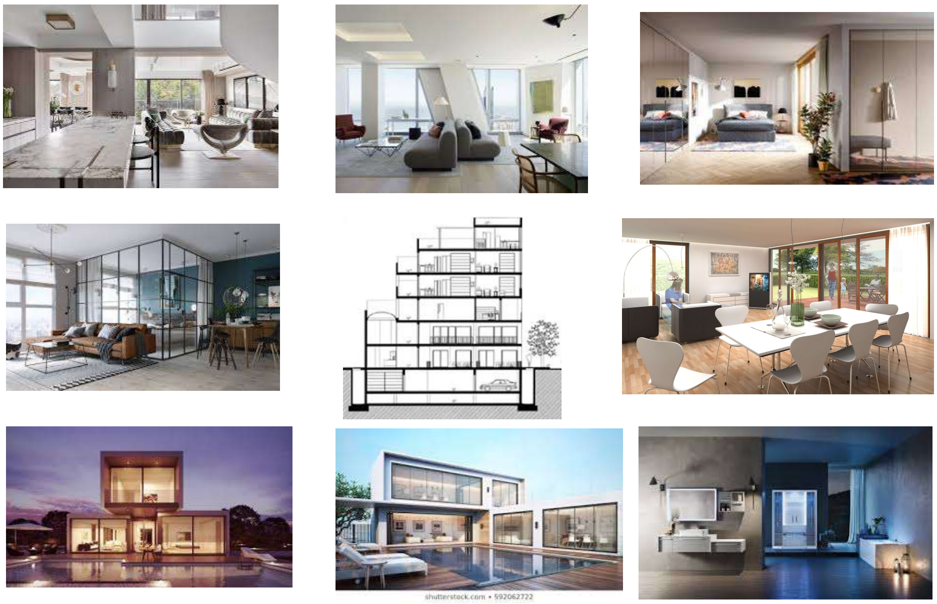
THERMAL COMFORT IN BUILDINGS

Can you find the hidden objects?

1 octopus 2 turtles 3 rays 4 jellyfishes 5 fishes 6 crabs

Where is the intruder?



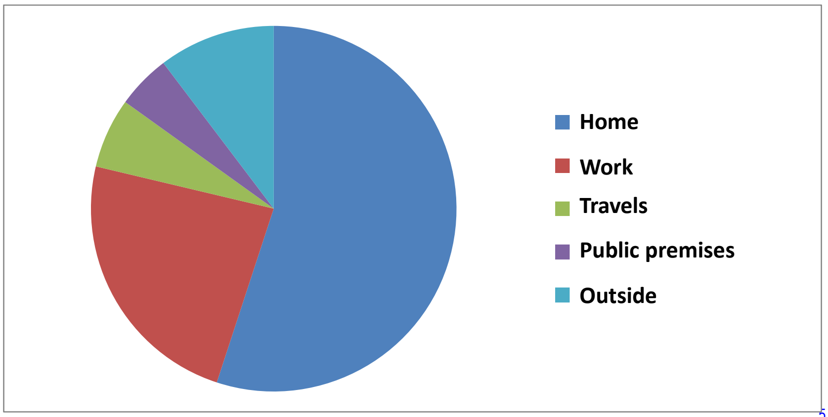
EUROPEAN DIRECTIVE EPBD (Art.1)

The objective of the European Energy Directive for Buildings is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.

4

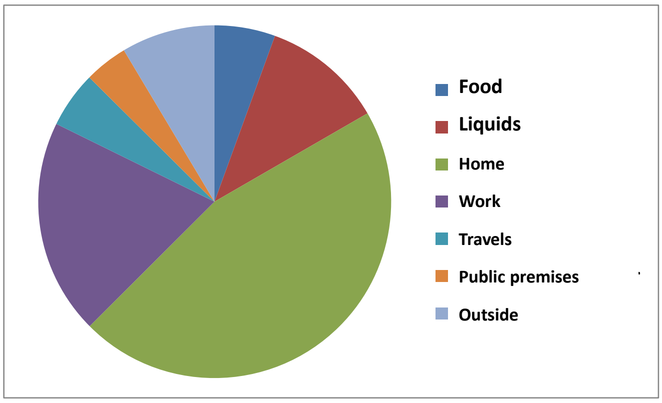
INDOOR - OUTDOOR

- People spend ~90 % of their time indoor (work, transportation, home)



5

Intake for a person a day



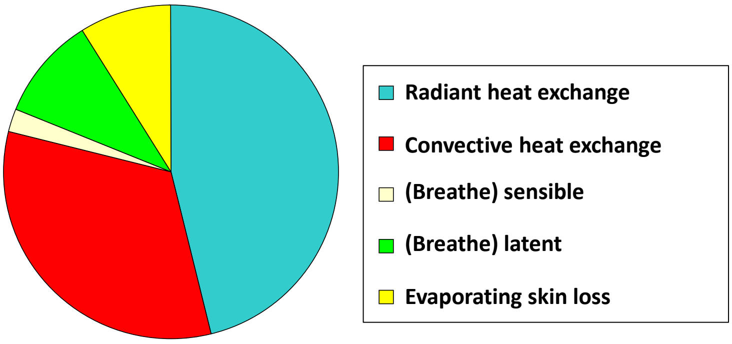
- **1 kg FOOD**
- **2 kg LIQUIDS**
- **15 kg AIR**

