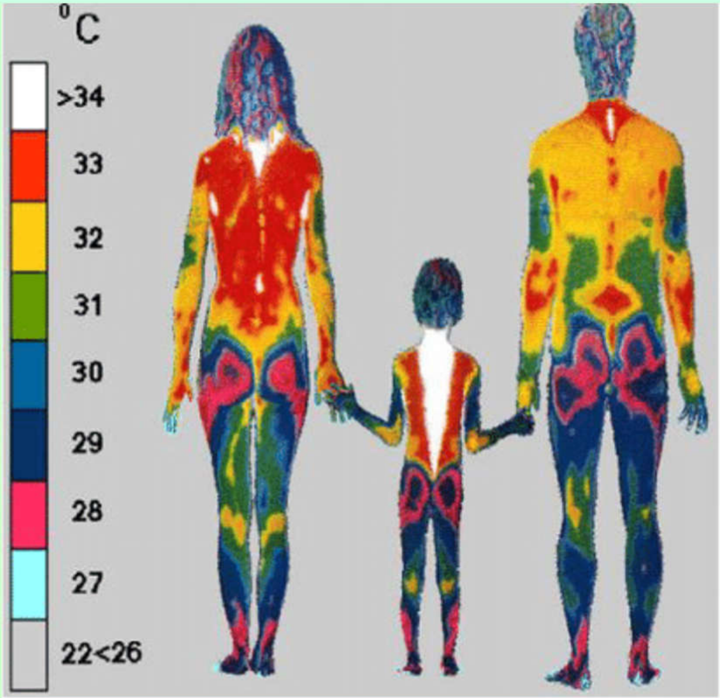

Thermal comfort and human factors

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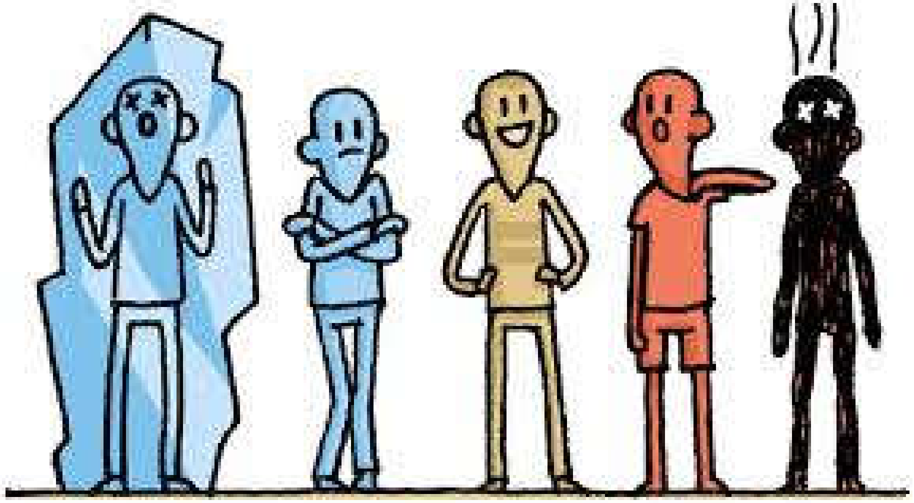
Sep 2024

Contents

- What is thermal comfort?
- Comfort equation & analysis
- Influencing factors
- Adaptive thermal comfort
- Human factors



What is Thermal Comfort?

Definition

- That condition of mind which expresses satisfaction with the thermal environment.

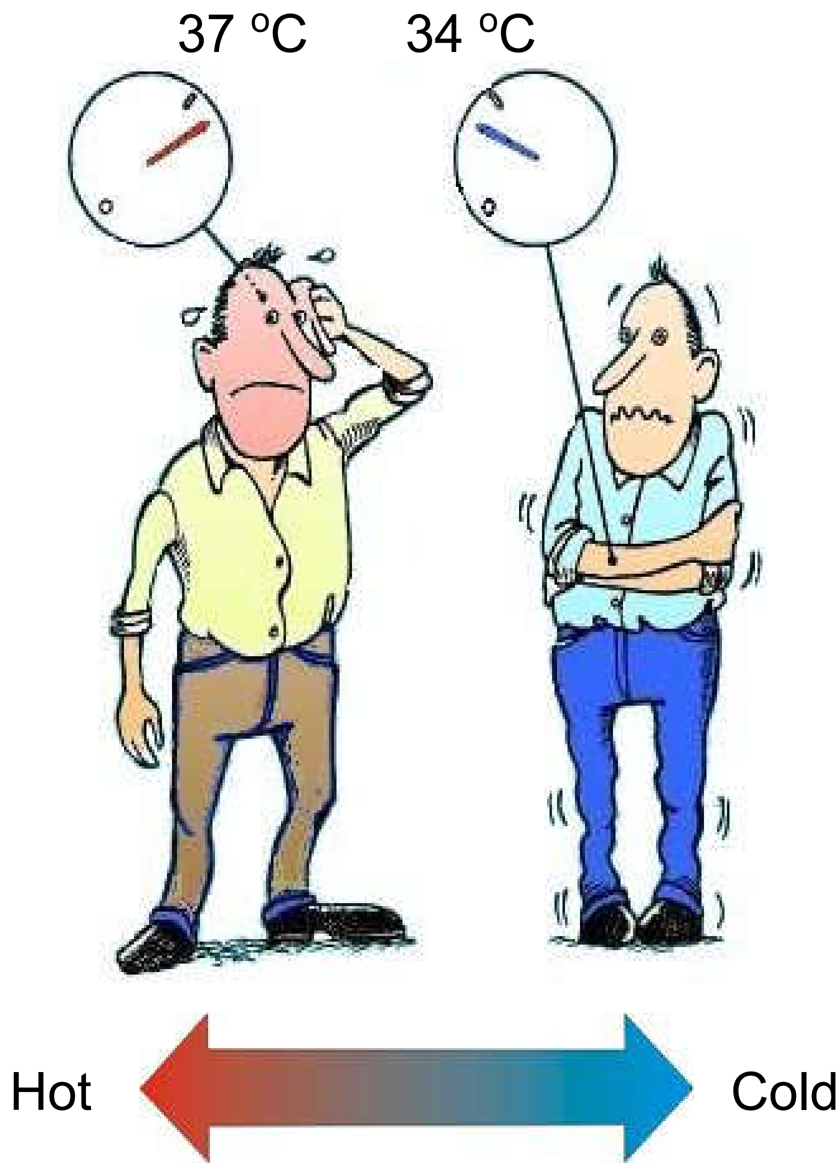
ISO 7730

熱舒適性

Thermal Environments

Thermal Comfort is a matter of many parameters - **Not** only the air temperature.

Body Temperature



Normal body core temperature: 37 ^{o}C.

We have separate Heat- and Cold-sensors.

Heat sensor is located in hypothalamus. Signals when temperature is higher than 37 ^{o}C.

Cold sensors are located in the skin. Send signals when skin temperature is below 34 ^{o}C.

Heating mechanism:

Reduced blood flow.

