7,70 | 8,30 | 8,90 | 9,60 | 10,40 | 11,10 | 12,00 | 12,85 | 13,60 | 14,30 | 15,10 | 16,00 |
| 2,10 | 3,60 | 4,17 | 4,65 | 5,05 | 5,50 | 6,00 | 6,60 | 7,20 | 7,82 | 8,45 | 9,00 | 9,75 | 10,50 | 11,20 | 12,10 | 12,90 | 13,70 | 14,35 | 15,10 | 16,00 |
| 2,20 | 3,75 | 4,25 | 4,72 | 5,20 | 5,60 | 6,10 | 6,70 | 7,35 | 8,00 | 8,55 | 9,15 | 9,85 | 10,60 | 11,30 | 12,10 | 12,90 | 13,70 | 14,40 | 15,15 | 16,00 |
| 2,30 | 3,85 | 4,35 | 4,80 | 5,25 | 5,70 | 6,22 | 6,80 | 7,40 | 8,10 | 8,65 | 9,30 | 9,90 | 10,70 | 11,40 | 12,20 | 12,95 | 13,70 | 14,40 | 15,20 | 16,00 |
| 2,40 | 3,95 | 4,40 | 4,90 | 5,35 | 5,80 | 6,30 | 6,90 | 7,50 | 8,20 | 8,80 | 9,40 | 10,00 | 10,80 | 11,50 | 12,25 | 13,00 | 13,75 | 14,45 | 15,20 | 16,00 |
| 2,50 | 4,00 | 4,50 | 4,95 | 5,40 | 5,85 | 6,40 | 6,95 | 7,55 | 8,25 | 8,85 | 9,50 | 10,05 | 10,85 | 11,55 | 12,30 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,60 | 4,07 | 4,55 | 5,05 | 5,47 | 5,95 | 6,45 | 7,00 | 7,65 | 8,35 | 8,95 | 9,55 | 10,10 | 10,90 | 11,60 | 12,32 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,70 | 4,10 | 4,60 | 5,10 | 5,53 | 6,00 | 6,50 | 7,05 | 7,70 | 8,40 | 9,00 | 9,60 | 10,16 | 10,92 | 11,63 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,80 | 4,15 | 4,62 | 5,15 | 5,56 | 6,05 | 6,55 | 7,08 | 7,73 | 8,45 | 9,05 | 9,65 | 10,20 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,90 | 4,20 | 4,65 | 5,17 | 5,60 | 6,07 | 6,57 | 7,12 | 7,75 | 8,50 | 9,10 | 9,70 | 10,23 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 3,00 | 4,22 | 4,67 | 5,20 | 5,65 | 6,12 | 6,60 | 7,15 | 7,80 | 8,55 | 9,12 | 9,70 | 10,23 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |

$$UGR = 8 \log \left[ \frac{0.25}{L_b} \sum \frac{L^2 \omega}{p^2} \right]$$



## Daylight

Kimball Art Museum, Louis Khan



## Average Daylight Factors

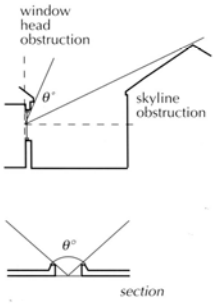



***Figure 16.7*** *Sky angle, θ, for a side window and a rooflight. The reference point is the centre of the window opening on the plane of the inside surface.*

The average daylight factor is the mean daylight factor on the horizontal working plane. It is given by the following equation:

$$\overline{D} = \frac{A_g}{A} \frac{\theta \tau}{(1-\rho^2)}$$

| | |
|---|---|
| $A_g$ | Glazed area of windows (not including window frames, glazing bars or other obstructions). |
| $A$ | Total area of enclosing room surfaces (ceiling, floor, walls including windows). |
| $\theta$ | Angle of visible sky, measured in section from a reference point in the centre of the window opening in the plane of the inside window wall |
| $\tau$ | Transmittance of glazing to diffuse light, including the effect of dirt. |
| $\rho$ | Mean reflectance of enclosing room surfaces. |

When there are several windows, with different glazing or different angles of external obstruction, $\overline{D}$ is calculated for each window separately, and the results are added together. If the windows have similar characteristics the daylight factor can be calculated from the total glazed area.

