RWTH AACHEN UNIVERSITY

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Chair and Institute of Industrial Engineering and Ergonomics Aachen University

Industrial Engineering, Ergonomics & Work Organization

Lesson 11

Work Ecology II - Illumination

Winter 2005/2006

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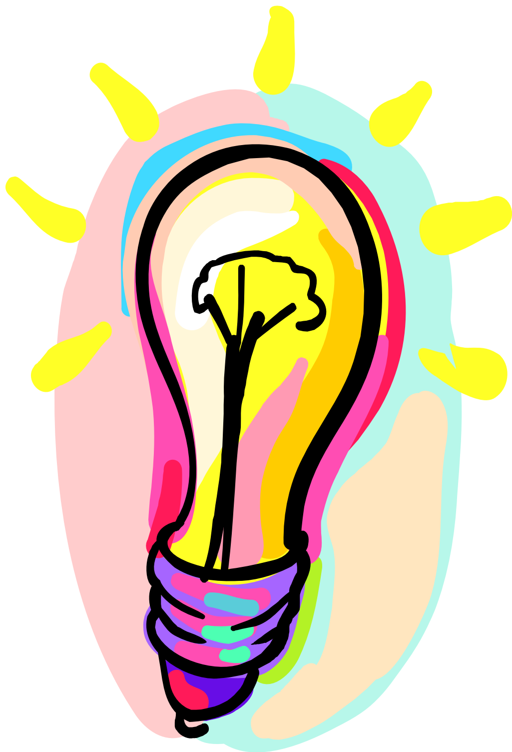
After attending this lecture the student should...

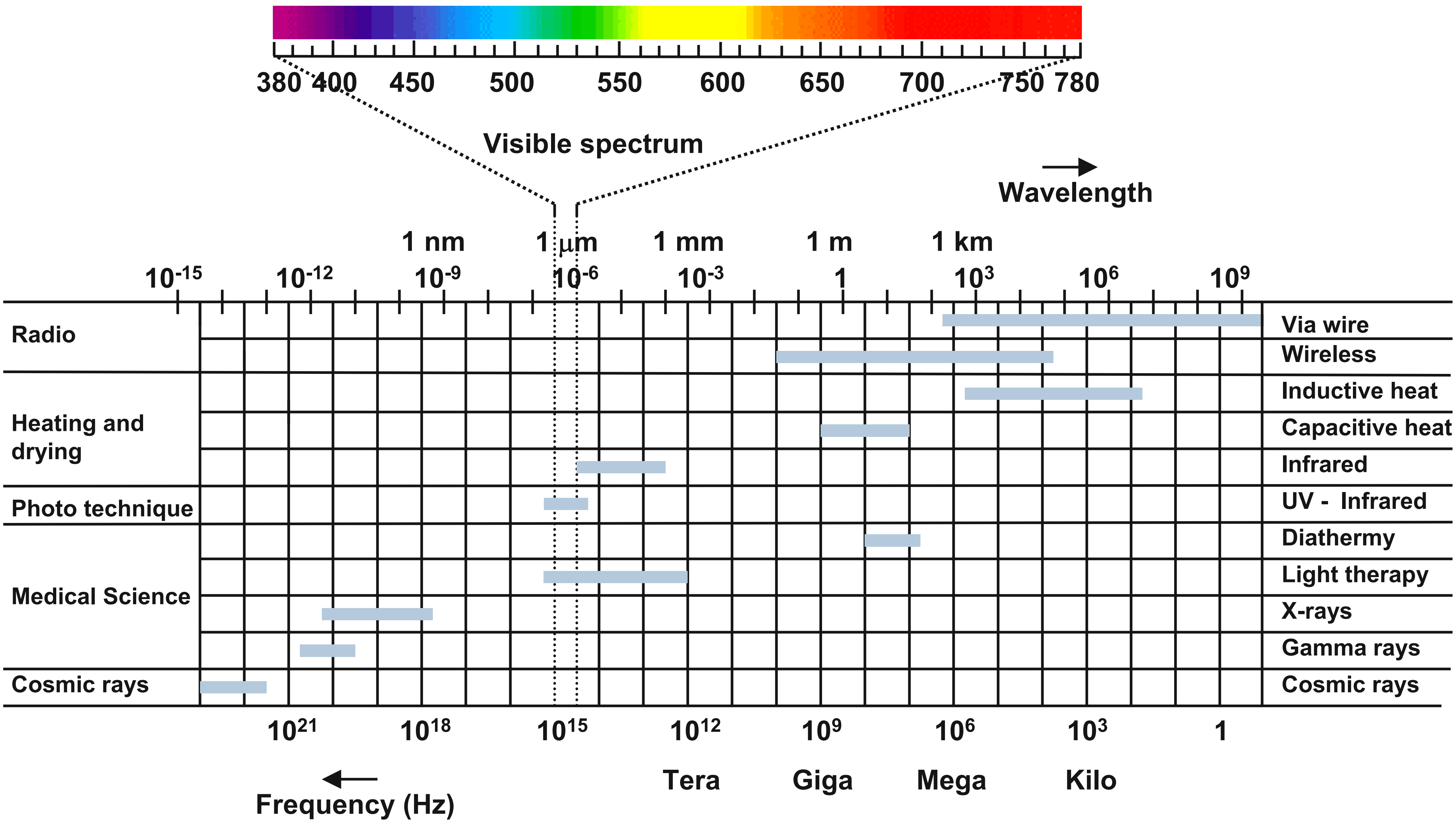
- have obtained an overview of the physical and physiological basics of illumination;
- be able to describe effects of lighting on work performance and health;
- have become familiar with the measurement of light;
- have a basic idea of the relevance of illumination for workplace design.

Why is illumination relevant to work organisation?

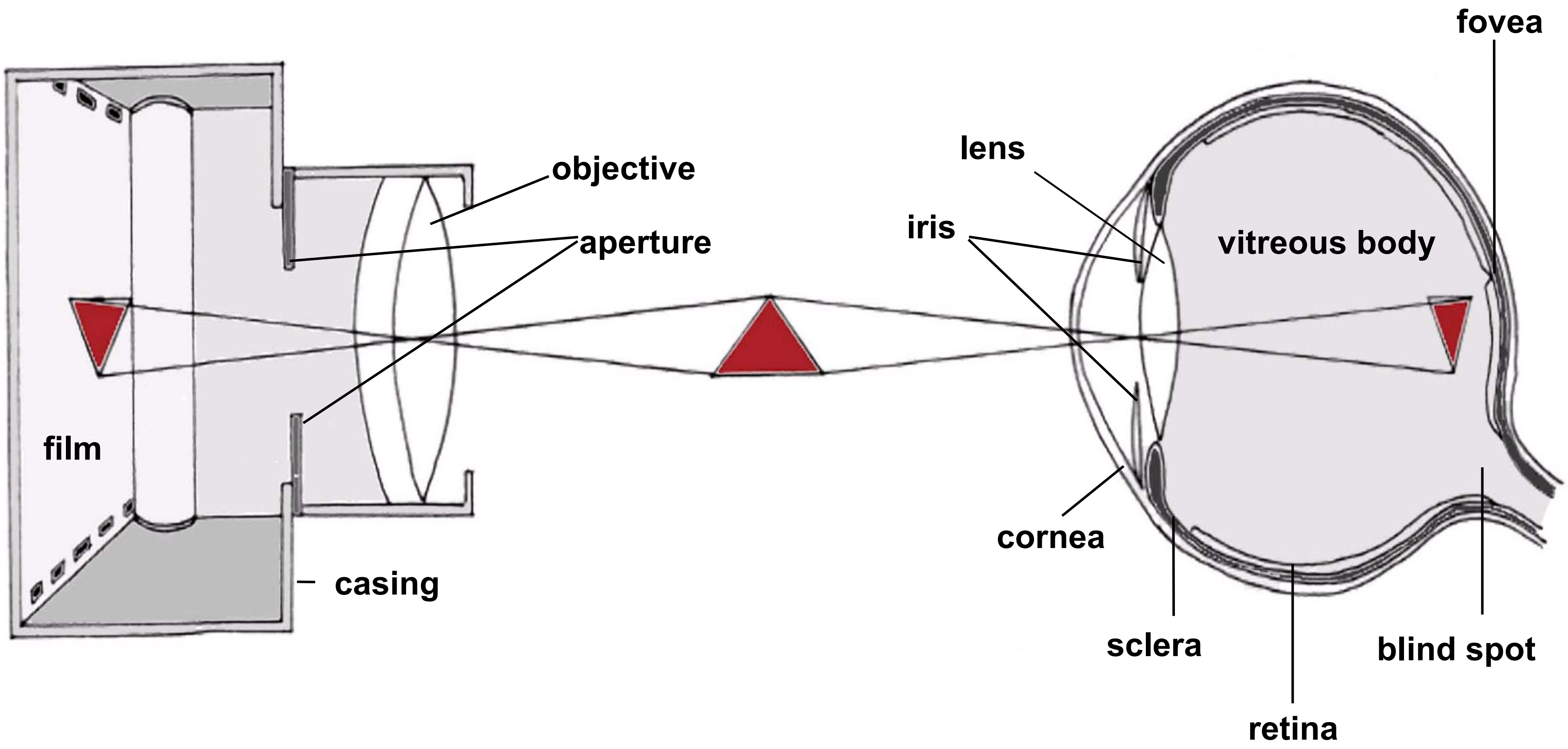
- Natural and artificial illumination influence the activity level and the productivity of the employees
- Glare can lead to reduced productivity and affected health
- The proportion of daylight, the light colouration, the light rendering and flicker-free artificial artificial illumination have an impact on the wellbeing of people
- Prevention of danger to people and equipment