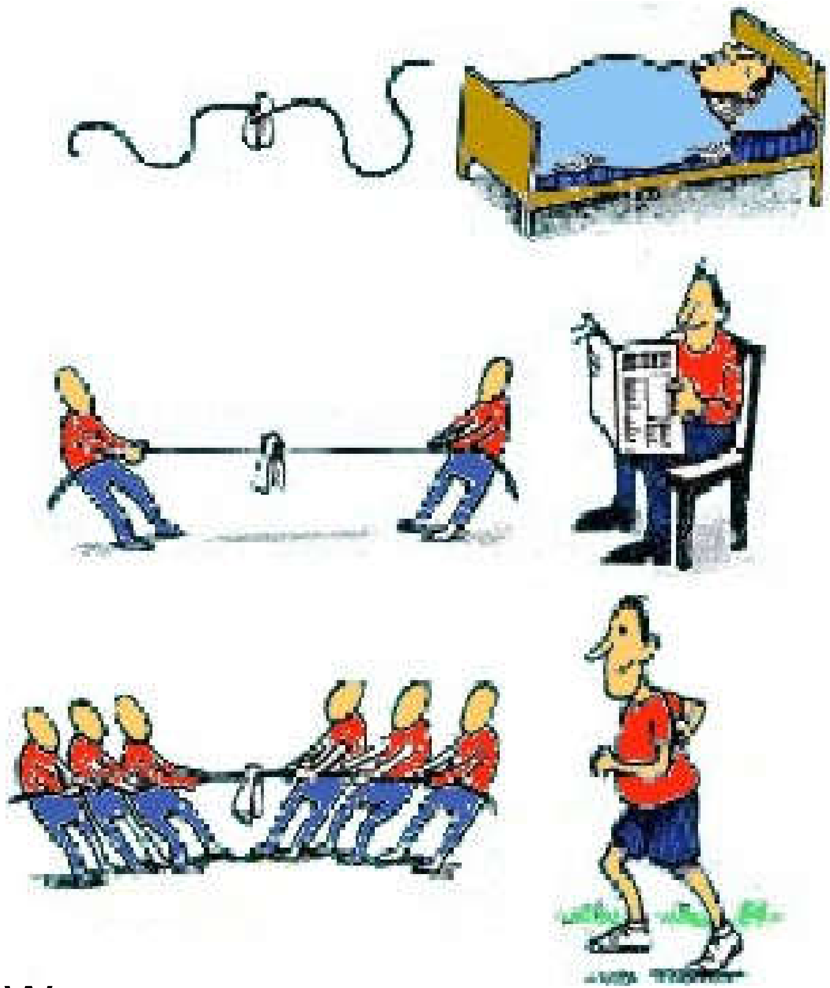
Shivering.

Cooling mechanism:

Increased blood flow.

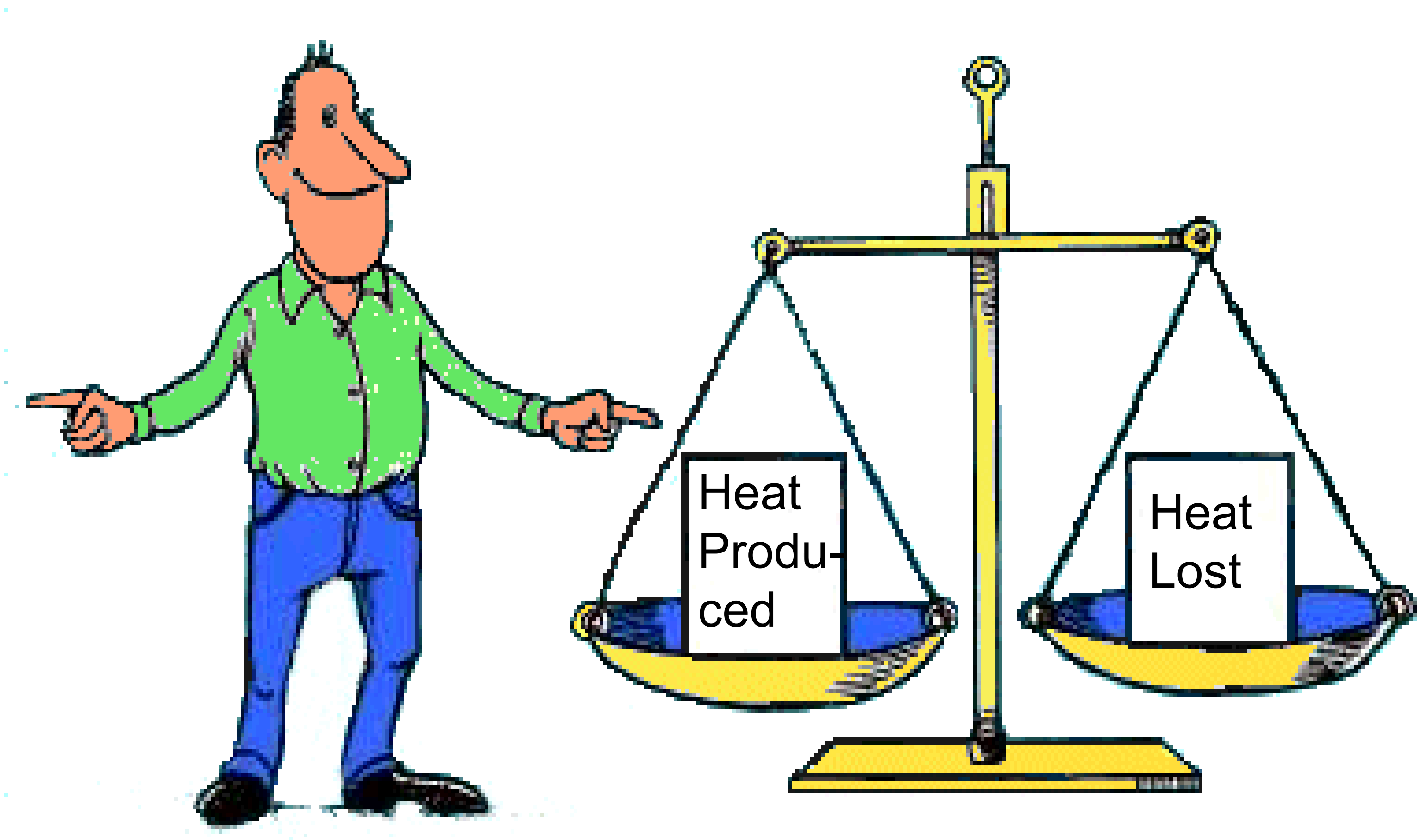
Sweating (Evaporation).

Perception of Thermal Environment



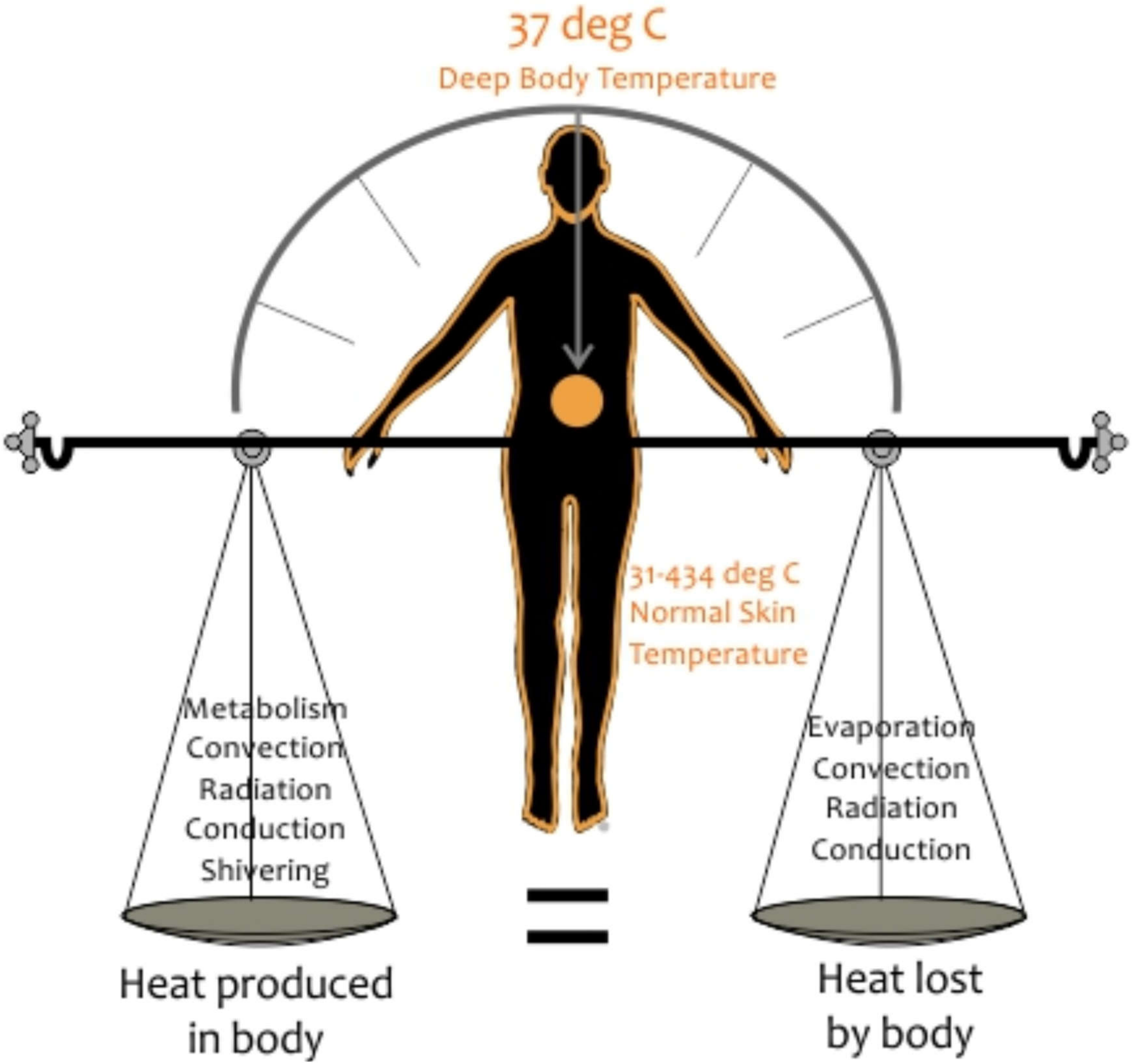
- Heat sensor in Hypothalamus send impulses when temperature exceeds 37 °C.
- Cold sensors sends impulses when skin temperature below 34 °C.
- The bigger temperature difference, the more impulses.
- If impulses are of same magnitude, you feel thermally neutral.
- If not, you feel cold or warm.