## Glazing Factors

**Equation 1:** Glazing Factor Calculation

$$\text{Glazing Factor} = \frac{\text{Window Area [SF]}}{\text{Floor Area [SF]}} \times \text{Window Geometry} \times \frac{\text{Actual } T_{vis}}{\text{Minimum } T_{vis}} \times \text{Window Height Factor}$$

**Table 1:** Daylighting Design Criteria

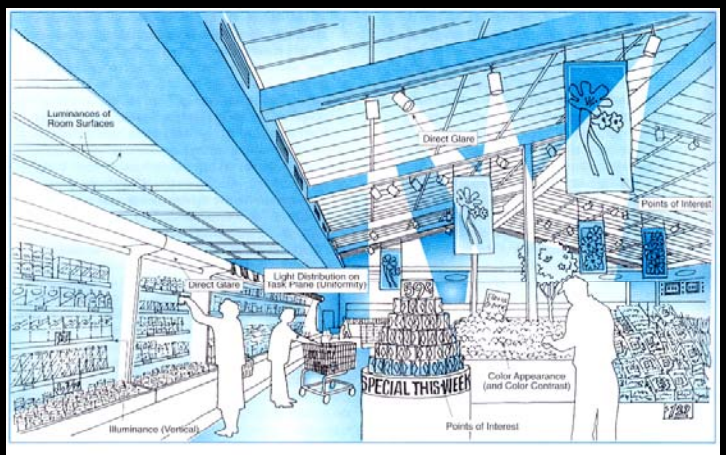
| Window Type | Geometry Factor | Minimum $T_{vis}$ | Height Factor | Best Practice Glare Control |
|---|---|---|---|---|
|  sidelighting daylight glazing | 0.1 | 0.7 | 1.4 | Adjustable blinds<br>Interior light shelves<br>Fixed transluscent exterior shading devices |
|  sidelighting vision glazing | 0.1 | 0.4 | 0.8 | Adjustable blinds<br>Exterior shading devices |
|  toplighting vertical monitor | 0.2 | 0.4 | 1.0 | Fixed interior<br>Adjustable exterior blinds |
|  toplighting sawtooth monitor | 0.33 | 0.4 | 1.0 | Fixed interior<br>Exterior louvers |
|  toplighting horizontal skylights | 0.5 | 0.4 | 1.0 | Interior fins<br>Exterior fins<br>Louvers |





## Applying Performance Metrics

There are ***many*** methods in approaching lighting design.
The quantitative approach (with 5 categories of considerations) is ***but one*** approach.
In any method though, the metrics introduced thus so far are useful in ***quantifying performance***.



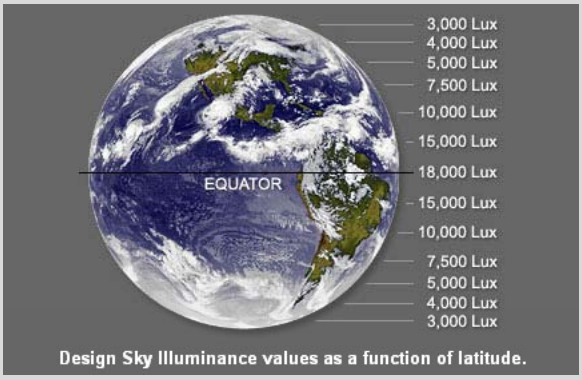

Supermarket produce section.

## *Supplementary Material – Describing the Sky*

The following slides would serve as a starting point for extra readings on sky descriptions.



## Describing Daylight – Skylight




Design Sky Illuminance values as a function of latitude.

… is sky luminance uniform?

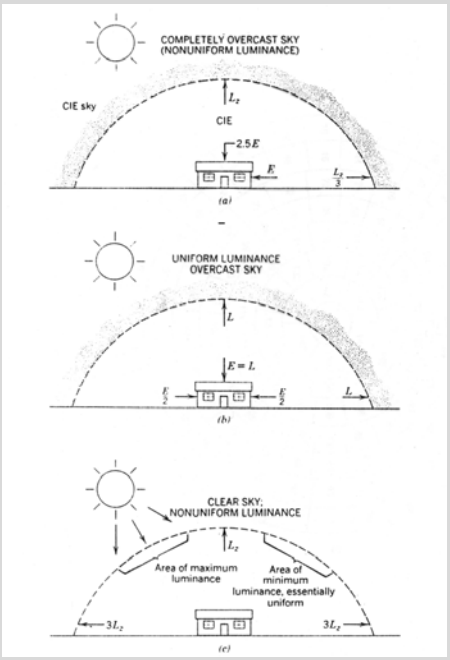
## Describing Daylight – Skylight

**CIE Sky Models**

CIE Standard Overcast Sky (1966)
Zenith 3 times brighter than Horizon

CIE Uniform Sky (1955)
Uniform luminance

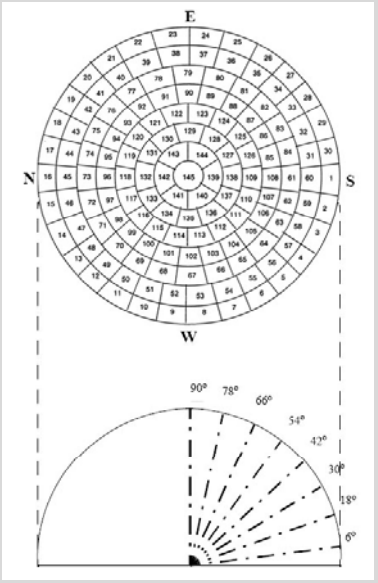
CIE Standard Clear Sky (1973)
Inverse of Overcast Sky
Area around sun brightest
Area opposite sun darkest