Importance of the air:

Surviving time:
4-6 weeks without food
Few days without drinking
Few minutes without breathing

6

Weight of the different heat rates



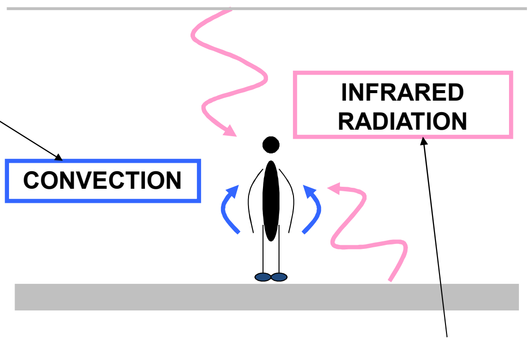
Sensible power: 80%
Latent power: 20%

Heat rate through the skin: 88%
Heat rate through lungs: 12%

7

Two important parameters for the indoor environment:

Air temperature:

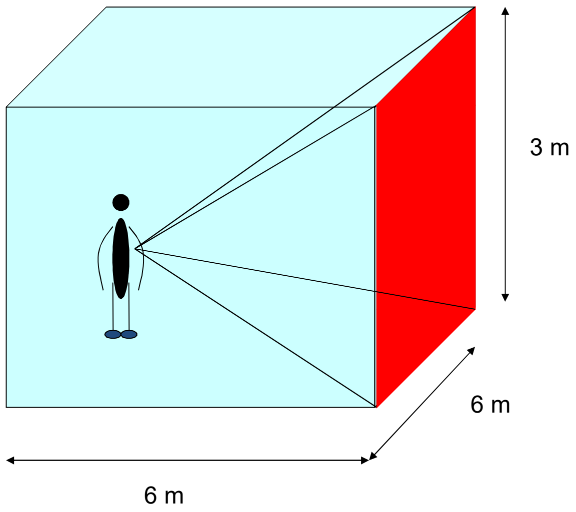


Mean radiant temperature:

Uniform temperature of a black cavity which leads to the same heat exchange between the human body and surrounding surfaces

8

How can we calculate the mean radiant temperature?



- Temperature of each surface
- View factor between a person and each surface

$$T_{mr} = \Sigma_k F_{v,p\text{-}k} T_{s,k}$$

- It depends on the position of the person in the room

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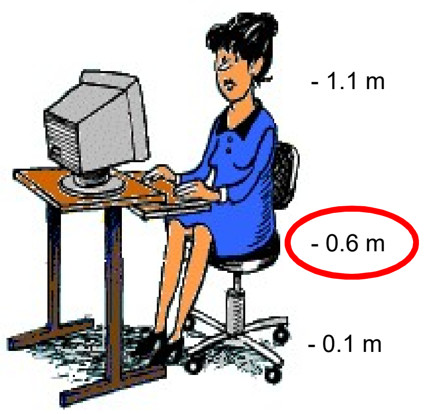
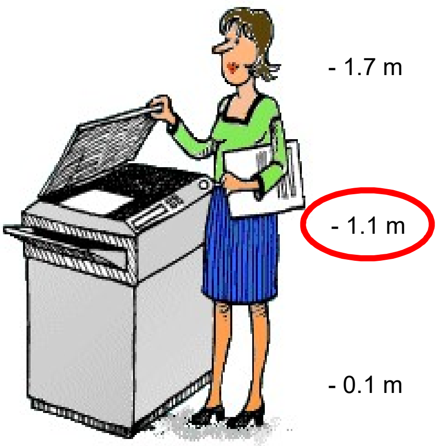
Reference height for comfort

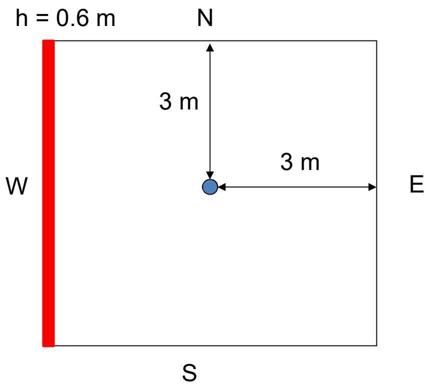


Barycentre of a seated person: 0.6 m height



Barycentre of a standing person: 1.1 m height

Some examples



Nord	0.095	26.0	2.47
Est	0.095	26.0	2.47
Sud	0.095	26.0	2.47
Ovest	0.095	30.0	2.85
Soffitto	0.2087	26.0	5.43
Pavimento	0.4114	26.0	10.70
			26.4

Nord	0.095	26.0	2.47
Est	0.095	26.0	2.47
Sud	0.095	26.0	2.47
Ovest	0.095	35.0	3.33
Soffitto	0.2087	26.0	5.43
Pavimento	0.4114	26.0	10.70
			26.9

Nord	0.095	26.0	2.47
Est	0.095	26.0	2.47
Sud	0.095	26.0	2.47
Ovest	0.095	40.0	3.80
Soffitto	0.2087	26.0	5.43
Pavimento	0.4114	26.0	10.70
			27.3