The Energy Balance



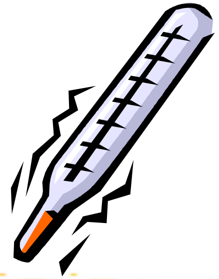
Thermal Comfort can only be maintained when heat produced by metabolism equals the heat lost from body. (Thermal neutrality)

Body temperature and heat balance



(Source: https://nzeb.in/knowledge-centre/passive-design/thermal-comfort/)

What is thermal comfort?



- General heat balance

$$S = M - W - E - (R + C)$$

where

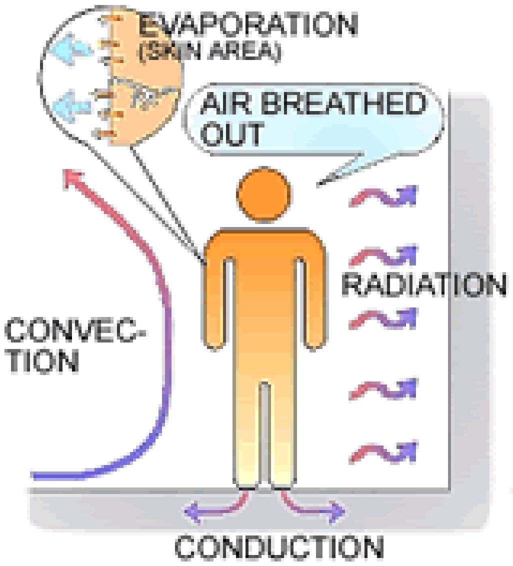
S = rate of heat storage of human body

M = metabolic rate

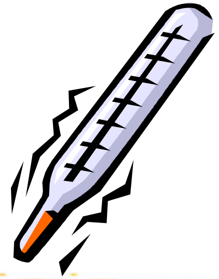
W = mechanical work done by human body

E = rate of total evaporation loss

R + C = dry heat exchange through radiation & convection

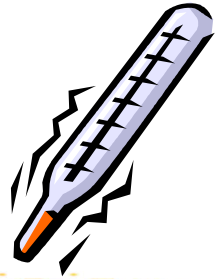


What is thermal comfort?



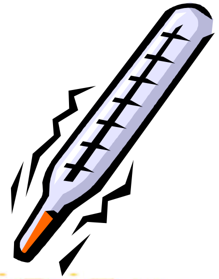
- Rate of heat storage, S
  - proportional to rate of change in mean body temp.
  - normally, S is zero; adjusted by the thermo-regulatory system of the body
- Metabolic rate, M
  - heat released from human body per unit skin area
    - depends on muscular activities, environment, body sizes, etc.; unit is “met” (= 58.2 W/m^2)
    - 1 met = seated quiet person (100 W if body surface area is 1.7 m^2)

What is thermal comfort?



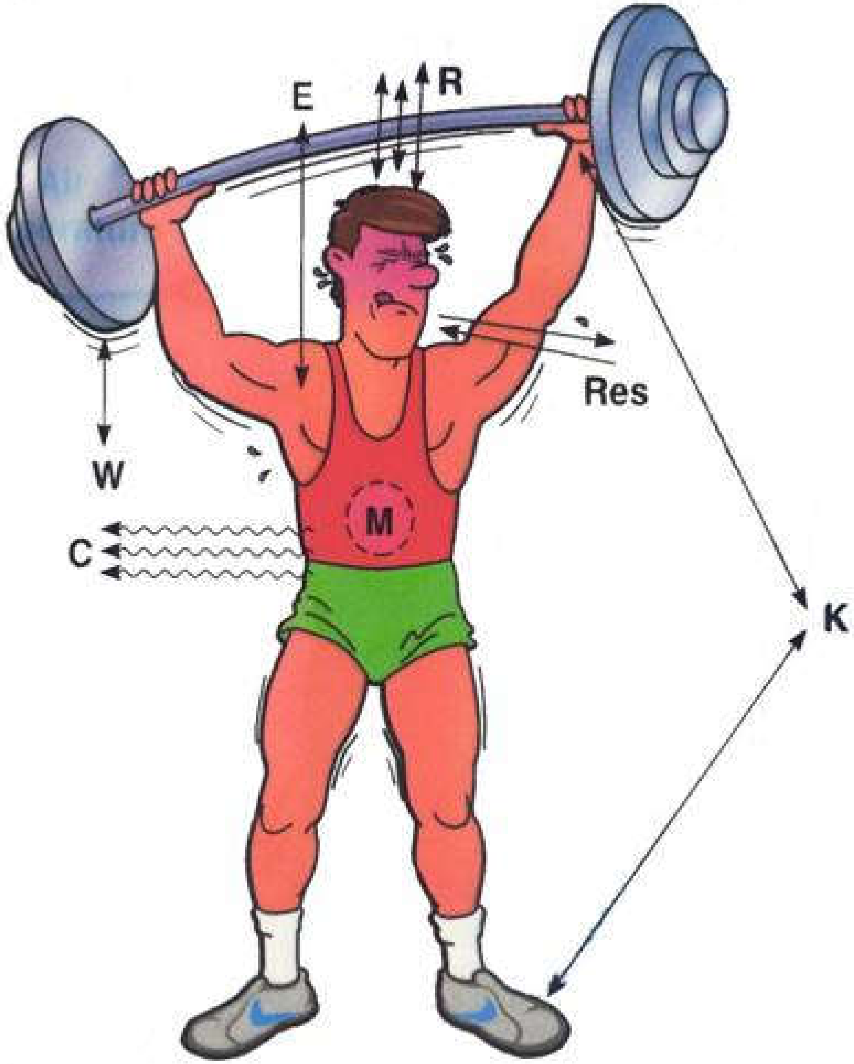
- Mechanical work, W
  - energy in human body transformed into external mechanical work
- Evaporative heat loss, E
  - release of latent heat energy from evaporation of body fluid
    - respired vapour loss, E_{res} (respiration heat losses: latent E_{rel} and sensible E_{rec})
    - evaporative heat loss from skin E_{sk} (include skin diffusion E_{dif} and regulatory sweating E_{rsw})

What is thermal comfort?