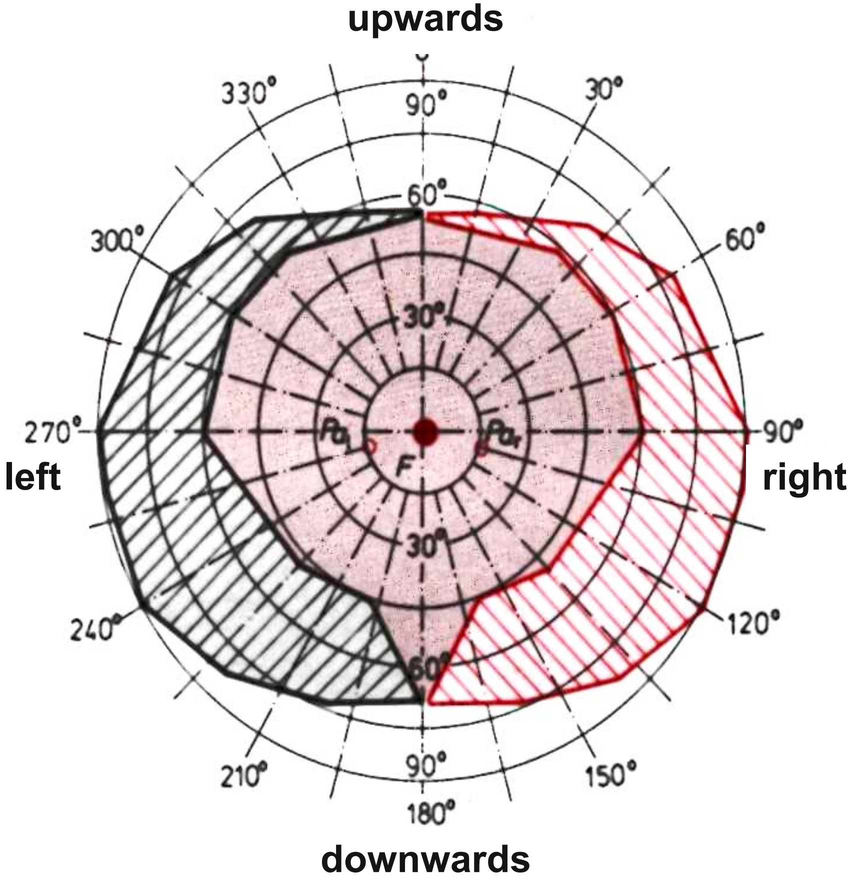


The Radiant Energy (Electromagnetic) Spectrum



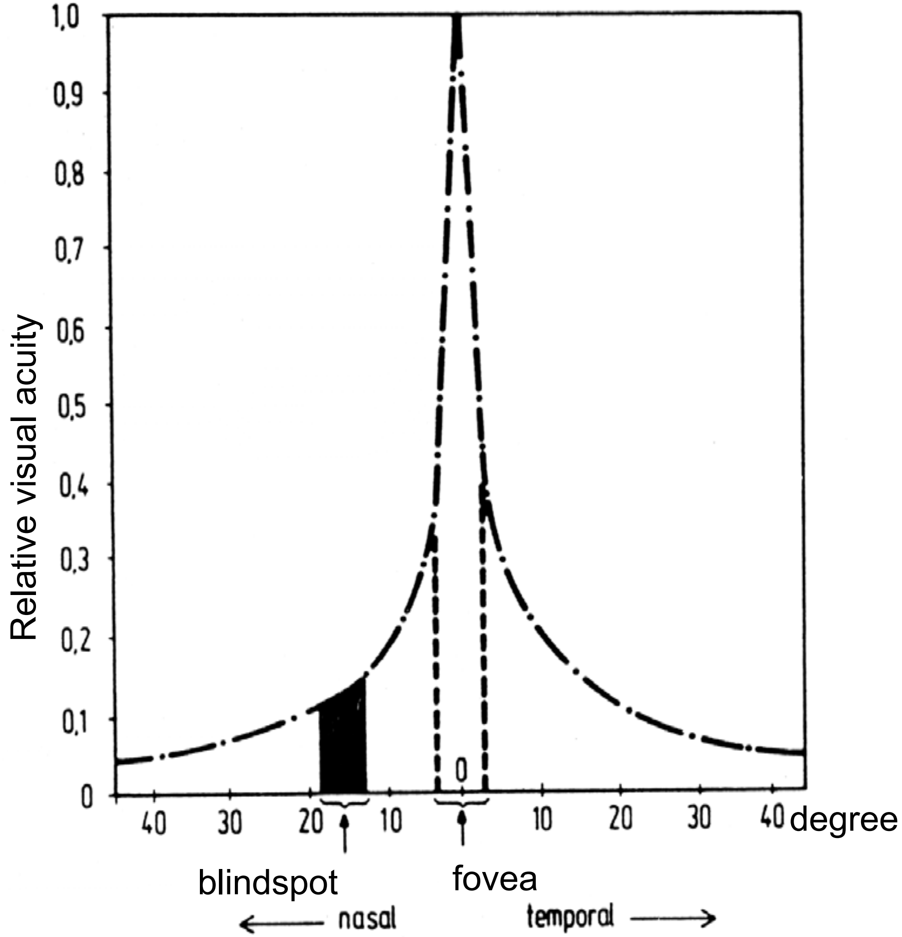
Schematic Cross-Section through the Human Eye





F = fovea centralis
Pa_l = blind spot of the left eye
Pa_r = blind spot of the right eye

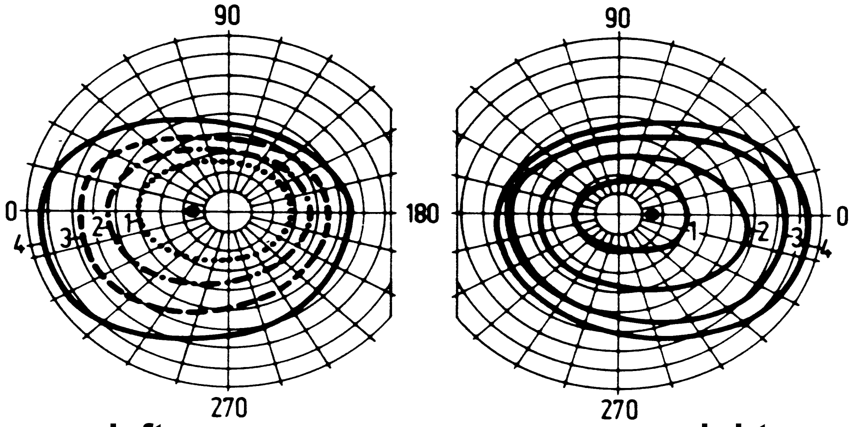
left eye
right eye
both eyes



Dependence between visual acuity and location of retina

Handbuch für Beleuchtung, SLG, 5. Auflage, 1992
(Handbook of Illumination, 5th Edition)

Field of Vision (• = _blind spot)_



left eye

right eye

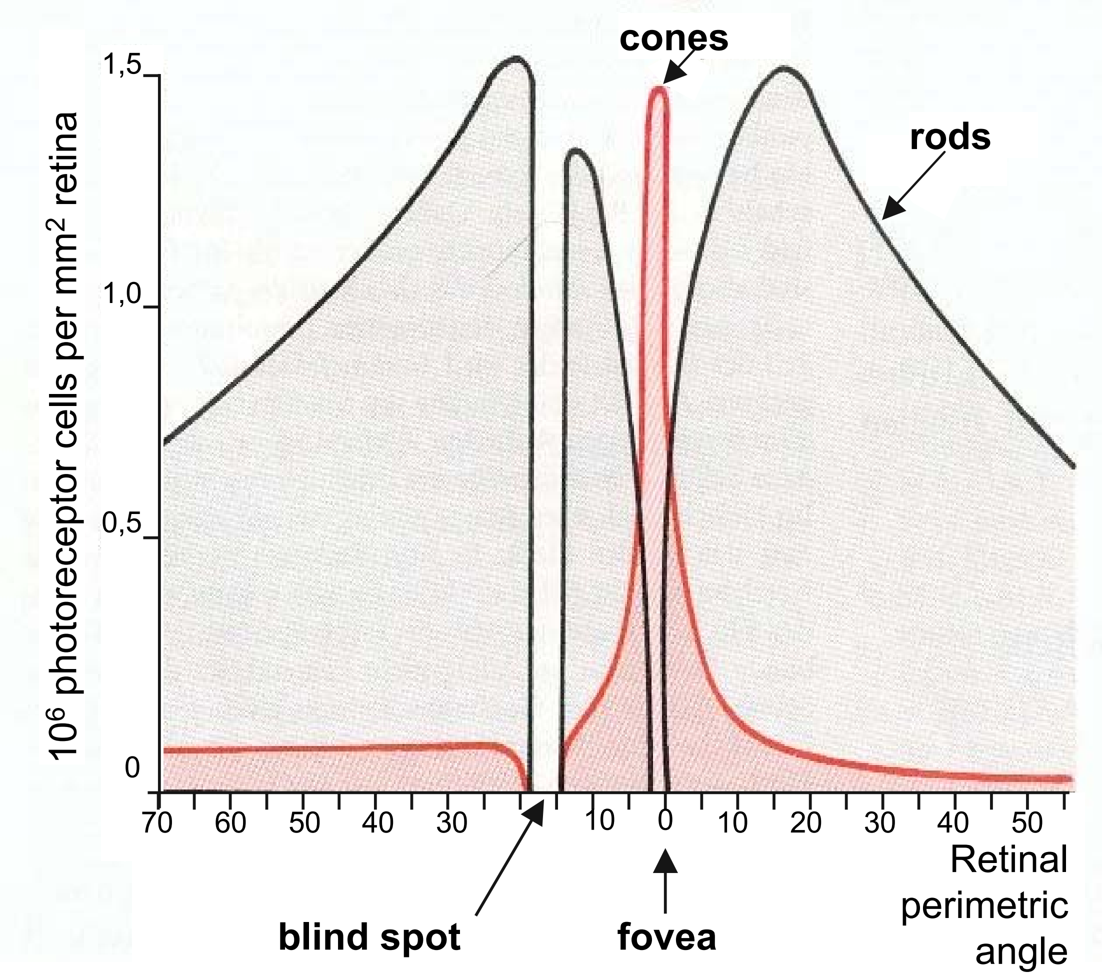
Boundaries of **colours:**

1 = green
2 = red
3 = blue
4 = non-coloured

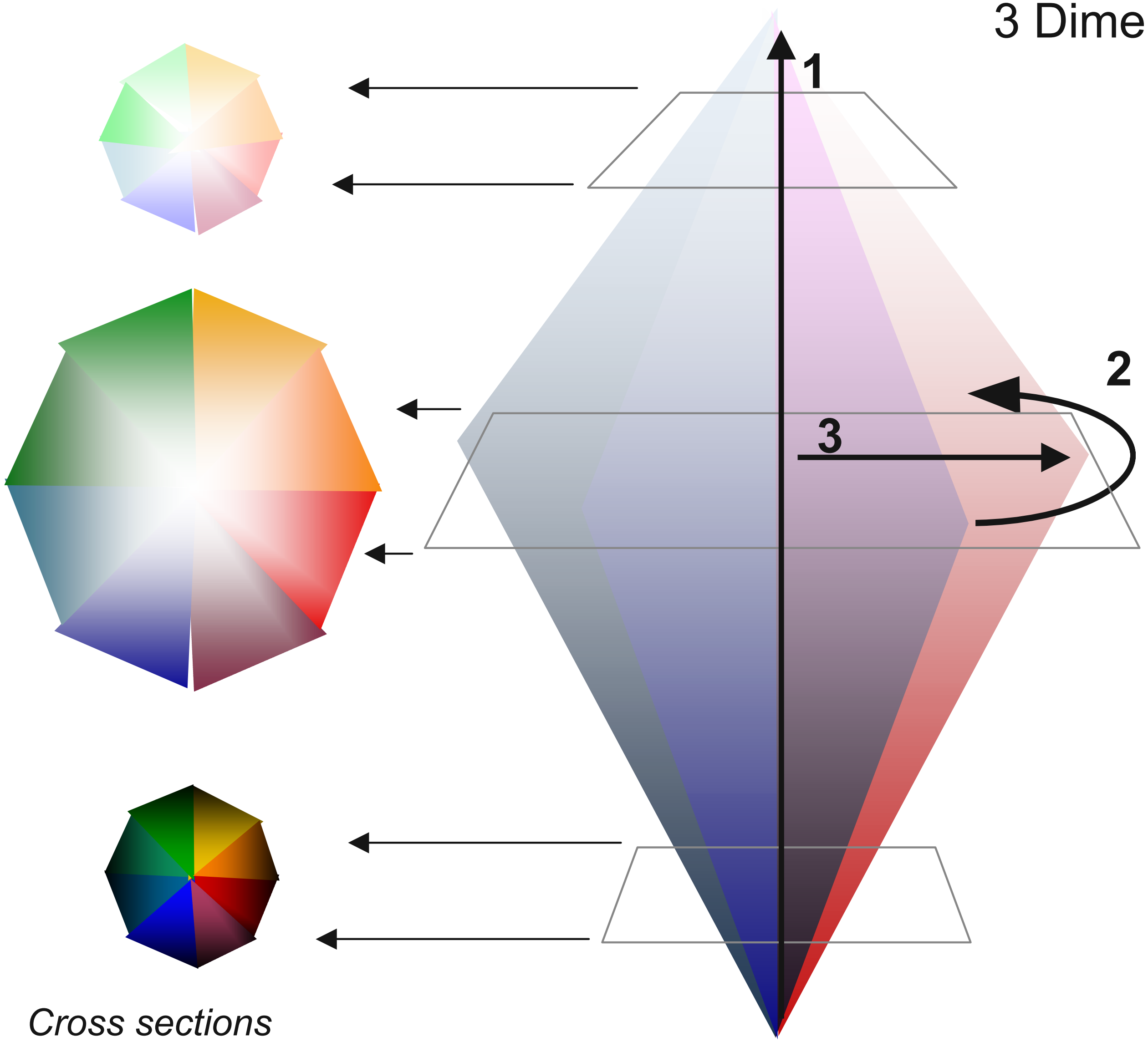
Boundaries of **brightness:**

From 1 to 4: increasingly required brightness

Distribution of cones and rods across the retina (_right eye_)



Quelle: Handbuch für Beleuchtung, SLG, 5. Auflage, 1992



Cross sections through the colour spindle

3 Dimensions of Colour Perception

1. Brightness =
- Vertical dimension of the colour range
- refers to the light intensity

2. Hue =
- located at the outside of the colour circle
- qualitative change of colour subject to the wave length

3. Saturation =
- Distance from the middle axis to the outside
- Colours with the highest saturation are at the outside

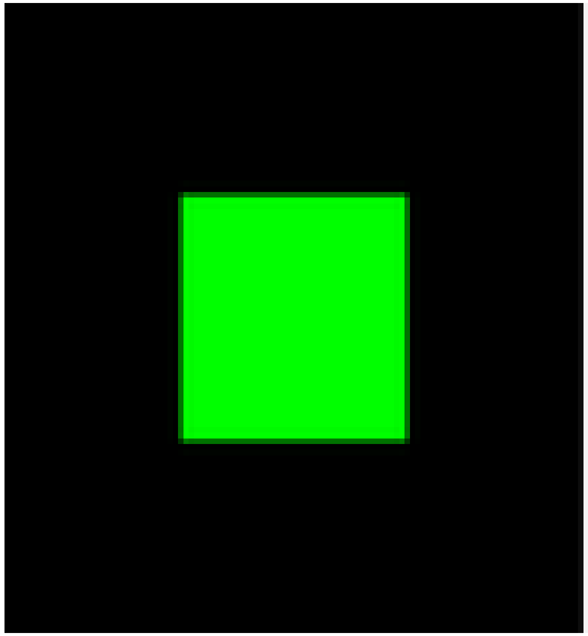
Colour Temperature

- temperature, that a black body should have so that its light will evoke the same colour effect as the actual illumination
- measurement for the predominant colour proportion of light: the bigger the blue proportion, the higher the colour temperature
- dimension unit : Kelvin (K)

Light Source	Colour Temperature	
candle	1500 K	**< 3300K = warm white**
filament bulb (100W)	2800 K	
halogen bulb	3000 K	
studio lamps	3400 K	**3300 - 5000 K = neutral white**
fluorescent tube	4000 K	
morning/ evening sun	5000 K	
forenoon/ afternoon sun	5500 K	**> 5000 K = daylight white**
midday sun	5800 K	
overcast sky	6800 K	
blue sky	11000 K	

Relativity of Colour
Example

Look at the green square for 30 seconds and afterwards at white area next to it!