Nord	0.095	26.0	2.47
Est	0.095	26.0	2.47
Sud	0.095	26.0	2.47
Ovest	0.095	45.0	4.28
Soffitto	0.2087	26.0	5.43
Pavimento	0.4114	26.0	10.70
			27.8

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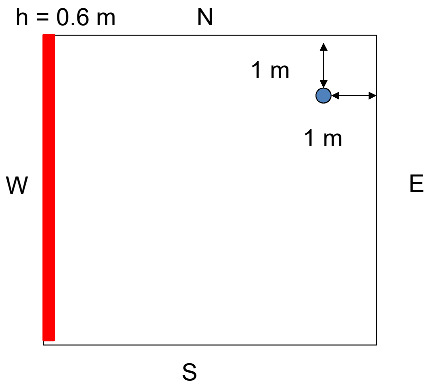


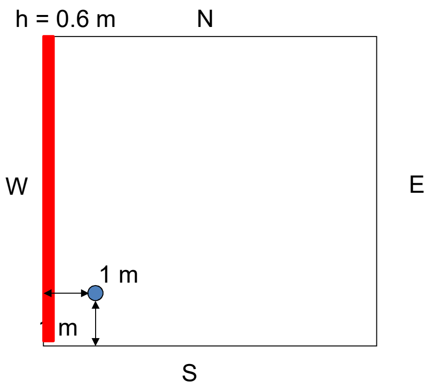
Nord	0.2184	26.0	5.68
Est	0.2214	26.0	5.76
Sud	0.0154	26.0	0.40
Ovest	0.0478	30.0	1.43
Soffitto	0.1544	26.0	4.01
Pavimento	0.3426	26.0	8.91
			26.2

Nord	0.2184	26.0	5.68
Est	0.2214	26.0	5.76
Sud	0.0154	26.0	0.40
Ovest	0.0478	35.0	1.67
Soffitto	0.1544	26.0	4.01
Pavimento	0.3426	26.0	8.91
			26.4

Nord	0.2184	26.0	5.68
Est	0.2214	26.0	5.76
Sud	0.0154	26.0	0.40
Ovest	0.0478	40.0	1.91
Soffitto	0.1544	26.0	4.01
Pavimento	0.3426	26.0	8.91
			26.7

Nord	0.2184	26.0	5.68
Est	0.2214	26.0	5.76
Sud	0.0154	26.0	0.40
Ovest	0.0478	45.0	2.15
Soffitto	0.1544	26.0	4.01
Pavimento	0.3426	26.0	8.91
			26.9

12



Nord	0.015	26.0	0.40
Est	0.048	26.0	1.24
Sud	0.219	26.0	5.68
Ovest	0.219	30.0	6.55
Soffitto	0.155	26.0	4.01
Pavimento	0.344	26.0	8.91
			26.8

Nord	0.015	26.0	0.40
Est	0.048	26.0	1.25
Sud	0.219	26.0	5.70
Ovest	0.219	35.0	7.67
Soffitto	0.155	26.0	4.03
Pavimento	0.344	26.0	8.93
			28.0

Nord	0.015	26.0	0.40
Est	0.048	26.0	1.25
Sud	0.219	26.0	5.70
Ovest	0.219	40.0	8.76
Soffitto	0.155	26.0	4.03
Pavimento	0.344	26.0	8.93
			29.1

Nord	0.015	26.0	0.40
Est	0.048	26.0	1.25
Sud	0.219	26.0	5.70
Ovest	0.219	45.0	9.86
Soffitto	0.155	26.0	4.03
Pavimento	0.344	26.0	8.93
			30.2

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Simplified method

$$T_{mr} = \Sigma_i (A_i T_i) / \Sigma_i (A_i)$$

Nord	0.125	26.0	3.25
Est	0.125	26.0	3.25
Sud	0.125	26.0	3.25
Ovest	0.125	30.0	3.75
Soffitto	0.25	26.0	6.50
Pavimento	0.25	26.0	6.50
			26.5

Nord	0.125	26.0	3.25
Est	0.125	26.0	3.25
Sud	0.125	26.0	3.25
Ovest	0.125	35.0	4.38
Soffitto	0.25	26.0	6.50
Pavimento	0.25	26.0	6.50
			27.1

Nord	0.125	26.0	3.25
Est	0.125	26.0	3.25
Sud	0.125	26.0	3.25
Ovest	0.125	40.0	5.00
Soffitto	0.25	26.0	6.50
Pavimento	0.25	26.0	6.50
			27.8

Nord	0.125	26.0	3.25
Est	0.125	26.0	3.25
Sud	0.125	26.0	3.25
Ovest	0.125	45.0	5.63
Soffitto	0.25	26.0	6.50
Pavimento	0.25	26.0	6.50
			28.4

In the simplified method it is supposed that the reference point is in the centre of the room