- Dry heat exchange, R + C
  - through convective and radiative heat transfer
    - heat loss by radiation if skin temp. > temp. of surrounding surfaces
    - heat loss by convection if skin temp. > dry bulb temp.
  - **mean radiant temperature** (t_r) is that uniform temp. of an imaginary black enclosure which result in the same heat loss by radiation as the actual enclosure

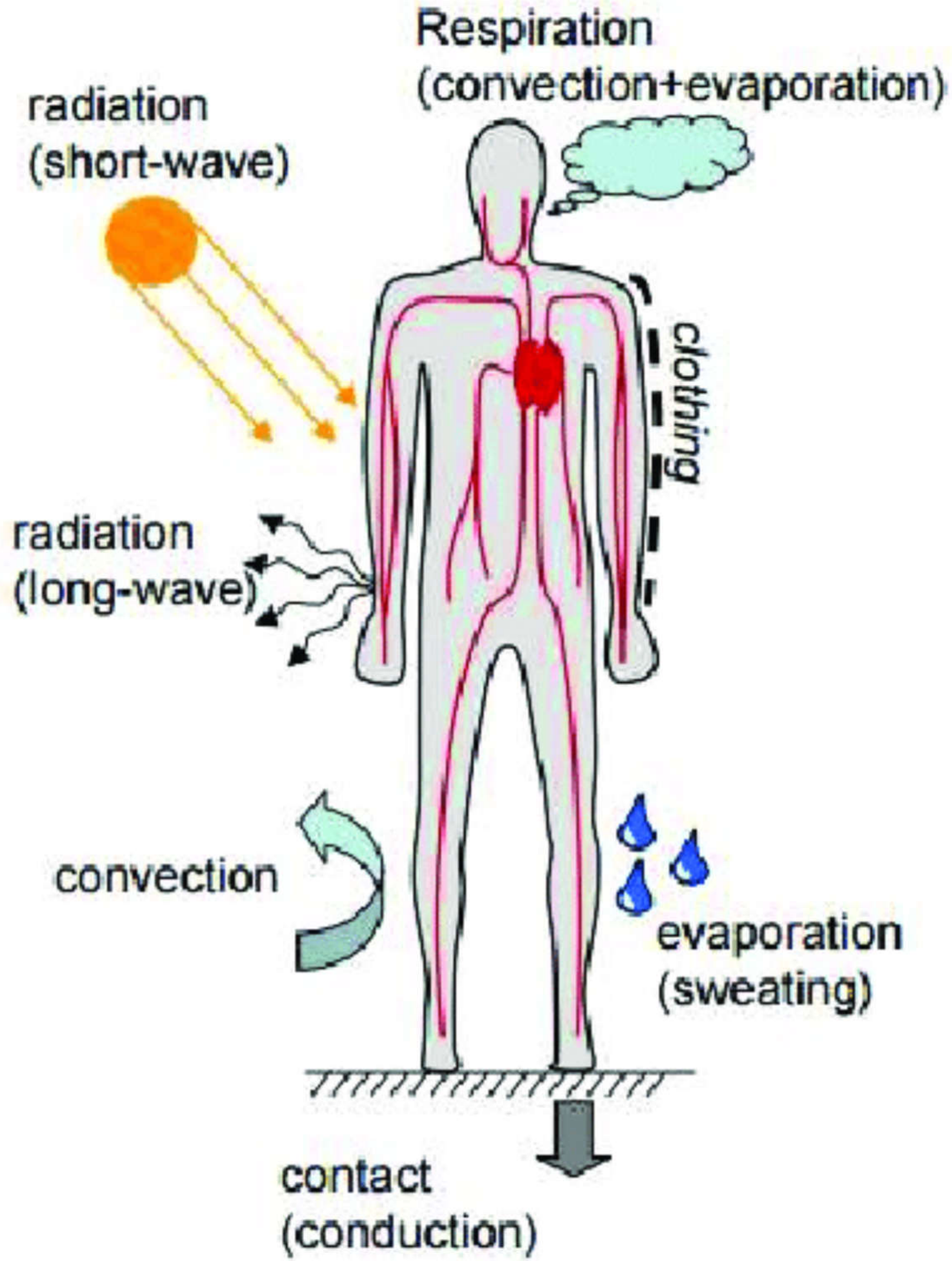
The Energy Balance

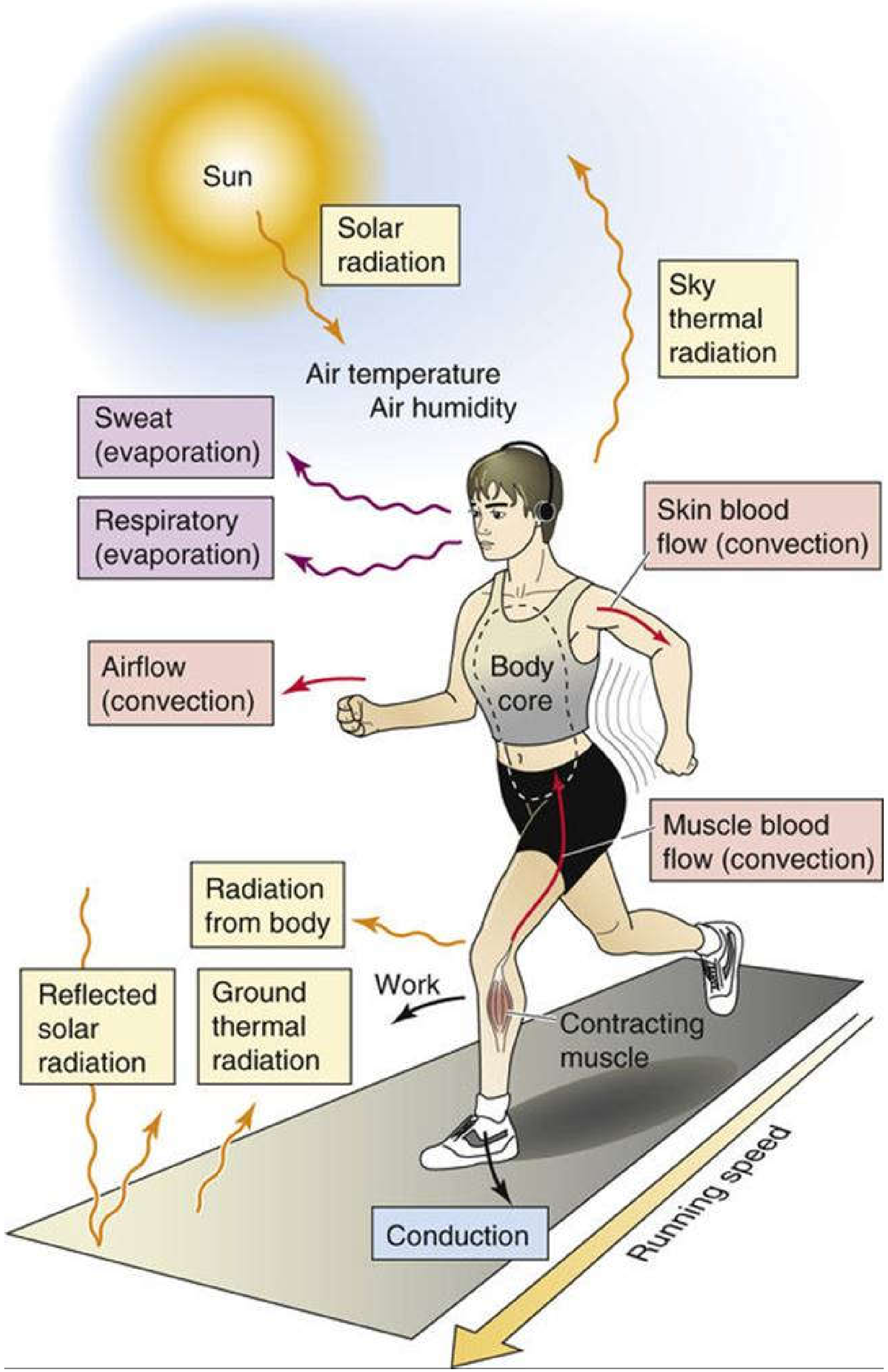


- The dry heat loss (R+C) represents ~70% at low Clo-values and ~60% at higher Clo-values
- Conduction (K) is normally insignificant compared to the total heat exchange