The white area will be showing the after-vision on the retina. A square will appear which has the complementary colour of the green square (red).

Young-Helmholtz Trichromatic Theory

- three types of colour receptors: red, green, blue
- other colours = combinations

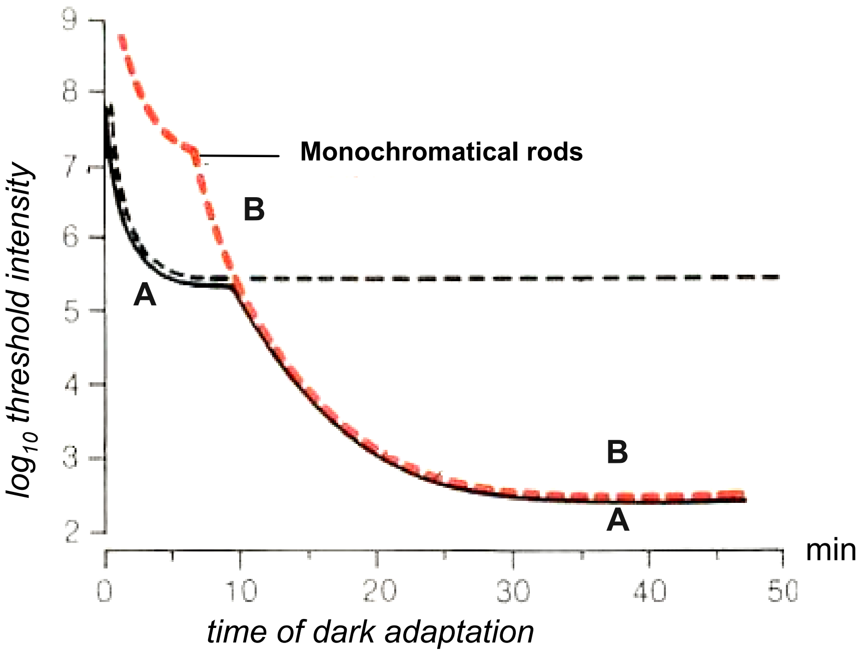
Opponent-Colours Theory

- three systems
- two „opposing“ elements: red vs. green, blue vs. yellow, black vs. white.

State of the Art = Visual Processing in two Stages

- There are three different kinds of cones, which are most sensitive to light of different wave lengths and work in the way predicted by the **trichromatic theory**. One kind of light reacts to light of a short wave length (light perceived as being blue). Another one reacts to light of a middle Length (green) an a third one to light with a long wave length(red). Colour-blind people lack one kind of these receptor-cells.
- In the next stage the ganglia-cells of the retina combine the output of those three kinds of cones in a varying manner. They work as assumed in the **opponent-colour theory**. Some of the cells in the system are activated by the light that generates the perception of red and are repressed ba light that leds to the perception of green. Other cells react in the diametrical manner.
- Together these two kinds of ganglia cells constitute the physiological base for the red-green-system of reciprocal repression. (Other ganglia cells form the blue-yellow-system and the black-blue-system in the same manner).

Dark adaptation of humans

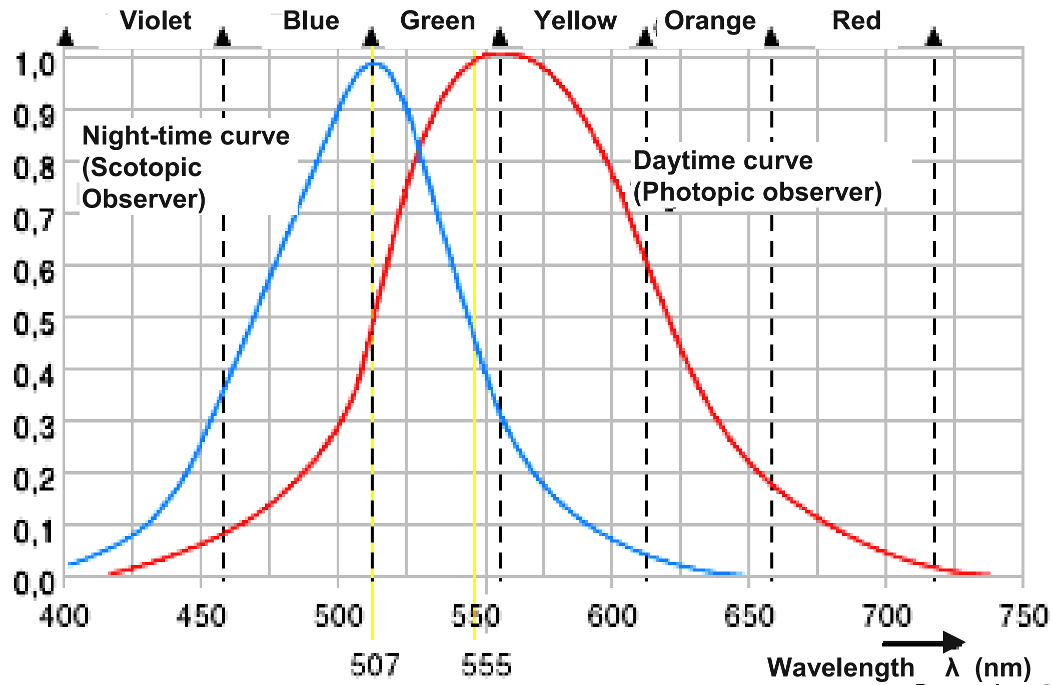


(A) average curve for standard subjects

(B) curve of dark adaptation for colour blind people

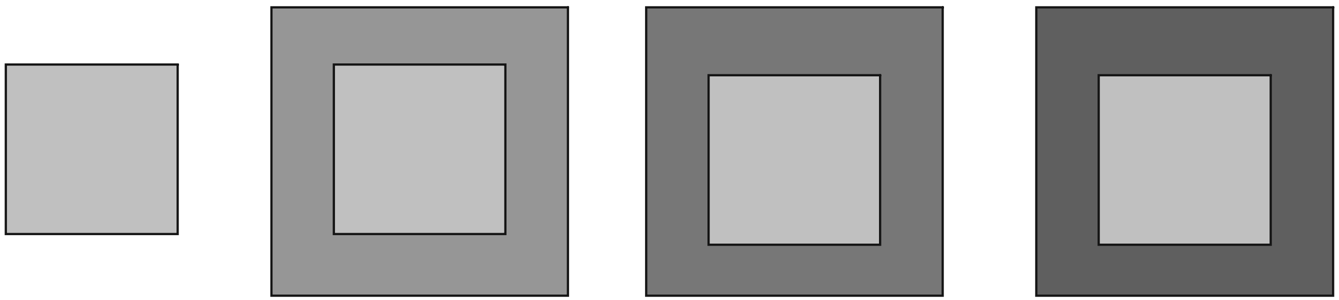
(C) curve of dark adaptation for standard subjects

Spectral luminous efficiency curves V (λ) and V' (λ) for the human eye

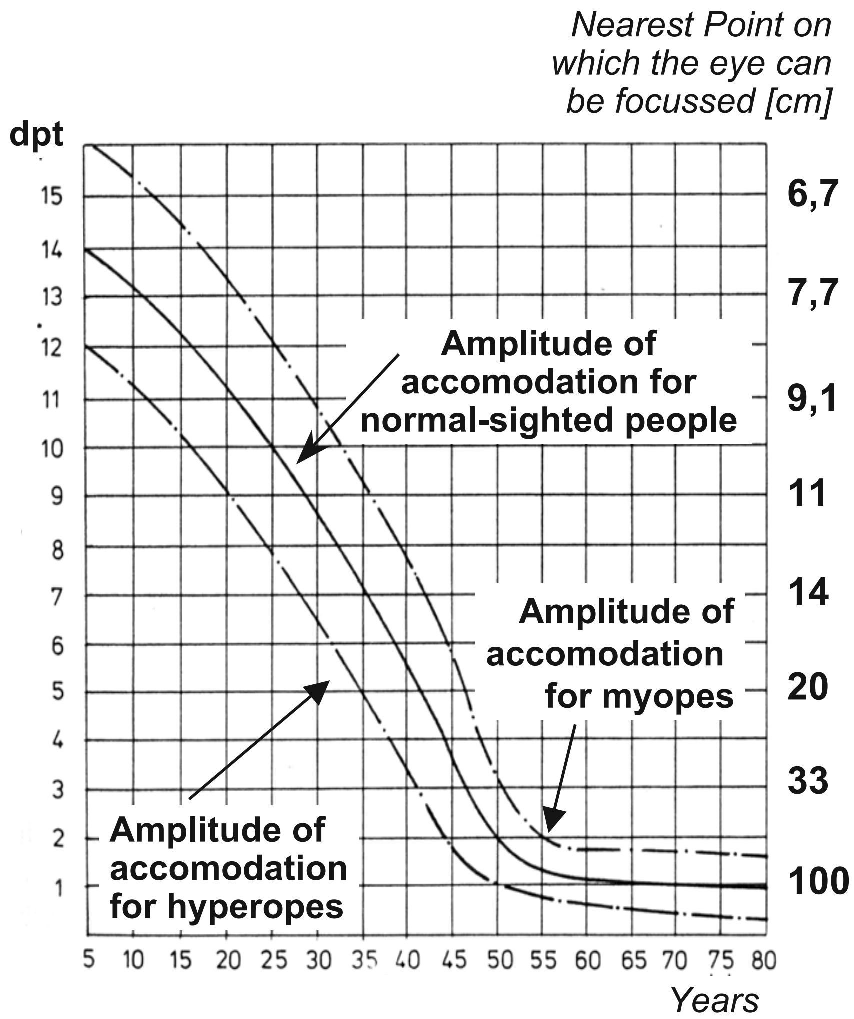


Quelle: Baer, 1999

- There have to be contrasts in brightness, so that different objects in a space can be perceived.
- They render borders - like corners and edges- visible, which give form, size and position to objects.
- A grey spot seems to be brighter close to a dark background:



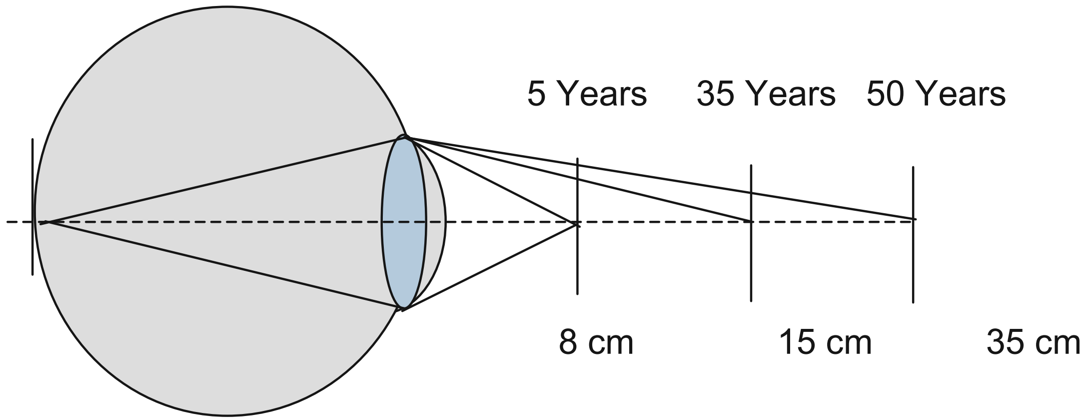
Effects of age on amplitude of accomodation