## Describing Daylight – Mapping Sky Luminance

EKO MS-300LR Sky Scanner



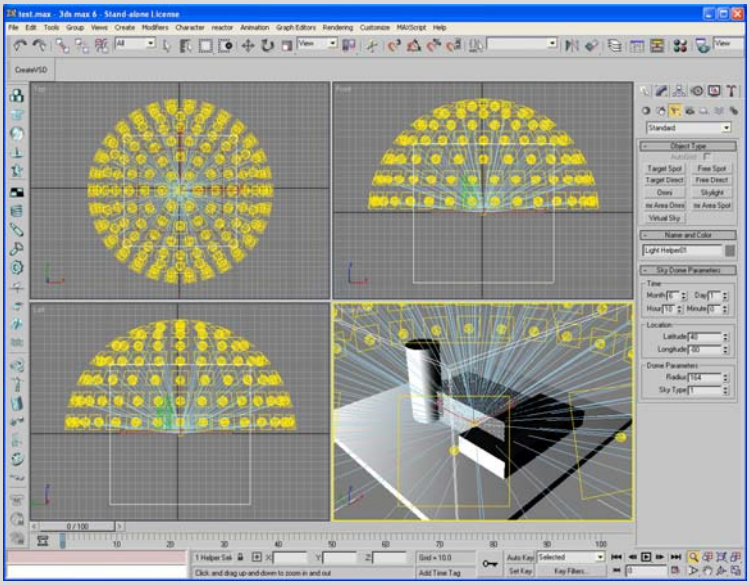

Subdivision of Sky Hemisphere
149 similar area patches
Tregenza (1986) Subdivision of the Sky Hemisphere for Luminance Measurements

## Describing Daylight – The NEW CIE General Sky (March 2004)

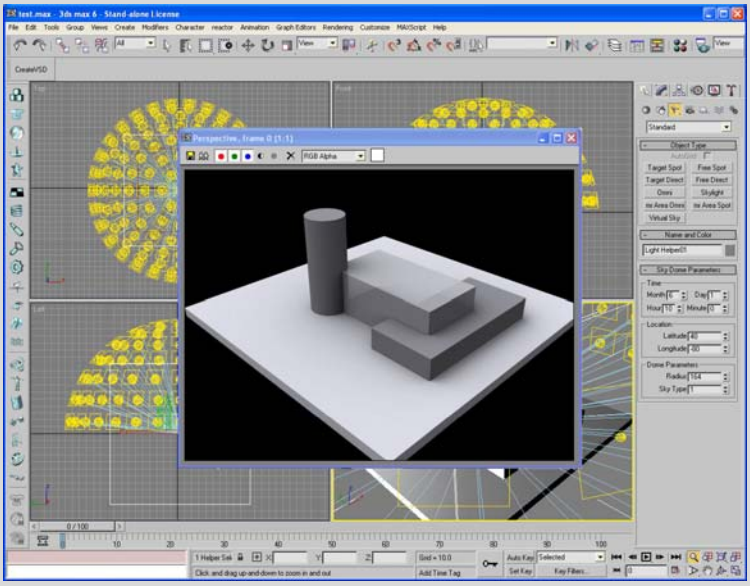
| Type | Description of Luminance Distribution |
|---|---|
| 1 | **CIE Standard Overcast Sky**<br>Steep Luminance gradation towards zenith, azimuthal uniformity |
| 2 | Overcast, with steep luminance gradation and slight brightening towards the sun |
| 3 | Overcast, moderately graded with azimuthal uniformity |
| 4 | Overcast, moderately graded and slight brightening towards the sun |
| 5 | **Sky of uniform luminance** |
| 6 | Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun |
| 7 | Partly cloudy sky, no gradation towards zenith, brighter circumsolar region |
| 8 | Partly cloudy sky, no gradation towards zenith, distinct solar corona |
| 9 | Partly cloudy, with obscured sun |
| 10 | Partly cloudy, with brighter circumsolar region |
| 11 | White-blue sky with distinct solar corona |
| 12 | **CIE Standard Clear Sky**<br>Low luminance turbidity |
| 13 | **CIE Standard Clear Sky**<br>Polluted atmosphere |
| 14 | Cloudless turbid sky with broad solar corona |
| 15 | White-blue turbid sky with broad solar corona |



## Demo – Virtual Sky Domes – Implementing new CIE (04) Sky model in 3D Max



Demo – Virtual Sky Domes





What do we do with these?