Parameters influencing the Heat Loss from a person

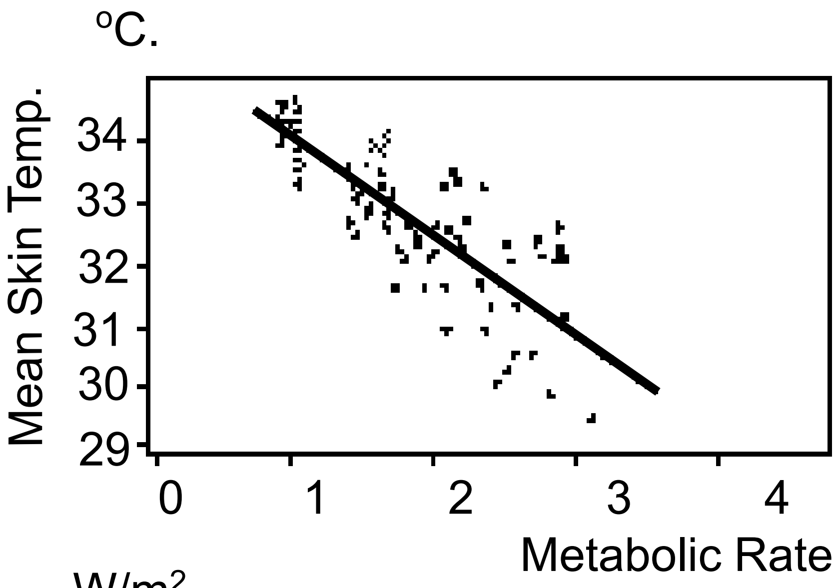
Heat exchange between the human body and the environment

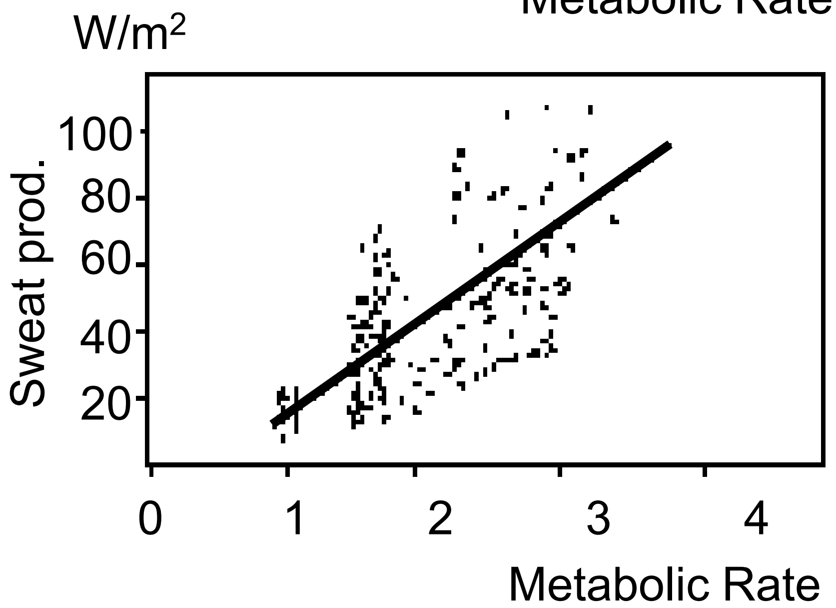




(Source: http://dx.doi.org/10.1088/1757-899X/252/1/012031 & https://doctorlib.info/physiology/medical/336.html)

Conditions for Thermal Comfort





Two conditions must be fulfilled to maintain Thermal Comfort:

- Heat produced must equal heat lost
- Signals from Heat- and Cold- sensors must neutralise each other

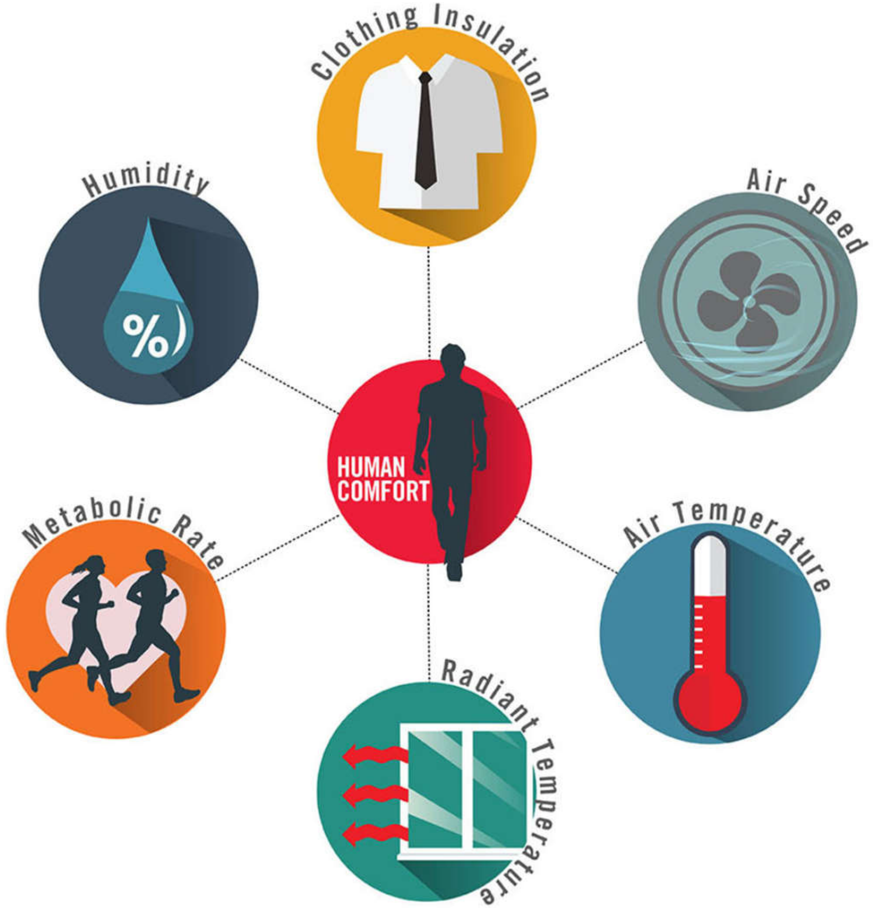
The sweat production is used instead of body core temperature, as measure of the amount of warm impulses.

Relation between the parameters found empirically in experiments.

No difference between sex, age, race or geographic origin.

Comfort equation & analysis

- Factors affecting thermal comfort:
  - Surface temperature
  - Air temperature
  - Humidity
  - Air movement
  - Metabolic rate
  - Clothing



Video: Thermal Comfort in Buildings Explained - HVACR Design (11:04)
https://youtu.be/yEWT_XmqCtQ

Comfort equation & analysis

- Fanger's comfort criteria
  - Developed by Prof. P. O. Fanger (Denmark)
  - **Fanger's comfort equation**:

$$f\,(M,\ I_{cl},\ V,\ t_r,\ t_{db},\ P_s) = 0$$

where M = metabolic rate (met)