Source: Handbuch für Beleuchtung 1975 (modified)

Old-age-related hyperopia - Presbyopia

Near-point development with progressing age



Amplitude of Accomodation

$$\Delta D = \frac{1}{g_p} - \frac{1}{g_r}$$

g_p: distance near point
g_r: distance far point

Measurement in Radiation Physics:

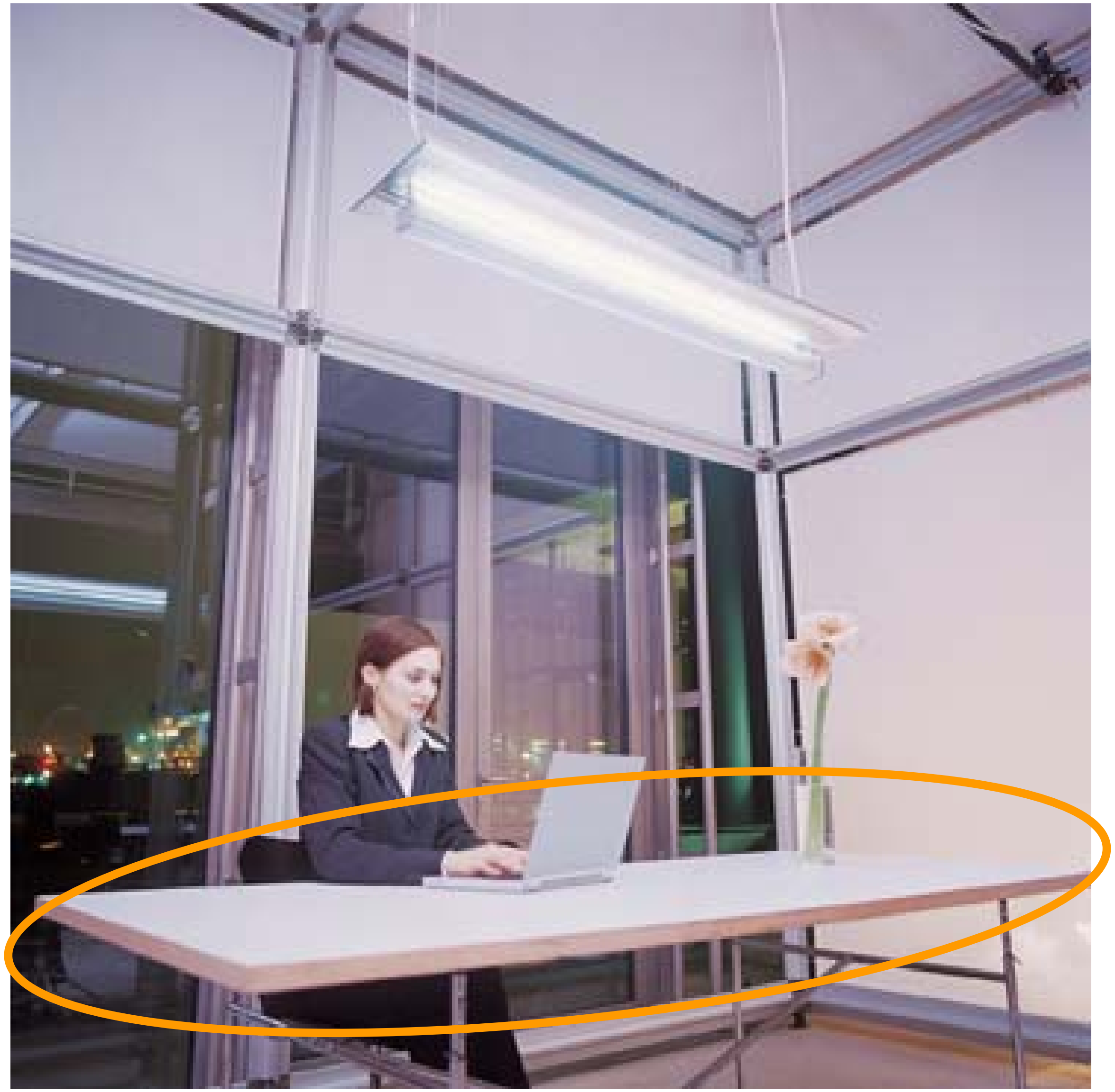
- In order to analyse the energy emitted by the sun, i.e. the whole frequency range
- They are described by the index e (energetical)

Photometric Quantities:

- Conduce to the research of the radiation perceivable by the human eye (380-780 nm), in order to describe illumination of a workplace
- They are labelled with the index V (Visibilität)
- However, the sensitivity curves of human eyes differentiate; followingly photometric quantities refer to the sensitivity curve of a stanardised eye

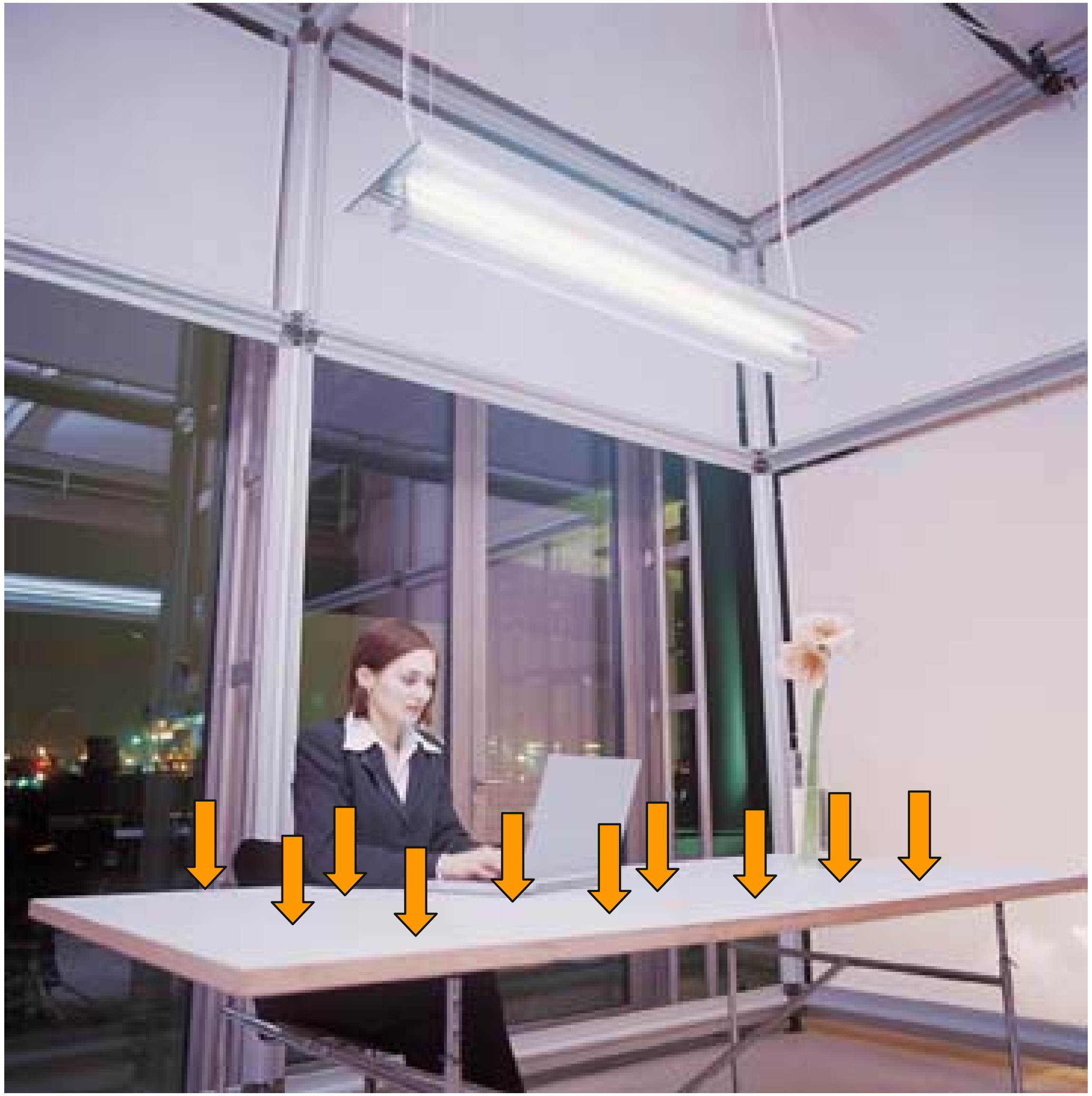
Luminous Flux (Φ) → Lumen (lm)

- Visual quantity of radiant flux which expresses its capacity to produce visual sensation
- Radiant flux multiplied by the relative spectral sensitivity of the human visual system
- The fundamental measurement on which all other parameters are based



Illuminated Surface (A)
→ Square Metre (m^2)