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Effect of solar radiation

Solar radiation transmitted in a room: additive effect

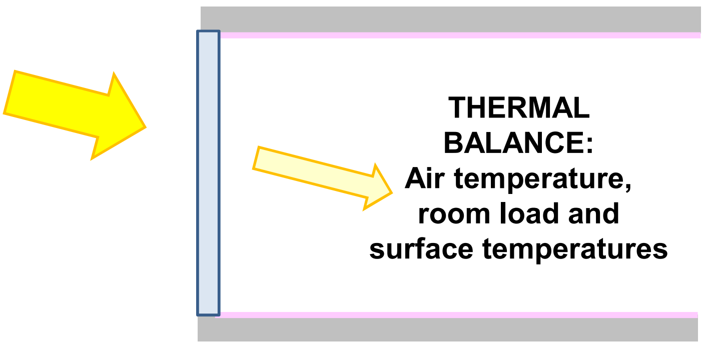
Direct transmitted solar radiation: not only effect as part of the solar gain, but also on thermal comfort in summer

Calculation of Tmr in standard conditions (based on the energy balance of the room)

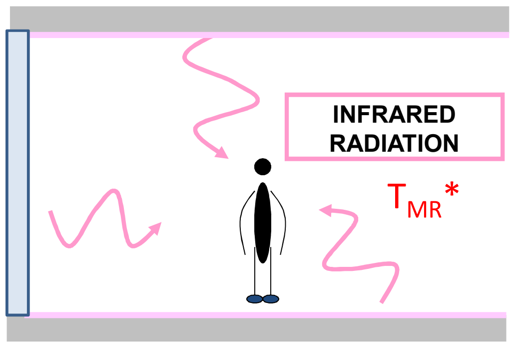
Then a correction on the mean radiant temperature has to be introduced to take into account of the effect of the direct solar radiation as increase of the perceived Tmr

ΔMRT

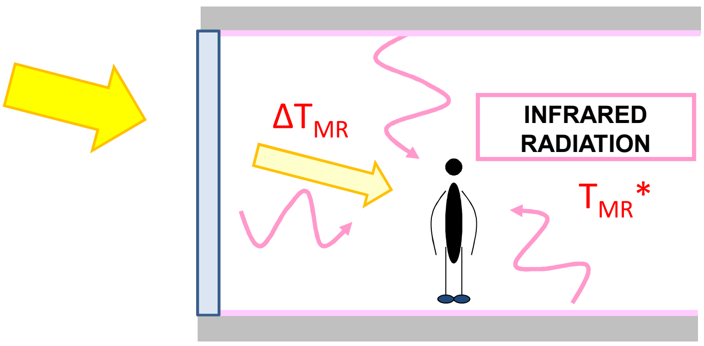
First step: calculation of the room balance



Second step: calculation of mean radiant temperature based on the room balance



Third step: calculation of the additional increase of the mean radiant temperature due to the incident solar radiation



COMFORT BASED ON FANGER THEORY

Combination of 6 variables:

- **Metabolic activity**
- **Clothing resistance,**
- **Air temperature,**
- **Mean radiant temperature**
- **Air velocity**
- **Relative humidity**

Comfort evaluation

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Operative temperature

Combination of:

- **Mean radiant temperature**
- **Air temperature**

$$t_o = \frac{h_c \cdot t_a + h_r \cdot t_{mr}}{h_c + h_r}$$

In moderate environments $h_c = h_r$:

$$t_o = \frac{t_a + t_{mr}}{2}$$

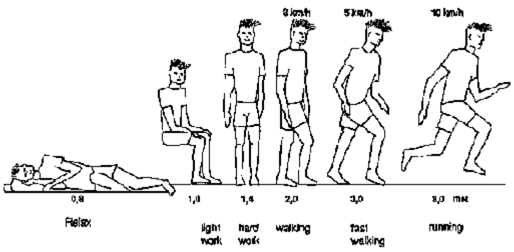
The other parameters

- **Relative humidity: negligible effects**

- **Metabolic rate**

  1 met = 58.2 W/m²

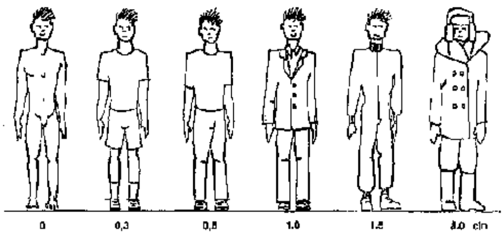
  Sedentary activity:
  1.2 met



- **Clothing resistance**

  1 clo = 0.155 m² K/W

  Usual clothing resistances:
  Summer: 0.5 clo
  Winter: 1.0 clo



COMFORT BASED ON FANGER THEORY

Combination of 6 variables:

- **Metabolic activity**
- **Clothing resistance,**
- **Air temperature,**
- **Mean radiant temperature**
- **Air velocity**
- **Relative humidity**