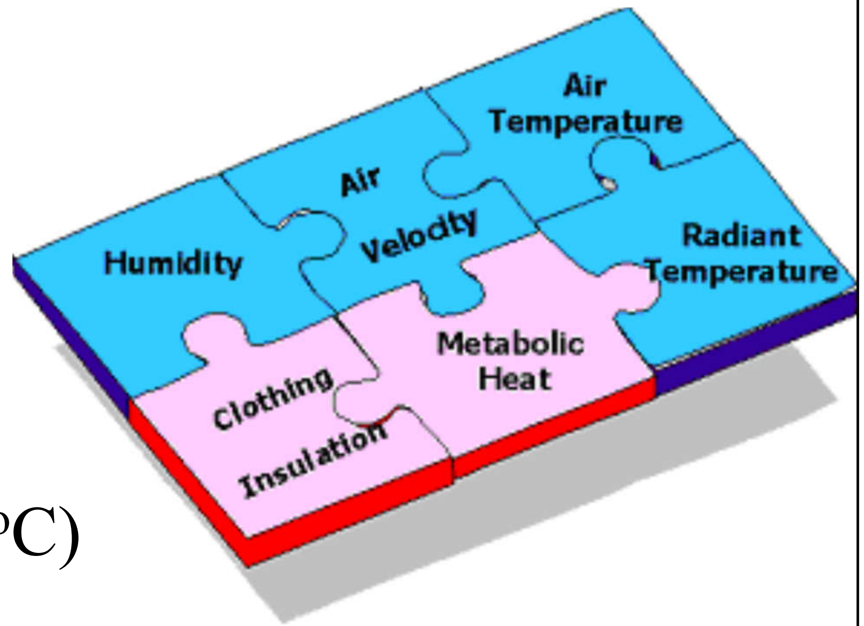
I_{cl} = cloth index (clo)

V = air velocity (m/s)

t_r = mean radiant temp. (^oC)

t_{db} = dry-bulb temp. (^oC)

P_s = water vapour pressure (kPa)



The Comfort Equation

Comfort Equation:

$$M - W = H + E_c + C_{res} + E_{res}$$

$$E_c = 3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (M - W - P_a\right] + 0.42 \cdot \left(M - W - 58.15\right)$$

$$C_{res} = 0.0014 \cdot M \cdot \left(34 - t_a\right)$$

$$E_{res} = 1.72 \cdot 10^{-5} \cdot M \cdot \left(5867 - P_a\right)$$

H is either measured directly or calculated

The Comfort Equation (cont'd)

What to measure

Air Temperature + Mean Radiant Temperature
+ Air Velocity + Humidity

OR

Operative Temperature + Air Velocity + Humidity

OR

Equivalent Temperature + Humidity

What to estimate

MET - VALUE (Metabolism)
CLO - VALUE (Clothing level)

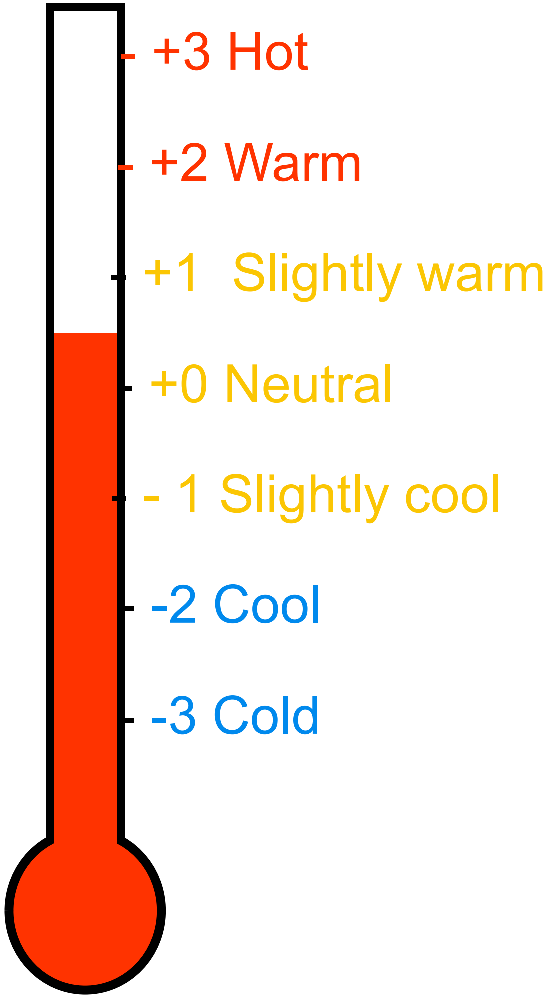
Comfort equation & analysis

- Three conditions needed for thermal comfort:
  - 1. Thermal balance (heat loss = heat production)
  - 2. Mean skin temperature at appropriate level
  - 3. Sweating at a preferred rate (related to activity)
- Fanger's equation is complex but it may be transformed to comfort diagrams
  - It can also be used to yield three indices:
    - Predicted mean vote (PMV)
    - Predicted percentage of dissatisfied (PPD)
    - Lowest possible percentage dissatisfied (LPPD)

Comfort equation & analysis

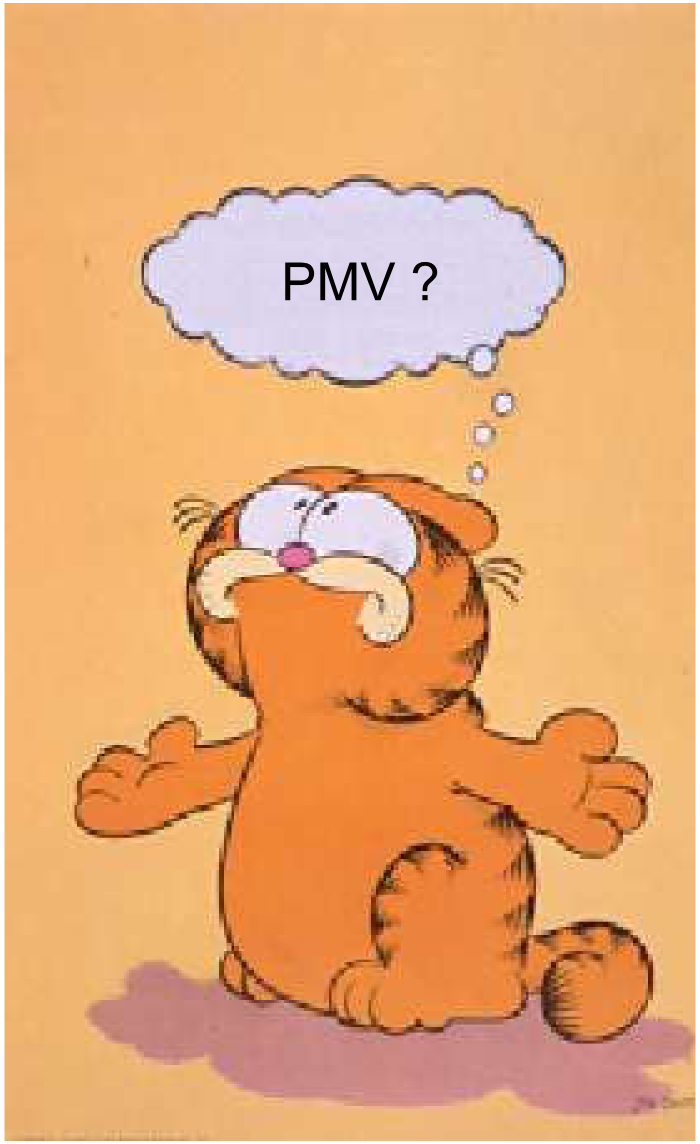
- Predicted mean vote (PMV)
  - A complex function of six major comfort parameters
  - Predict mean value of the subjective ratings of a group of people in a given environment
- Predicted percentage of dissatisfied (PPD)
  - Determined from PMV as a quantitative measure of thermal comfort
    - 'Dissatisfied' means not voting -1, +1 or 0 in PMV
    - Normally, PPD < 7.5% at any location & LPPD < 6%