Photometric Quantities

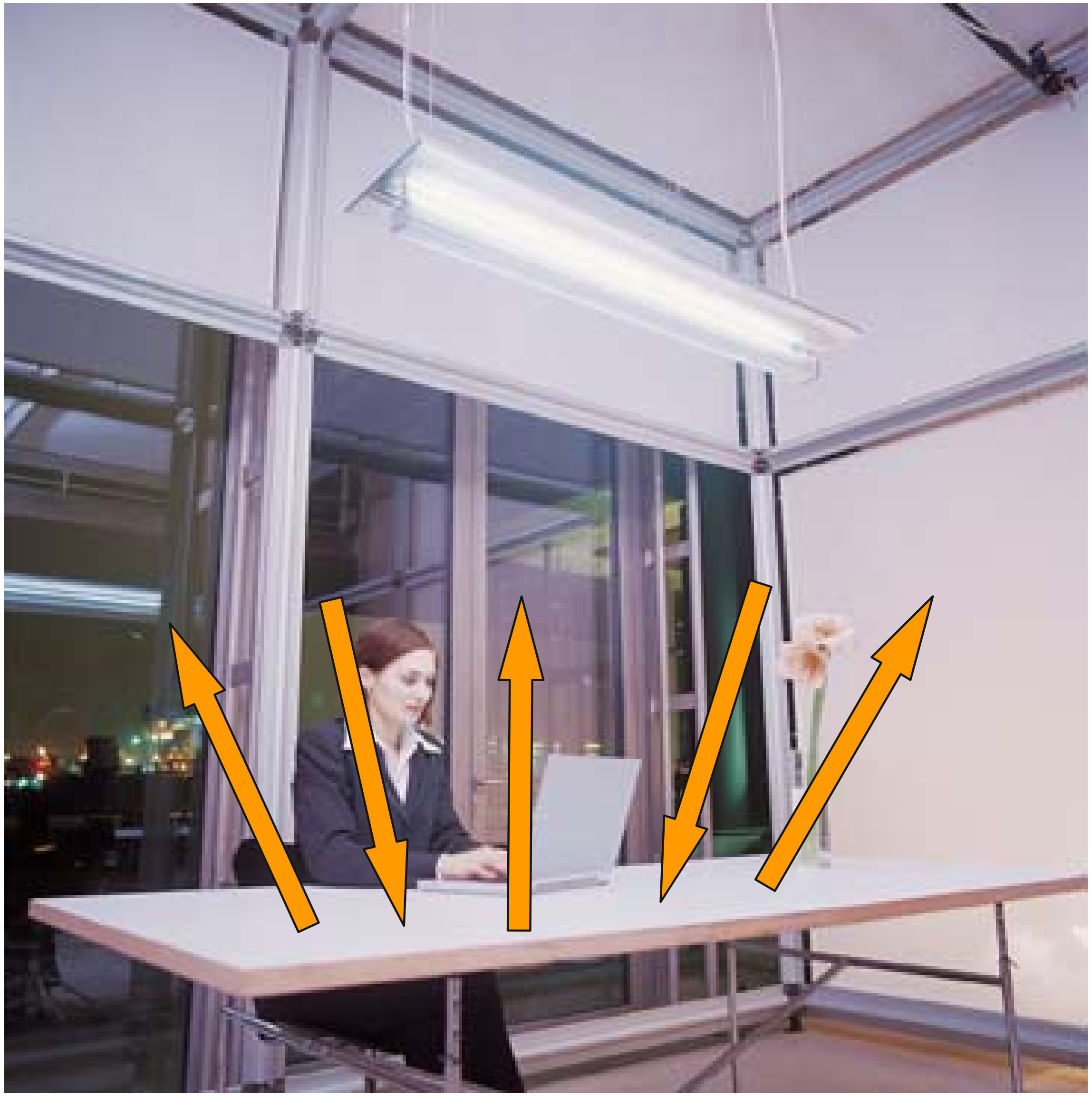


Illuminance

$$E_V = \frac{\Phi_V}{A}$$

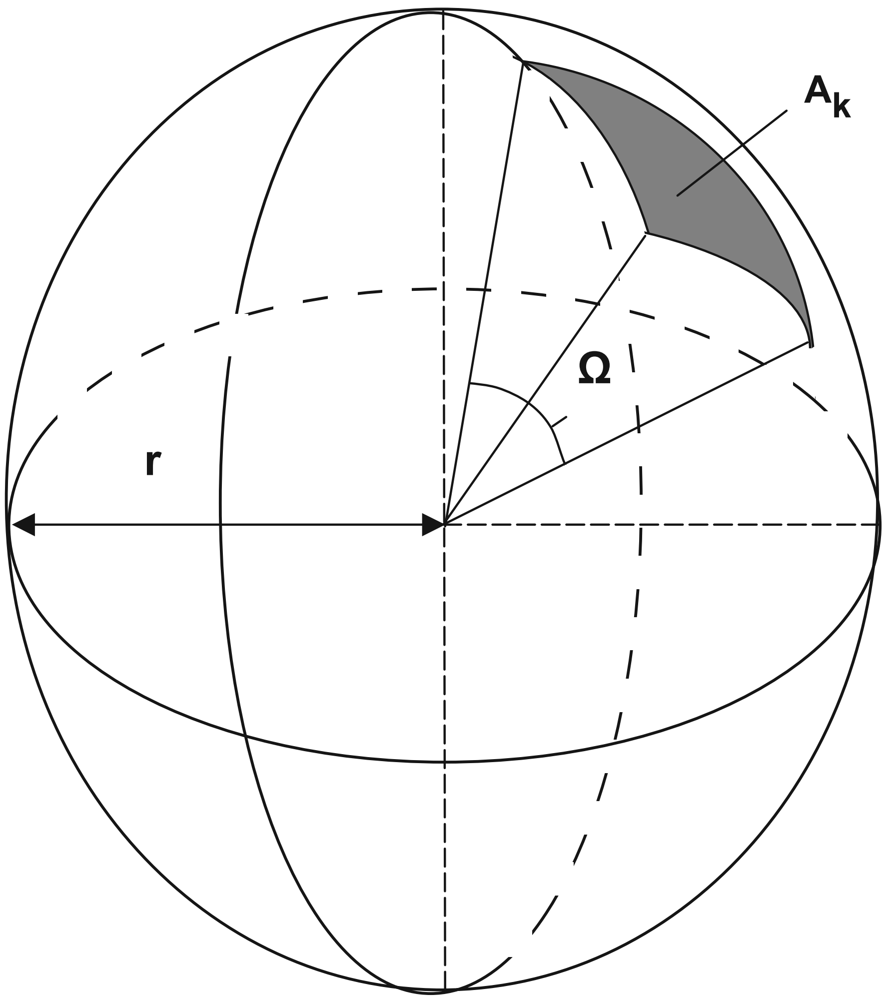
$$[1lx = \frac{1lm}{1m^2}]$$

- The luminous flux density at a surface, i.e. the luminous flux incident per unit area
- Quotient of the luminous flux by the area of the surface when the latter is evenly illuminated
- The illuminance at an area is 1 Lux (lx), if a luminous flux of 1 lumen (lm) falls perpendicularly onto an area of 1 m^2
- Independent of the reflectance of an illuminated surface
- The most frequently used quantity in illumination engineering
- Recipient-related quantity



Reflectance (ρ)

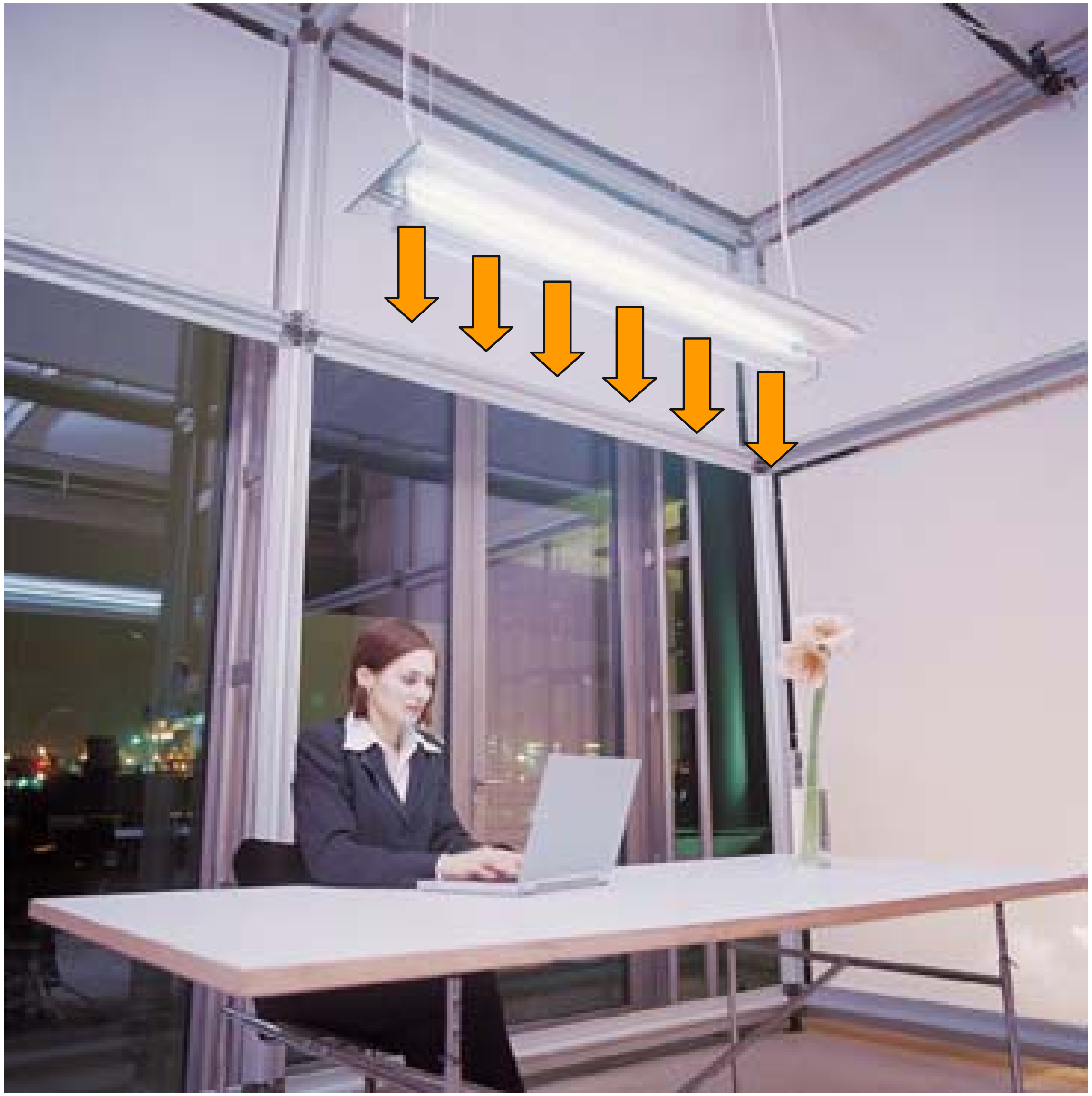
- Ratio of the luminous flux that is reflected from a given surface to the luminous flux incident on the same surface
- Specification in %



Solid angle(Ω) → Steradiant (sr)

$$\Omega = \frac{A_K}{r^2}$$

•für A_K = 1m² und r = 1m ist Ω= 1sr

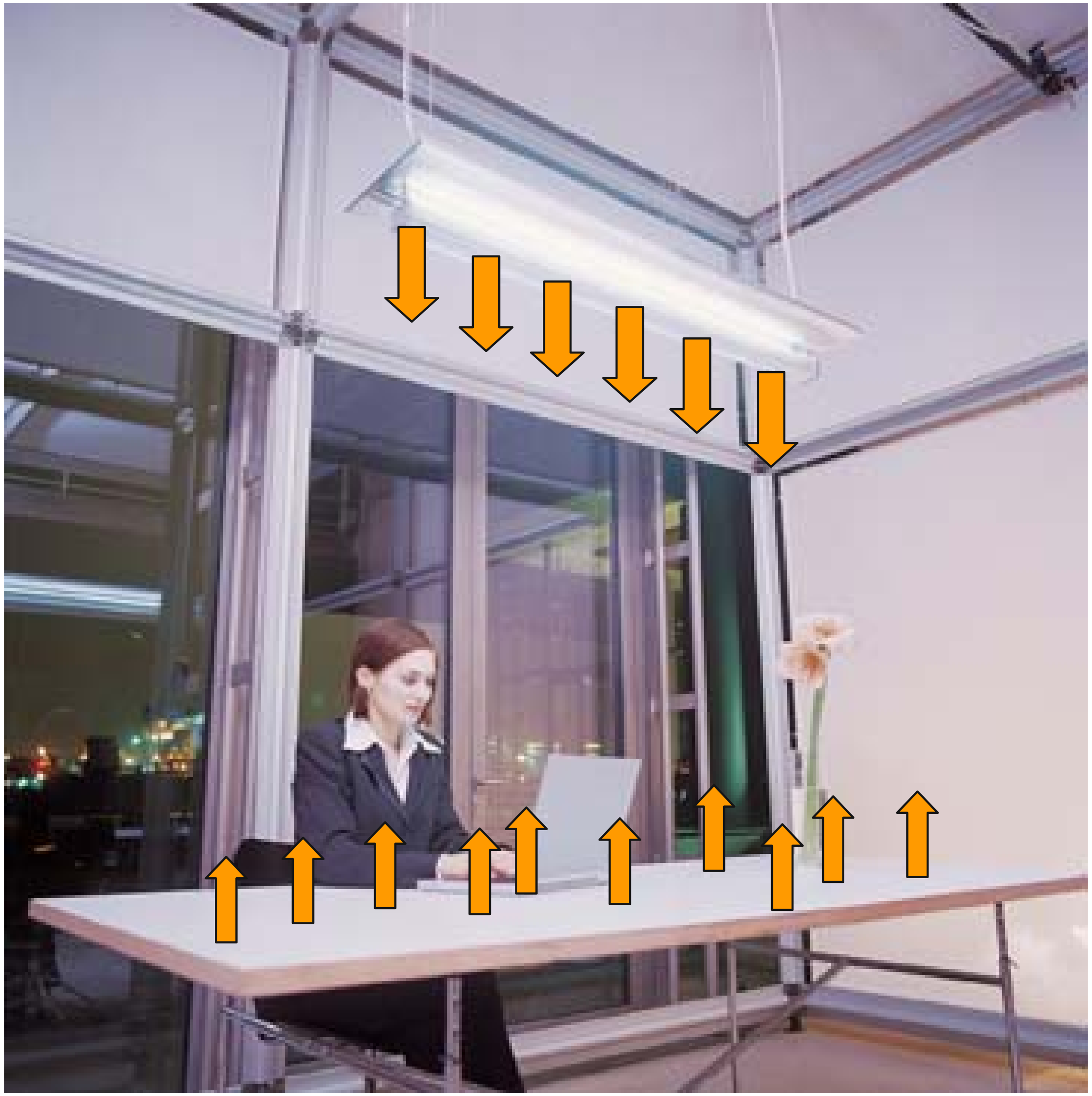


Luminous intensity

$$I_V = \frac{\Phi_V}{\Omega}$$

$$[1cd = \frac{1lm}{1sr}]$$

- Luminous flux emitted per solid angle unit to a specifiv direction
- Direction dependant, independant of recipient quantity
- sender-related quantity



Luminance

$$L = \frac{I_V}{A_B}$$

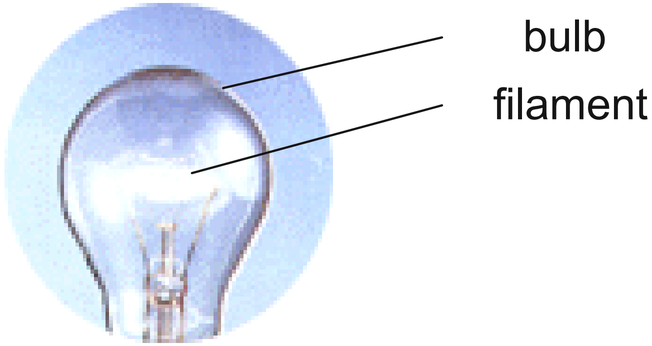
$$[\frac{1cd}{1m^2}]$$

- Luminous intensity of a light source in relation to the emitting area of the emitter (light source or reflecting area)
- Subjective quantity to the brightness sensitivity, only perceivable to the human being
- sender-related quantity