Operative temperature

Predictive Mean Vote

PMV and PPD

Percentage of People Dissatisfied

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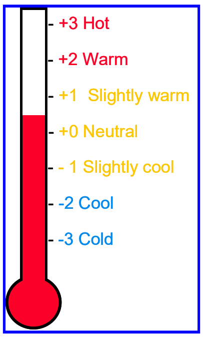
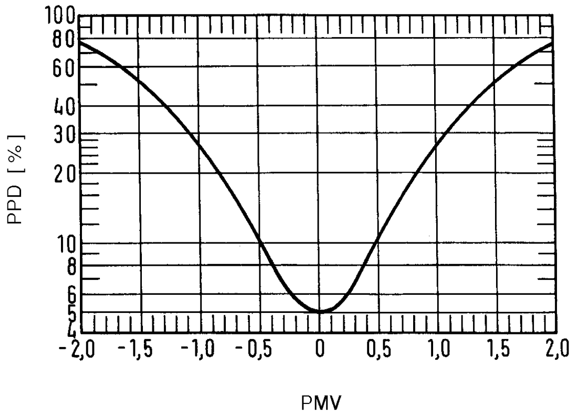
PMV (Predicted Mean Vote) & PPD (Percentage of People Dissatisfied)





Standard EN ISO 7730

Class	PPD	PMV
A	< 6%	-0.2 < PMV < 0.2
B	< 10%	-0.5 < PMV < 0.5
C	< 15%	-0.7 < PMV < 0.7

Standard EN 16798

Category	PPD	PMV
I	< 6%	-0.2 < PMV < 0.2
II	< 10%	-0.5 < PMV < 0.5
III	< 15%	-0.7 < PMV < 0.7
IV	< 25%	-1.0 < PMV < 1.0

Standard EN 16798

The standard is a revision of EN 15251:2007.

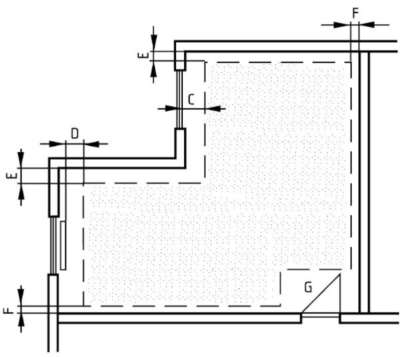
The standard provides not only for global comfort conditions (PMV, PPD) but also quality ranges for local discomfort, IAQ, lighting and acoustics.

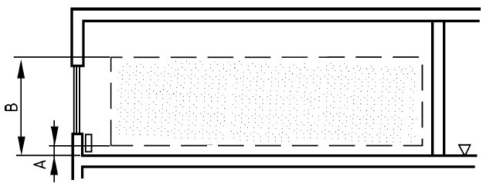
Category	Level of expectation
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

The categories are related to the level of expectations the occupants may have. A normal level would be "Medium". A higher level may be selected for occupants with special needs (children, elderly, handicapped, etc.). A lower level will not provide any health risk but may decrease comfort.

Occupied zone

Distance from the inner surface of		Typical range (m)	Default value (m)
Floors (lower boundary)	A	0,00 to 0,20	0,05
Floors (upper boundary)	B	1,30 to 2,00	1,80
External windows and doors	C	0,50 to 1,50	1,00
HVAC appliances	D	0,50 to 1,50	1,00
External walls	E	0,15 to 0,75	0,50
Internal walls	F	0,15 to 0,75	0,50
Doors, transit zones etc.	G	Special agreement	-





Adaptive comfort 1/2

It is mainly addressed to the cooling season.

The principle: people experience differently and adapt, up to a certain extent, to a variety of indoor conditions, depending on their clothing, their activity and general physical condition. Physiological, psychological or behavioural adjustment of building occupants to the interior thermal environment in order to avoid or to limit thermal discomfort.

In naturally ventilated buildings these are often in response to changes in indoor environment induced by outdoor weather conditions.

The adaptive method only applies for occupants with sedentary activities (office buildings) without strict clothing policies where thermal conditions are regulated primarily by the occupants through opening and closing of building elements in the envelope (e.g. windows, ventilation flaps, roof lights, etc.).

Adaptive comfort 2/2

The upper limits shall be used to design buildings and passive thermal controls (e.g. orientation of glazing and solar shading, thermal building capacity, size and adjustability of operable windows, etc.) to avoid overheating. It shall be evaluated if increased air velocity (with or without personal control) can improve thermal comfort.

The model of adaptive comfort considers the perception of an environment by occupants. The basic concept is to consider the capability of people to adapt to an environment by playing on the different variables.

The concept of adaptation to an environment is based on the expectations of the occupants who play an active role in managing the indoor climate, reducing or neglecting the HVAC.

The 3 mechanisms of adaptation:

1. behavioural

   Includes all actions of the user (conscious or not) for the interaction with the thermal balance of the body. These actions can be subdivided into:
   - Personnel (by putting/removing clothing)
   - Technological (opening windows, control of solar radiation)
   - Cultural (e.g. resting in the warmest hours of the day)

2. physiological

   Depends on the capability of a person to acclimate in a different environment by reducing the metabolic rate.

   This mechanism is more frequent in populations facing constantly with severe climatic conditions.