...are artificial light sources which are among others differentiated according to their nature of conversion

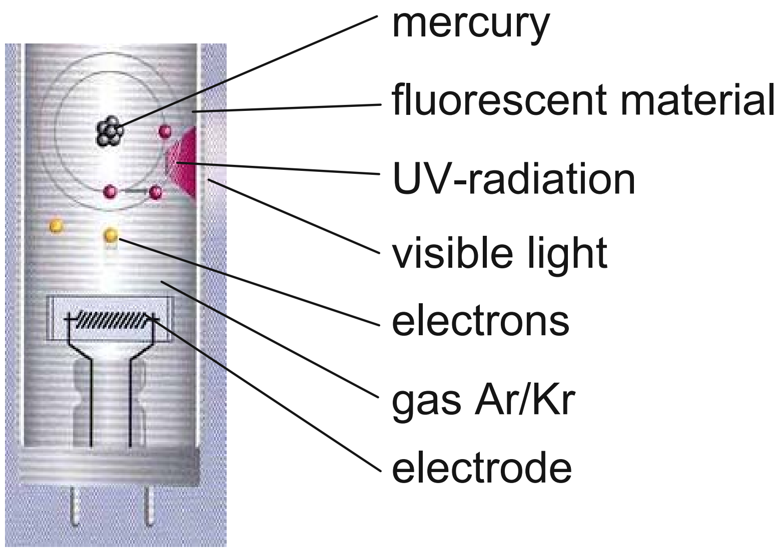
- **chemical energy conversion**
  e.g. burning light sources; candle, irrelevant to contemporary work organization

- **electric energy conversion**



- **temperature emitters**
  - Incandescent filament lamps
  - Halogen incandescent lamps

- **electric discharge**
  - low-pressure discharge lamps:
    e.g fluorescent lamps
  - high-pressure discharge lamps:
    e.g. halogen gas lamps

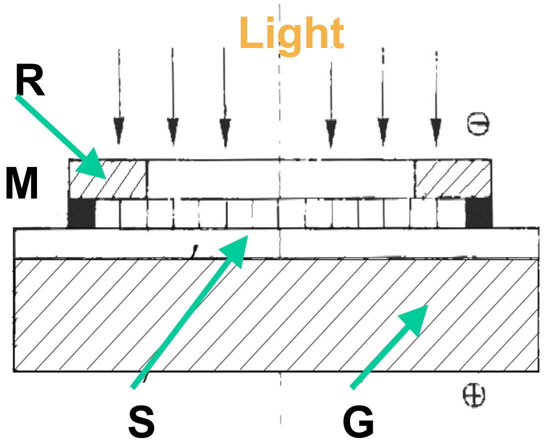


Source: nach Baer, Praktische Beleuchtungstechnik, 1999

Photometry

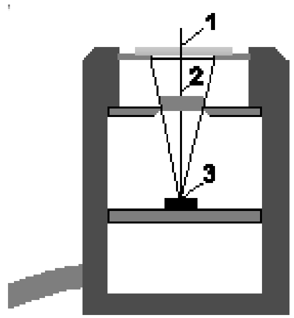
The measurement of intensity of light based on visual impression

Example: Luxmeter



Elements of a selenium photocell
G = Rear (positive) contact
S = Layer of metallic selenium
M = Electrically-conductive layer
R = Negative contact ring

Handbuch für Beleuchtung, 1975
(Handbook of Illumination, 5th Edition)



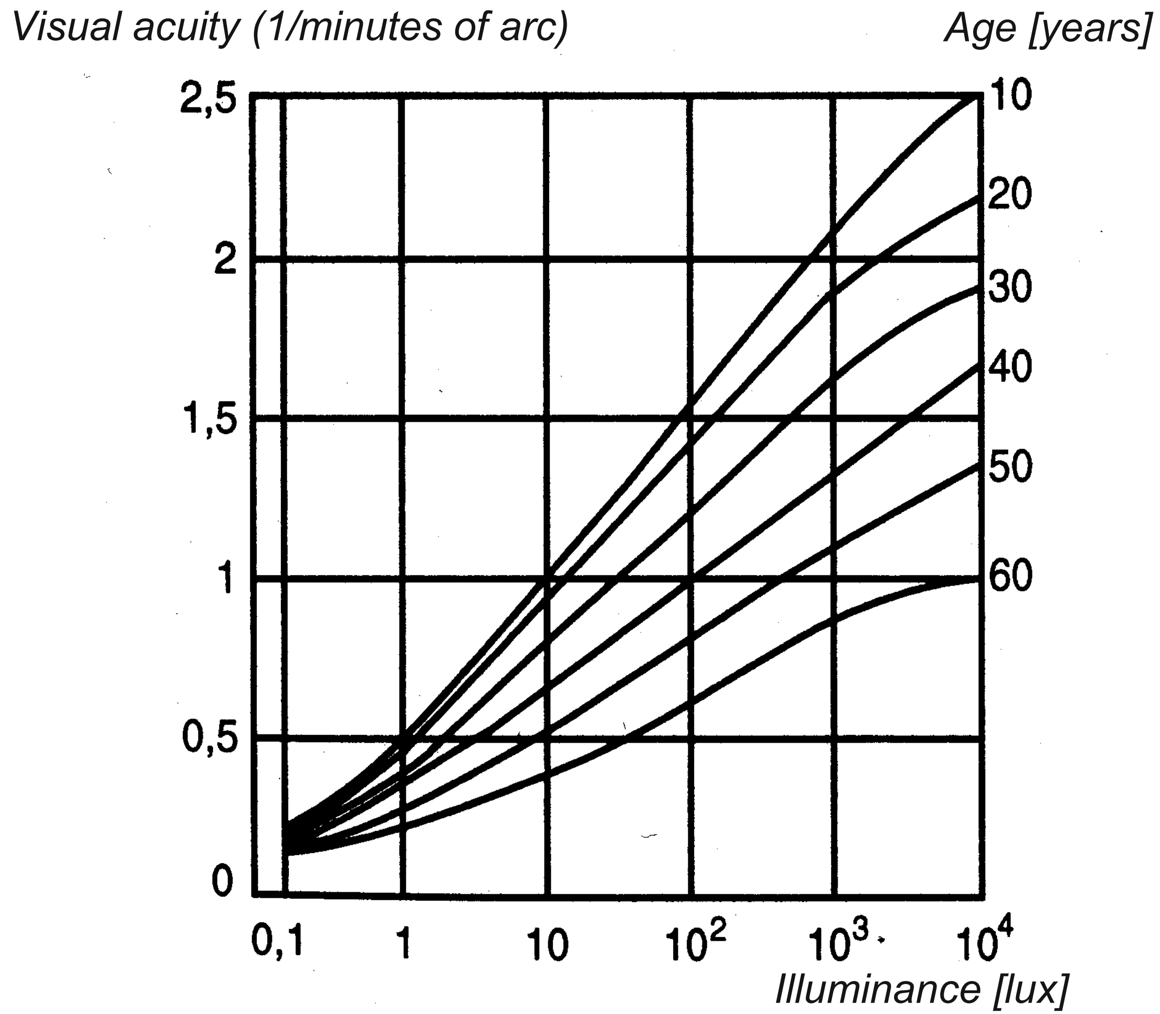
Structure of a measurement device for radiation intensity
1 cosine correction for accurate illuminance quantification
2 combination of filters
3 silicon photo cell

Fisch, Khanh 2000

Luminous flux of some representative light sources	
Glühlampe 220 V, 60 W	730 lm
Leuchtdiode	0,01 lm
Leuchtstoffröhre 220V, 40W	2.300 lm

Representative illuminance	
Overcast sky (day)	1000 bis 2000 lx
Full moon	0,25 lx
Living room illumination	120 lx
Bright workplace illumination	1000 lx
Minimal workplace illumination	250 lx

Effects of illuminance and age on visual acuity



Source: Studiengemeinschaft Licht 1968

Classification of Luminaires

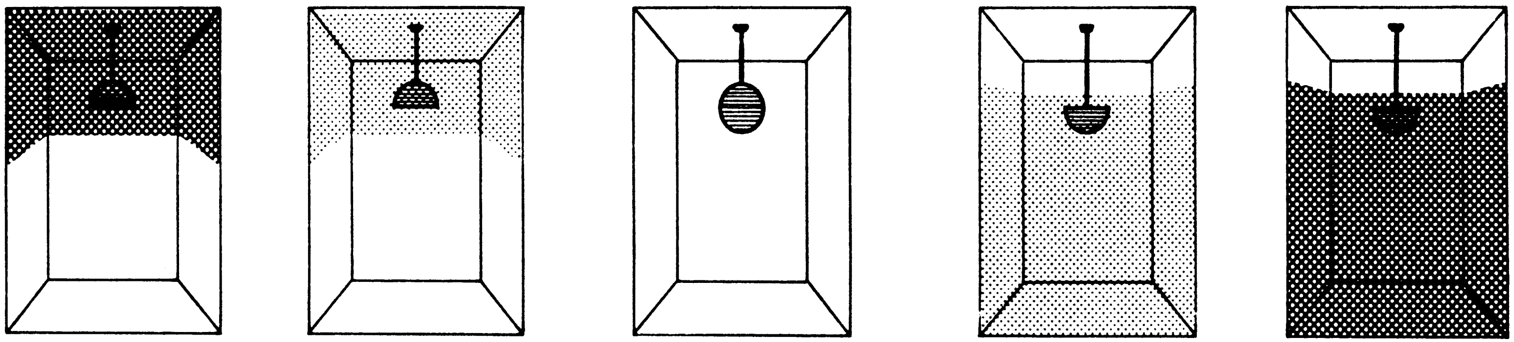
Luminaires...

... “are complete lighting units consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply” (IES Nomenclature Committee, 1979)

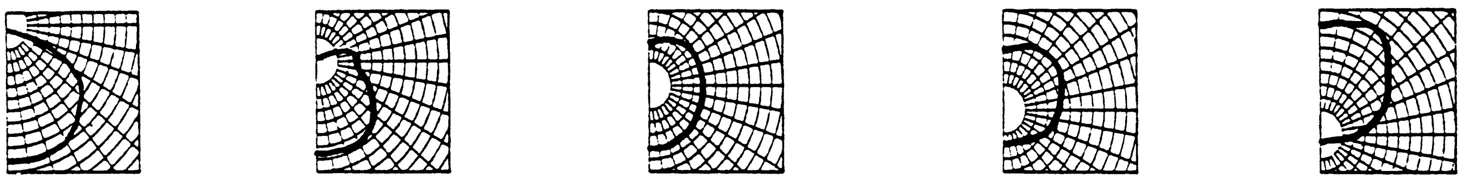
... can be categorized by proportion of lumens emitted above and below horizontal:

- direct
- semi-direct
- general diffuse
- semi-indirect
- indirect

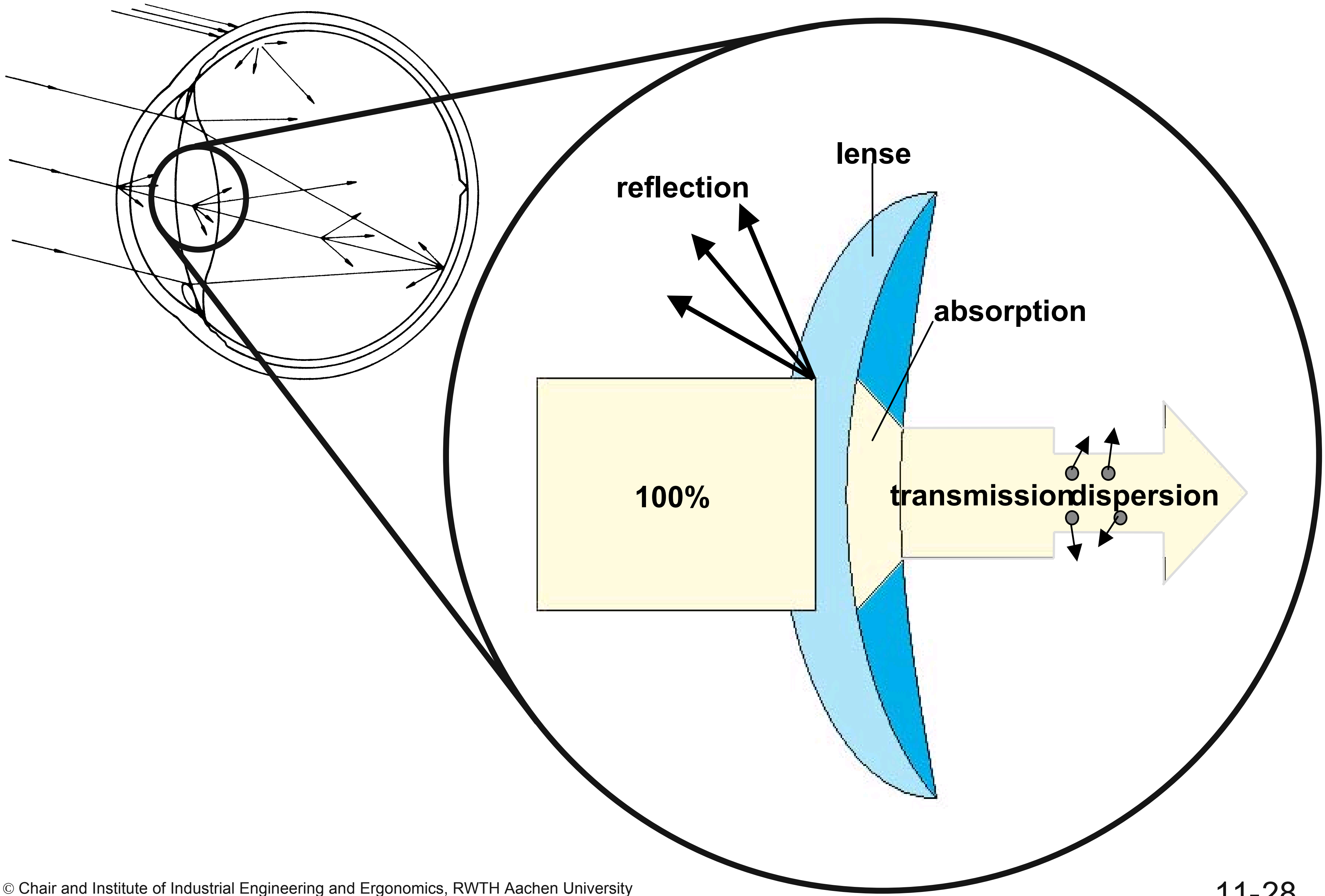
Direct | Semi-direct | General diffuse | Semi-indirect | Indirect



Luminous intensity distribution in the spherical coordinate system

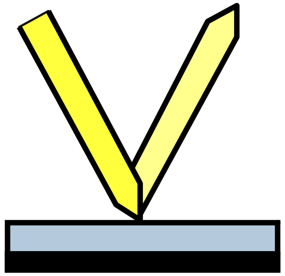


Source: Böcker 1981



lense
reflection
absorption
100%
transmission
dispersion

Types of Reflection



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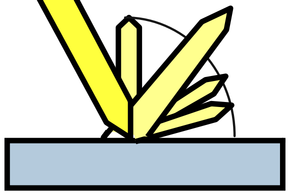
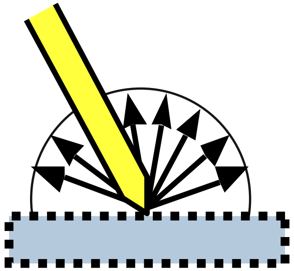
specular reflection (e.g., mirror)



$\sim \frac{1}{\pi/2}$

spread reflection + dispersion (e.g., polished aluminum)

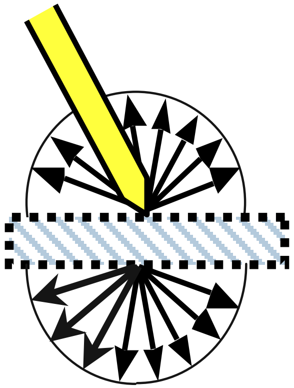


$\frac{1}{\pi}$

diffused reflection = dispersion (e.g., matt-finished surface, Lambertian surface)

$$L = \rho \frac{E}{\pi}$$

Transmission + Dispersion



$\sim \frac{1}{2\pi}$

matted glas

Source: Luczak et al. 2001

Reflectance for various surfaces

Metal mirror	95–99%
Highly polished silver	90–92%
Window grate	6–8%

<u>For diffused reflection</u> (r_{diff}):

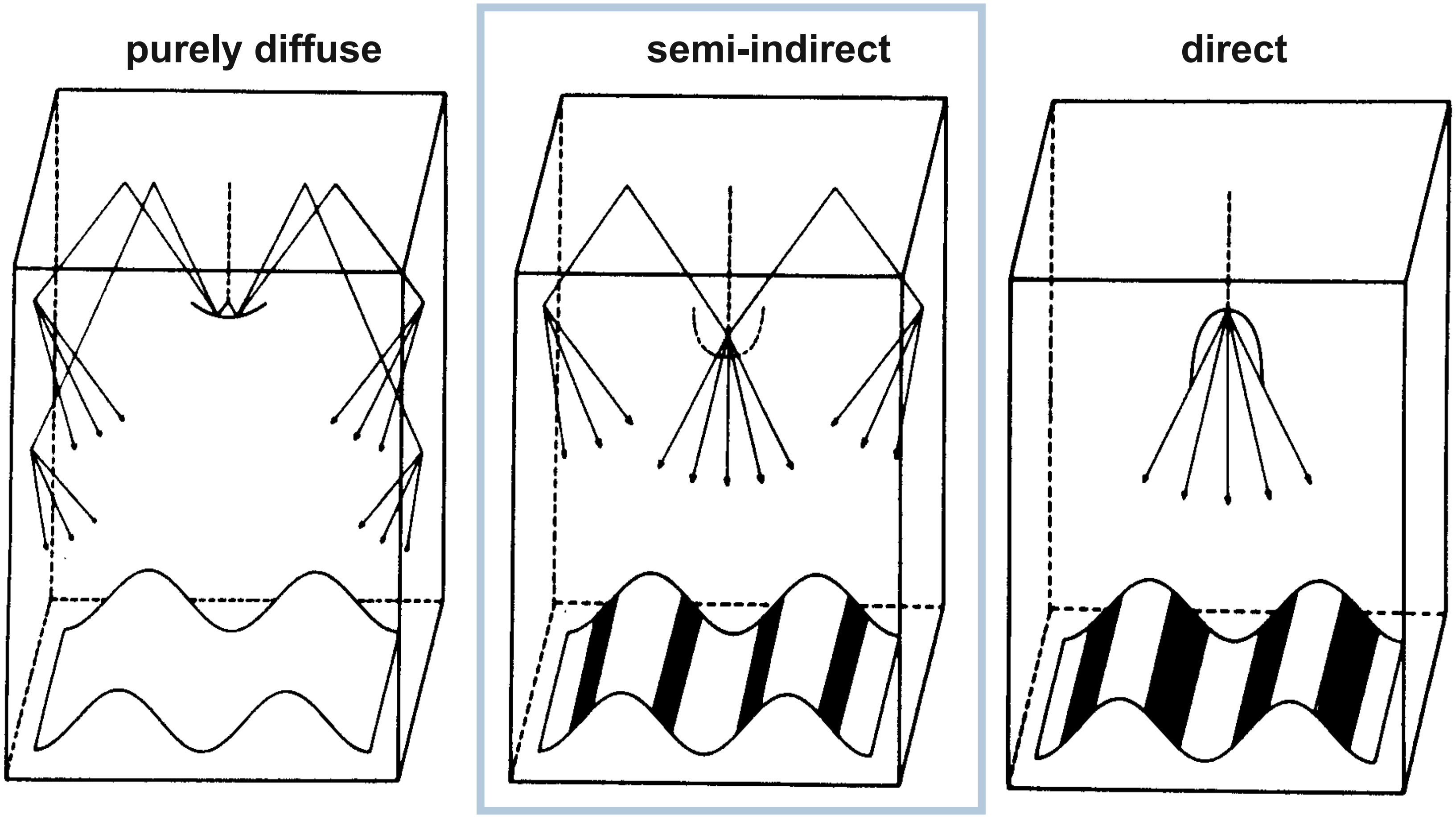
Paper:	white	70–85%
	light grey	40–60%
	dark grey	10–15%
Wood:	light	30–50%
	dark	10–25%
Velvet:	black	0,5–4%

Comparison between German (DIN 5035, 1972) and U.S. (Illuminating Engineering Society, 1972) recommendations for intensity of illumination, each in lx

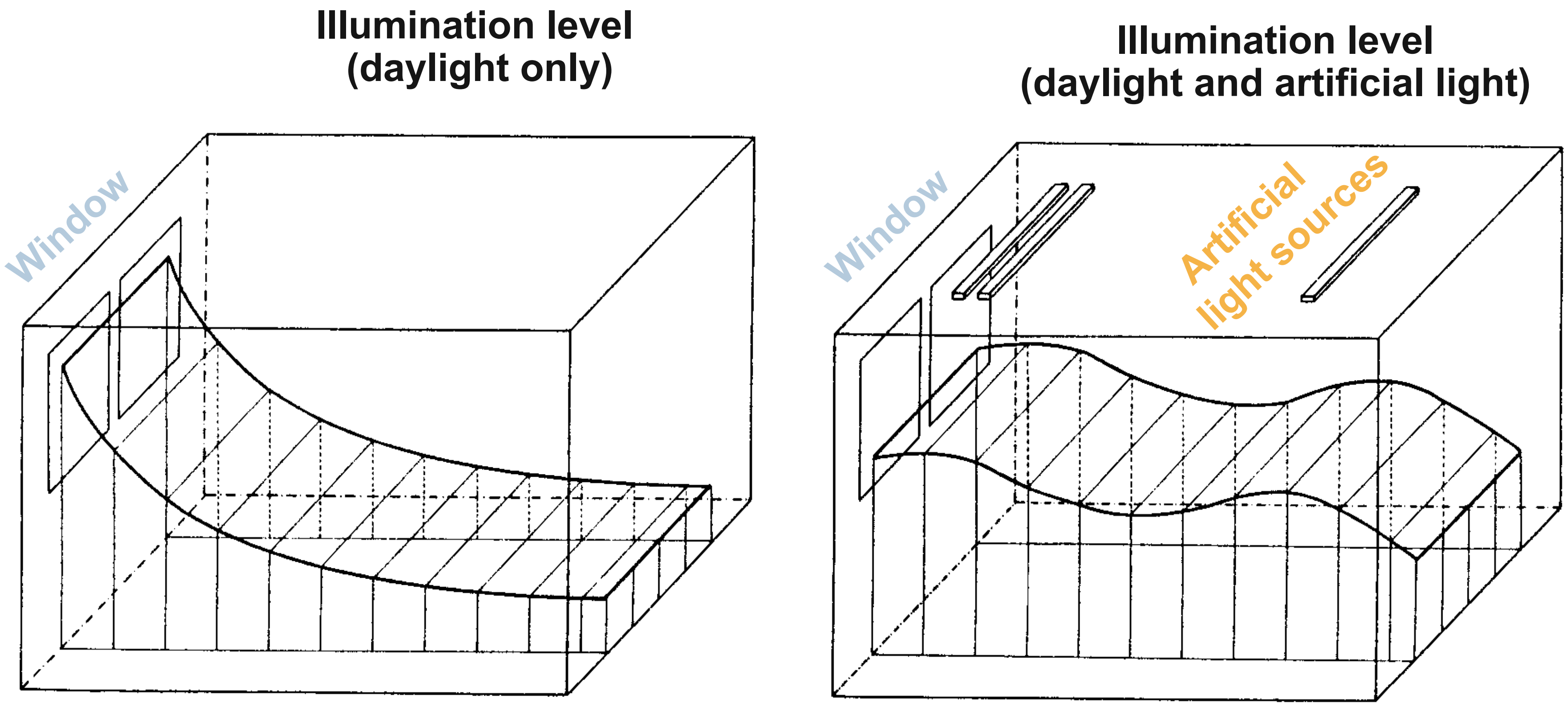
Task	DIN	IES
Rough assembly work	250	320
Precise assembly work	1000	5400
Very delicate assembly work	1500	10800
Rough work on toolmaking machine	250	540
Fine work on toolmaking machine	500	5400
Very precise work on toolmaking machine	1000	10800
Technical drawing	1000	2200
Book-keeping, office work	500	1600