3. psycological

   Different perception of sensory information due to past experiences. The personal comfort sensation can differ from the one which can predicted by the theory of Fanger due to the habit to face frequent warm solicitation

Versatile adaptation

In Japan in ministerial offices all people without ties
"Energy saving in summer"
la Repubblica 1 June 2005

460'000 tons less of CO_2

Il Sole 24 Ore, 1 June 2006

Farewell to ties in ENI
informal look and air conditioning at higher indoor temperatures
la Repubblica 3 July 2007

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THE IMPORTANCE OF CLOTHING

0.1 clo ~ 0.7 K

Garment Description	Thermal Insulation clo	Change of Operative Temp. K
Panties	0,03	0,2
T-shirt	0,09	0,6
Short sleeves shirt	0,15	0,9
Normal shirt, long sleeves	0,25	1,6
Shorts	0,06	0,4
Normal trousers	0,25	1,6
Light skirts (summer)	0.15	0,9
Heavy skirt (winter)	0,25	1,6
Thin sweater	0,20	1,3
Light, summer jacket	0,25	1,6
Normal jacket	0,35	2,2

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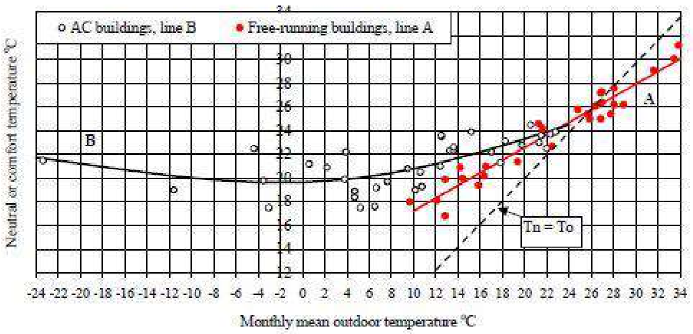
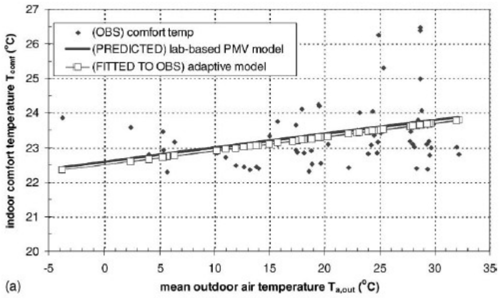
First studies on temperature acceptance in cooling

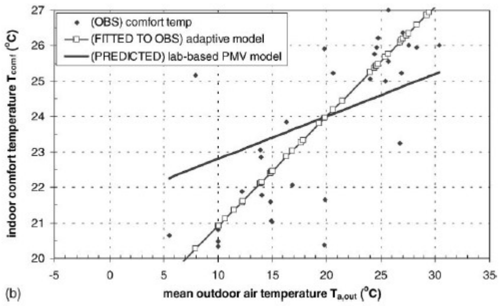


Humphreys in 1978 has already shown that in non-conditioned buildings the expectations are less restrictive than in cooled environments.