Kroemer, Grandjean 1997 p. 300; see also Sanders, McCormick 1992 p. 529

Light Distribution with the Corresponding Formation of Shadows



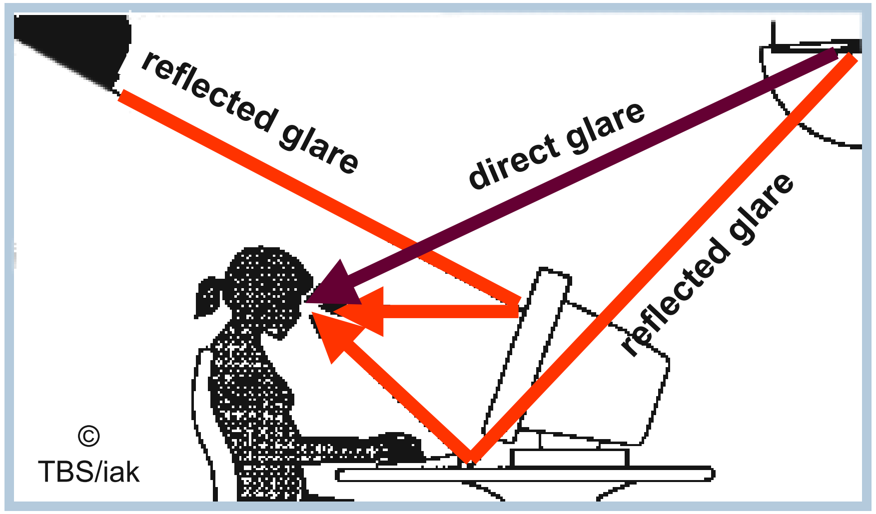
Source: Hartmann 1993



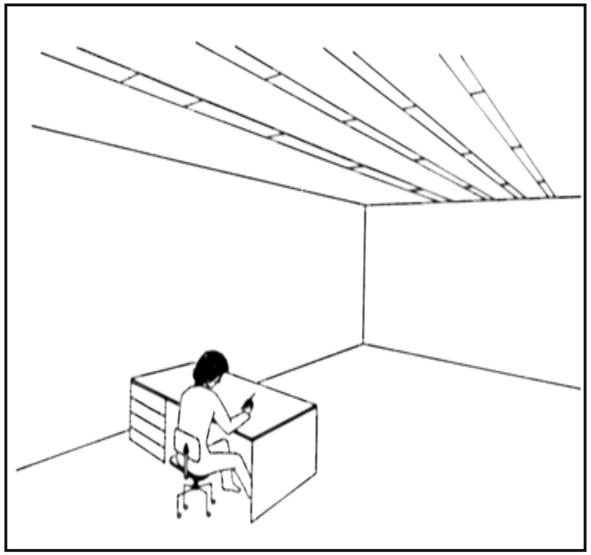
Source: Hartmann 1993

negative effects (e.g., shadows) can be avoided by an appropriate lighting design

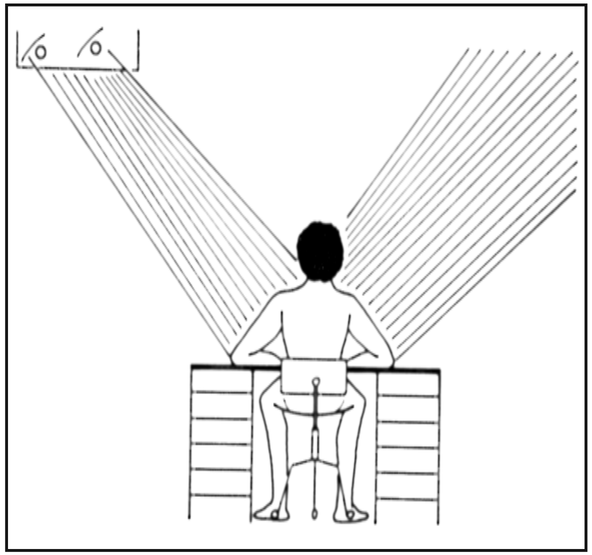
Prevention of direct or indirect glare



Light strips and singular luminaires arranged parallel to the direction of sight



Lateral reflection by lateral arrangement of luminaires



Source: Hartmann, E.: Beleuchtung am Arbeitsplatz, 1982

DIN EN 12464-1: European Standard for Lighting of Workplaces since 03/2004:

- **Make more use of natural light instead of artificial light:**
  - Big windows,
  - Arrangement of workplaces next to glass façade,
  - adjustable sun protection devices.
- **Consider qualitiy characteristics of illumination:**
  - Level of illumination,
  - Luminous intensity distribution,
  - Limitation of illumination,
  - Light direction and shadiness,
  - Light colour, colour fidelity and absence of flickering.
- **Steps in the planning Lighting:**
  - Choice of a lighting concept ,
  - Choice of the type of lighting,
  - Choice of luminaires with the according lamps,
  - Specification of number and arrangement of the luminaires in the room,
  - Development of a maintenance schedule for the ligting system.

Source: ASU protect, 1/04

1. **The illuminance has to be adjusted to the work task, the work equipment and the type of room.**
2. **The smaller the details in a work task, the higher should be the illuminance.**
3. **The lower the contrast, the higher should be the illuminance.**
4. **The illuminance should be as even as possible within the whole activity area.**
5. **General lighting in open-plan offices produce a high consistent illumination.**
6. **Danger of glare in case of high illuminance in combination with big bright objects.**
7. **Utilisation of dark equipment in combination with high illuminance.**
8. **The closer environment should never be brighter than the workplace itself.**
9. **Direct and indirect glare should be avoided or kept on the low.**
10. **The light colour should be comfortable and the colour fidelity should be very good.**
11. **Utilisation of warm white light for reduction of psychosomatic diseases as a result of light influence.**
12. **With proceeding age the visual acuity declines; it then has to be compensated through an increase in illuminance.**

13. The lighting should always be flicker- and jitter-free.
14. Workplaces with insufficient daylight should have a view to the outside.
15. The room should be illuminated evenly.
16. High contrasts have be avoided within the field of vision.
17. A view to the outside and daylight are important.
18. Windows should be equipped with adjustable light protection devices.
19. Ceiling lights should be glare-free and should preferably shine indirectly.
20. A combination of an even room lighting and individual workplace luminaires is ideal.

Questions of Learning Success

- ✓ Why is lighting relevant to work organization?
- ✓ How does the human eye work?
- ✓ Which dimensions of visual experience did you get to know?
- ✓ Please, name the different photometric quantities. How are they defined?
- ✓ Which types of artificial light sources are differentiated?
- ✓ How can light be measured?
- ✓ What types of luminaires did you learn of?
- ✓ Please, name the differnet types of reflection. How do they differ?
- ✓ What are the guideluines for lighting of workplaces?
- ✓ What types of radiation are harmful to humans? How can humans protect themselves?

Exercise

Work Ecology

Illumination

Photonmetric Quantity

= luminous flux per solid angle unit

Formula

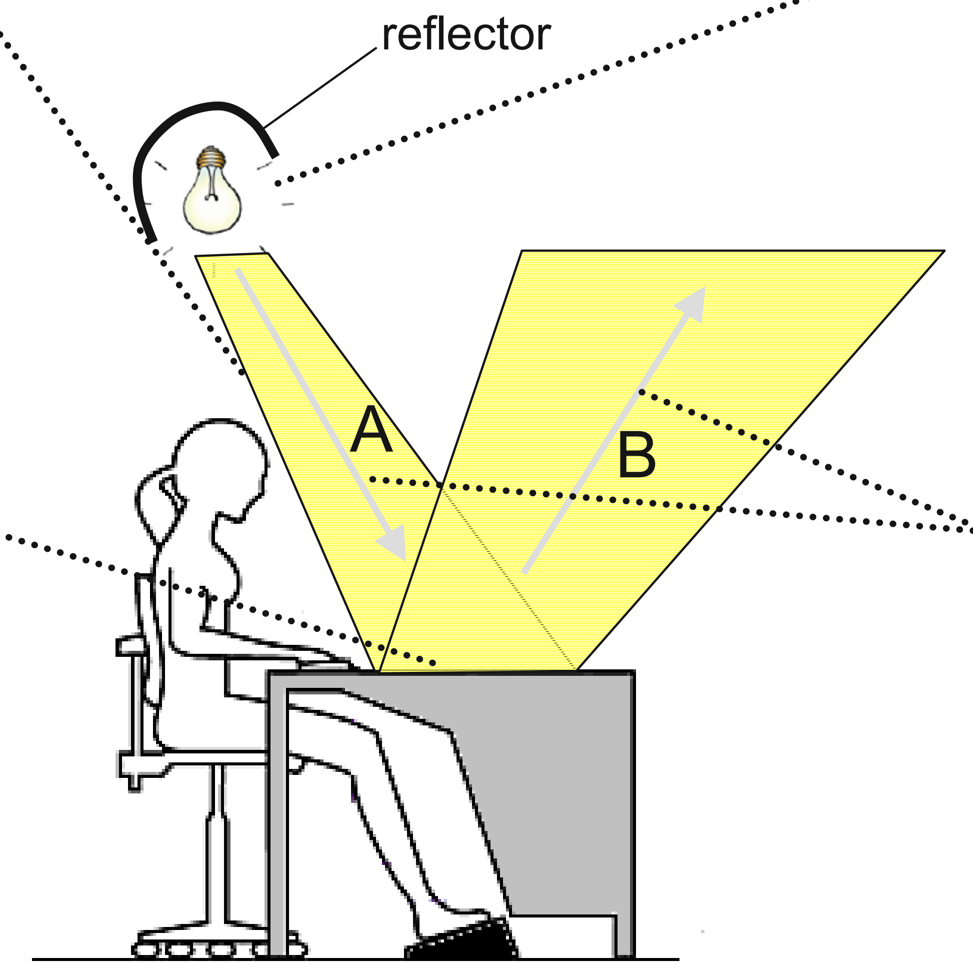
[Unit]

...

= intensity of the luminous flux Falling onto an area in a perpen-dicular angle

...= ...

[... = ...]



...

= visual, radiant flux

... = ...
= ...

[... = ... * ...
= ... * ...]

...

= relation of A to B

... = ...

[...]

An engineering office of 5 m length and 4 m width is equipped with three luminaires. Each luminaire contains two fluorescent lamps. The main task performed in this office is to work on technical drawings.

The nominal luminous flux of each fluorescent lamp amounts 3200 lm, aging and dirt of the lamps have to be taken into account by an increase in the demanded nominal illuminance of 25 %.

Check whether the requirements to the demanded nominal illuminance according to DIN 5035 in Table 1 are met. Take into account the aging and dirt of the lamps.

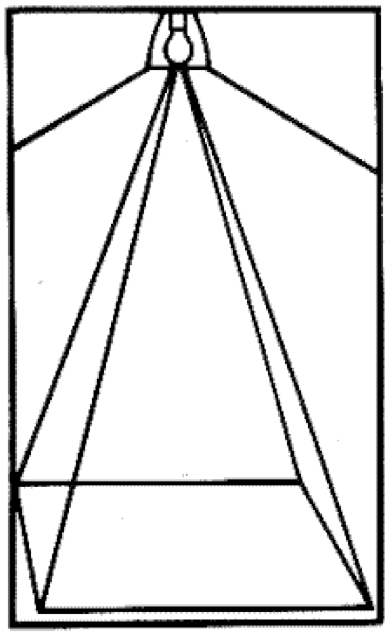
Nominal illuminance [lux]	Main Task
200	Storeroom with reading task
300	Rough work on machines with a tolerance > 0,1mm
500	Fine work on machines with a tolerance = 0,1mm
750	Technical drawings
1000	Maintenance and repair of precision instruments
1500	Optometrist and horologist
5000 and more	Special tasks, e.g. surgery

Table 1: Nominal illuminance for several tasks according to DIN 5035

A work desk in a watchmaker workshop has to be designed. The luminaire should be arranged perpendicularly above the workplace.

The work space amounts 80 cm x 60 cm, the average reflectance ρ is 40 %.

Aging and dirt of the lamp have to be taken into account by an increase in the demanded nominal illuminance (1500 lx) of 25 %.



Diffuse surface (Lambertian):

$$L = \rho \frac{E}{\pi}$$

Task a:

Determine the required luminous flux to radiate the workplace. Take the aging and dirt of the lamps into account.

Task b:

What is the maximal perceivable luminance of the work surface? Assume that the surface emits or reflects luminous flux in such a way that it has the same luminance regardless of viewing angle (Lambertian). The lamp is new and not dirty.

Task c:

To which degree does the illuminance on a desktop perpenducular below a lamp approximately reduce, if the distance between the desktop and the lamp doubles? Please, assume that the light emits divergently from the lamp and that both considered distances are big in comparison to the expansion of the light source.