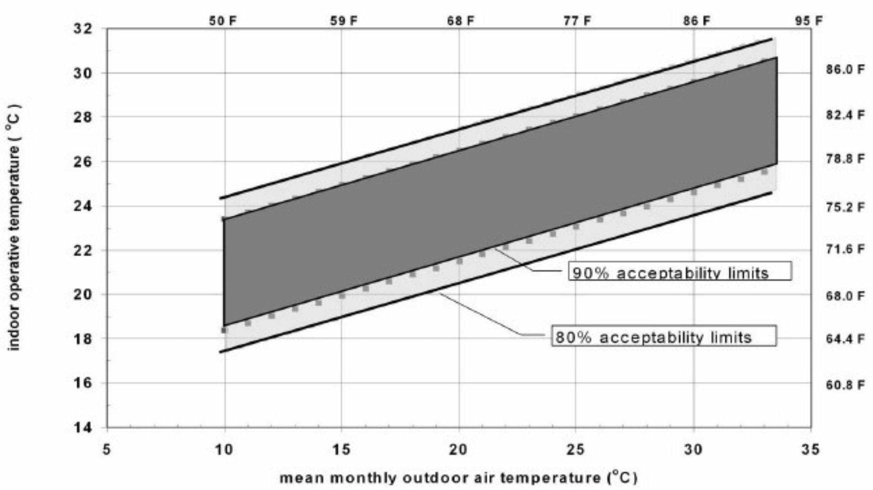
Introduction of adaptation in standards

Similar result has been achieved by De Dear and Brager in 2002





ASHRAE 55



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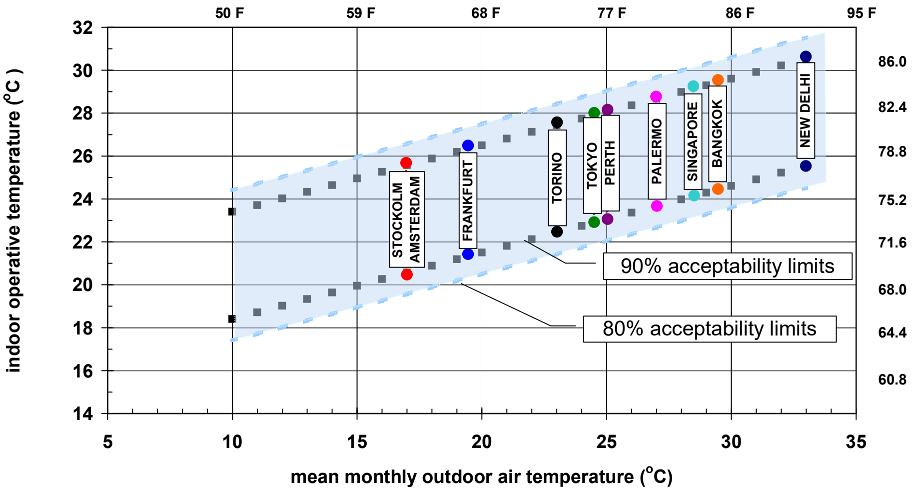
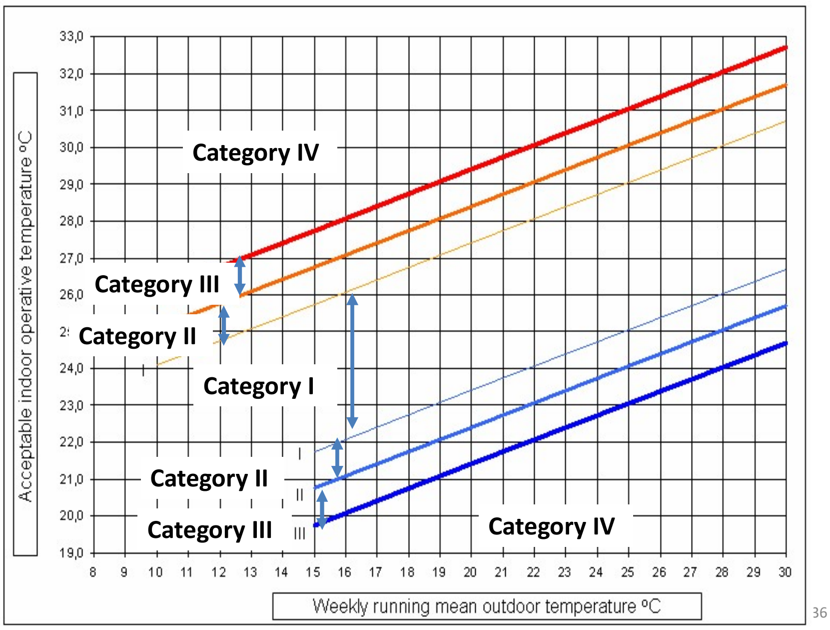
ASHRAE 55



EN 16798



EN 16798: definition of ranges for adaptive comfort

The equations representing the lines in Figure A.1 are

Category I	upper limit:	$\boldsymbol{\Theta_{i\ max}} = 0{,}33\Theta_{rm} + 18{,}8 + 2$
	lower limit:	$\Theta_{i\ min} = 0{,}33\ \Theta_{rm} + 18{,}8 - 2$
Category II	upper limit:	$\Theta_{i\ max} = 0{,}33\ \Theta_{rm} + 18{,}8 + 3$
	lower limit:	$\Theta_{i\ min} = 0{,}33\ \Theta_{rm} + 18{,}8 - 3$
Category III	upper limit:	$\Theta_{i\ max} = 0{,}33\ \Theta_{rm} + 18{,}8 + 4$
	lower limit:	$\Theta_{i\ min} = 0{,}33\ \Theta_{rm} + 18{,}8 - 4$

where Θ_i = limit value of indoor operative temperature, °C

Θ_{rm} = running mean outdoor temperature. These limits apply when $10 < \Theta_{rm} < 30$ °C for upper limit and $15 < \Theta_{rm} < 30$ °C for lower limit. Above 25 °C the graphs are based on a limited database.

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EN 16798: weekly running temperature

The outdoor running mean temperature is calculated by means of Formula

$$\Theta_{rm} = (1-\alpha)\cdot\left\{\Theta_{ed-1} + \alpha.\Theta_{ed-2} + \alpha^2\Theta_{ed\text{-}3}\right\}$$

where

Θ_{rm} = Outdoor Running mean temperature for the considered day (°C).

$\Theta_{ed\text{-}1}$ = daily mean outdoor air temperature for previous day

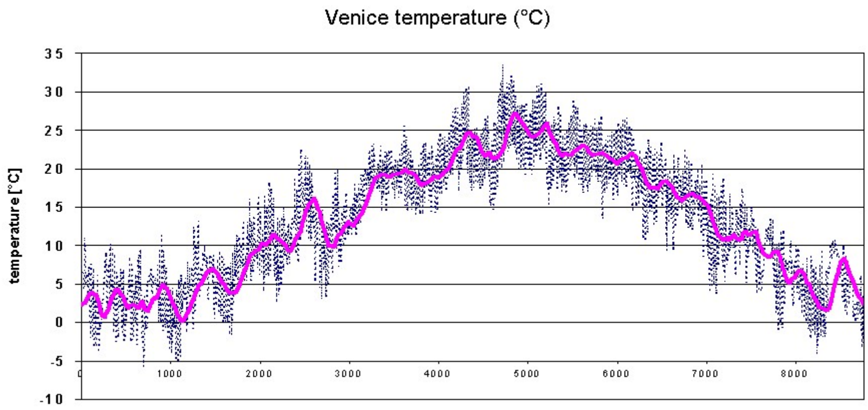
α = constant between 0 and 1 (recommended value is 0,8)

$\Theta_{ed\text{-}i}$ = daily mean outdoor air temperature for the *i-th* previous day

The following approximate formula shall be used where records of daily running mean outdoor temperature are not available:

$$\Theta_{rm} = \left(\Theta_{ed-1} + 0{,}8\ \Theta_{ed-2} + 0{,}6\ \Theta_{ed-3} + 0{,}5\ \Theta_{ed-4} + 0{,}4\ \Theta_{ed-5} + 0{,}3\ \Theta_{ed-6} + 0{,}2\ \Theta_{ed-7}\right)/\,3{,}8 \qquad \text{(H.2)}$$

Weekly running temperature in Venice



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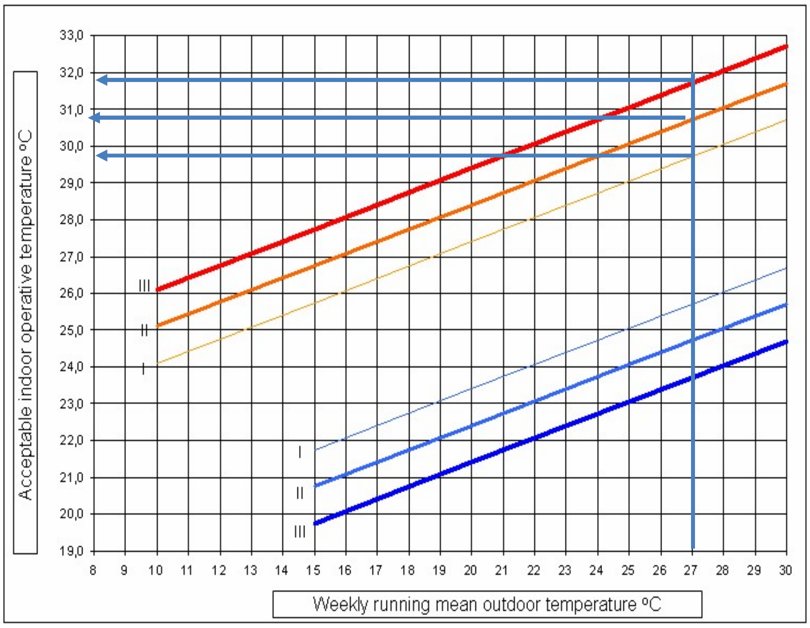
EN 16798



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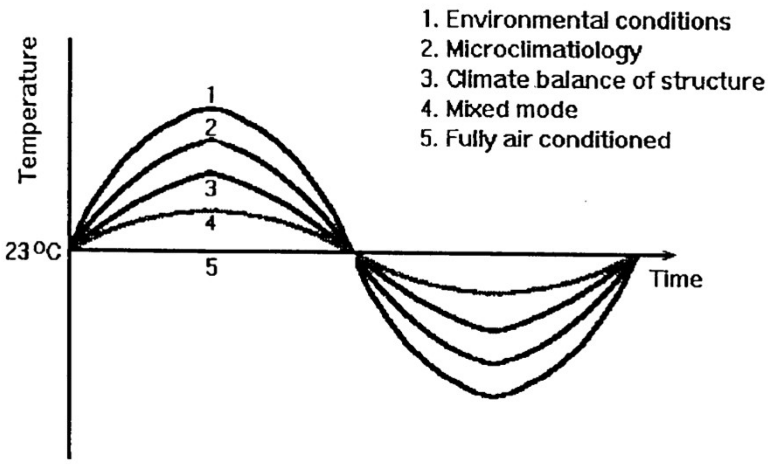
Principles of buildings naturally ventilated, HVAC and mixed



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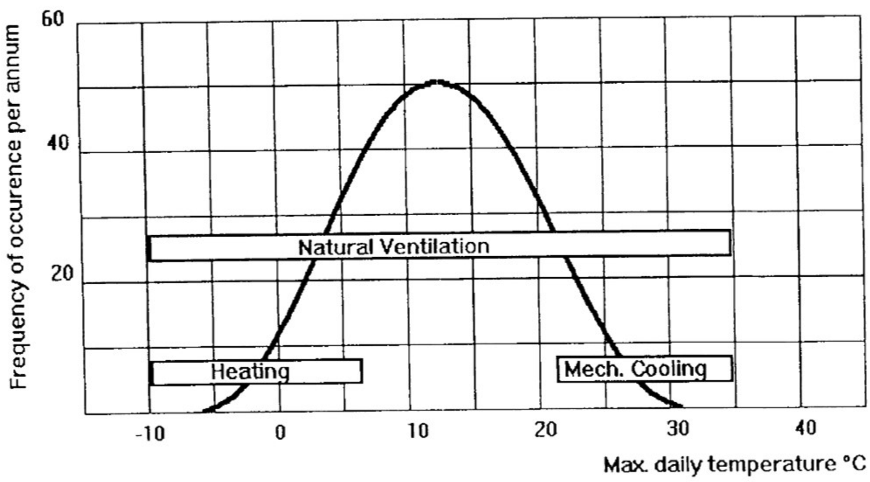
Do we have to work always with full air conditioning?



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