Predicted Mean Vote scale



The PMV index is used to quantify the degree of discomfort

Calculation of PMV index



$$PMV = (0,303e^{-2,100*M} + 0,028)*[(M-W)- H - E_c - C_{res} - E_{res}]$$

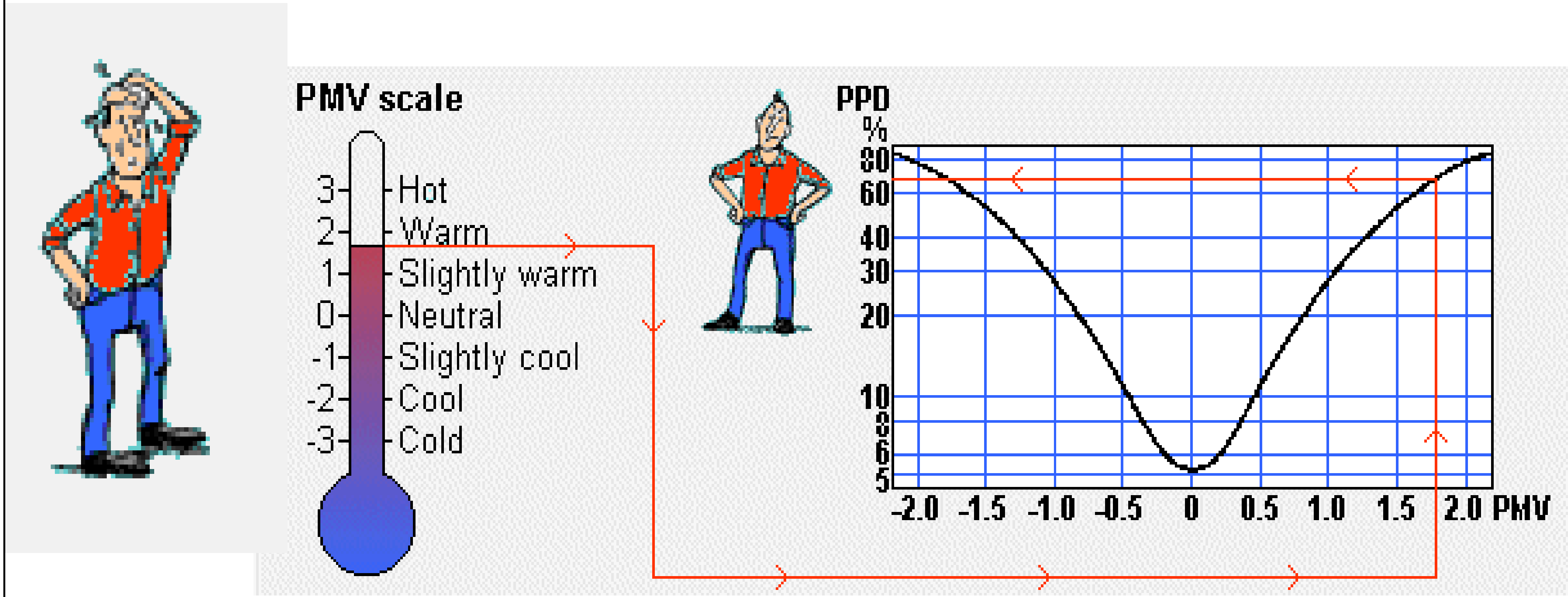
$$\Longrightarrow$$

$$PMV = (0,303e^{-2,100*M} + 0,028)*[58,15*(M-W)$$
$$-3,05*10^{-3}*[5733-406,7*(M-W)-p_a]-24,21*[(M-W)-1]$$
$$-10^{-3}*M*(5867-p_a)-0,0814*M*(34-t_a)$$
$$-3,96*10^{-8}*f_{cl*}[(t_{cl}+273)^4 - (t_{eq}+273)^4]$$
$$- f_{cl}*h_{c,eq}*(t_{cl}-t_{eq})]$$

$$h_{c,eq} = 2,38*(t_{cl} - t_{eq})^{0,25} \qquad f_{cl} \begin{cases} 1,00+0,2*I_{cl} \text{ for } I_{cl} <0,5 \text{ clo} \\ 1,05+0,1*I_{cl} \text{ for } I_{cl} >0,5 \text{ clo} \end{cases}$$

M [MET)] Icl [CLO]

PMV and PPD

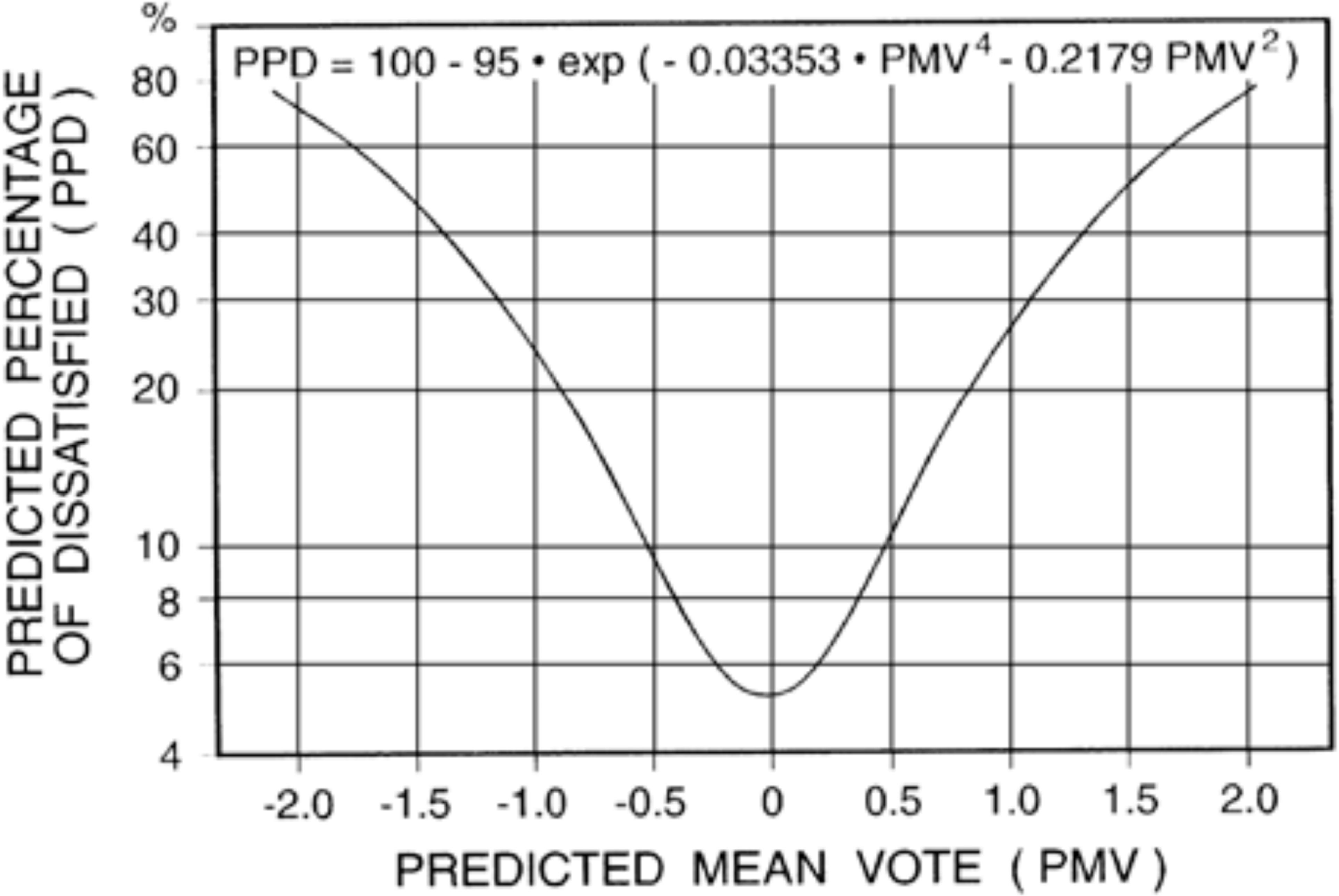


PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.

0 = neutral (still 5% people are dissatisfied)

PPD-index predicts the number of dissatisfied people.

Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV)



(Source: ASHRAE Standard 55-2013)

Comfort equation & analysis

- Comfort zones
  - Defined using isotherms parallel to equivalent temperature (ET) or operative temperature (OT)
  - ASHRAE comfort zones for summer and winter (for typical indoor and seated person)
  - Example of proposed comfort zones
    - Within 5 to 16 mm Hg water vapour pressure
    - For summer, $22.8\ ^{\circ}C \leq SET \leq 26.1\ ^{\circ}C$
    - For winter, $20.0\ ^{\circ}C \leq SET \leq 23.9\ ^{\circ}C$

(See also: Equivalent temperature - Wikipedia https://en.wikipedia.org/wiki/Equivalent_temperature
& Operative temperature - Wikipedia https://en.wikipedia.org/wiki/Operative_temperature)

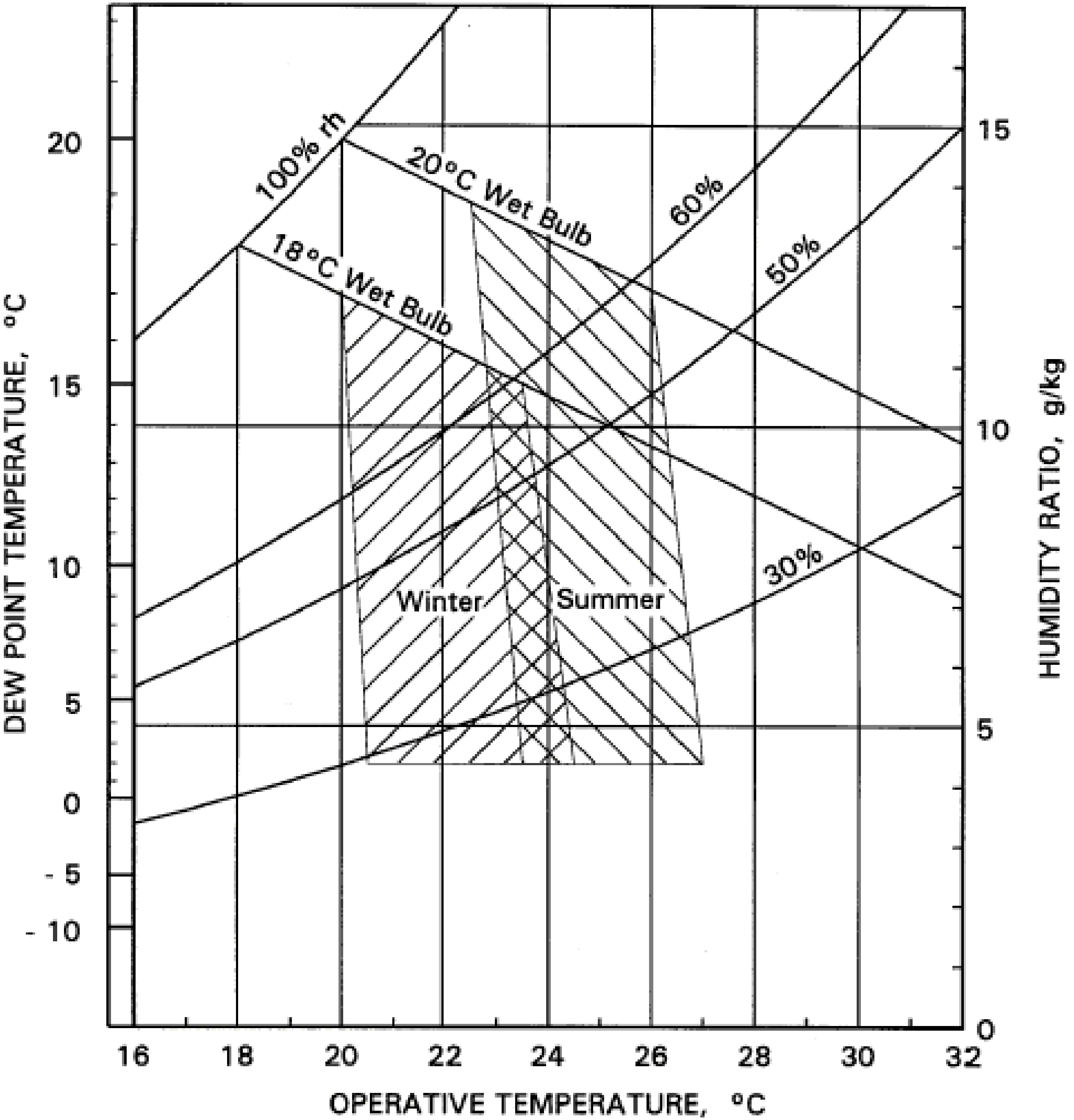
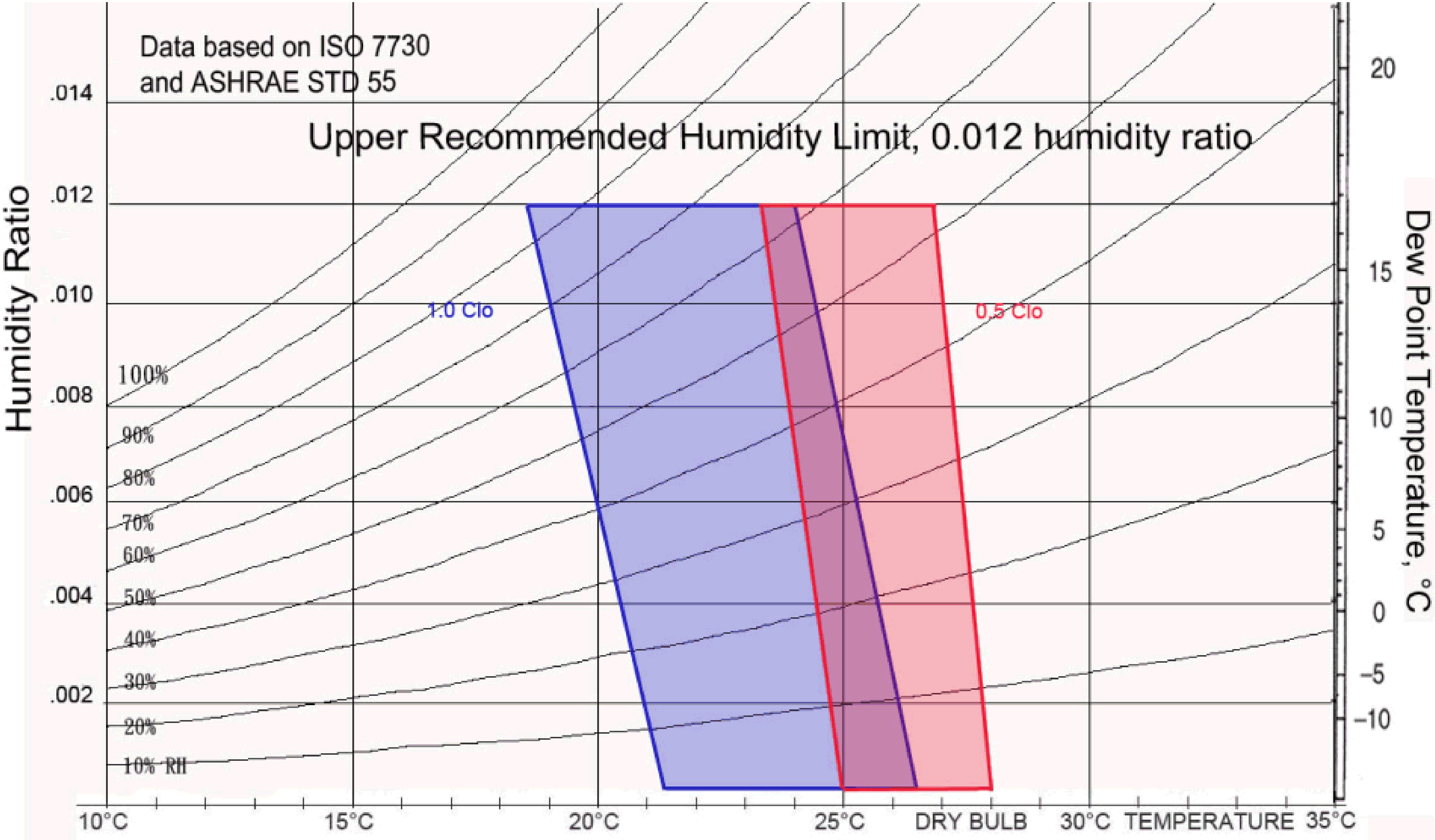


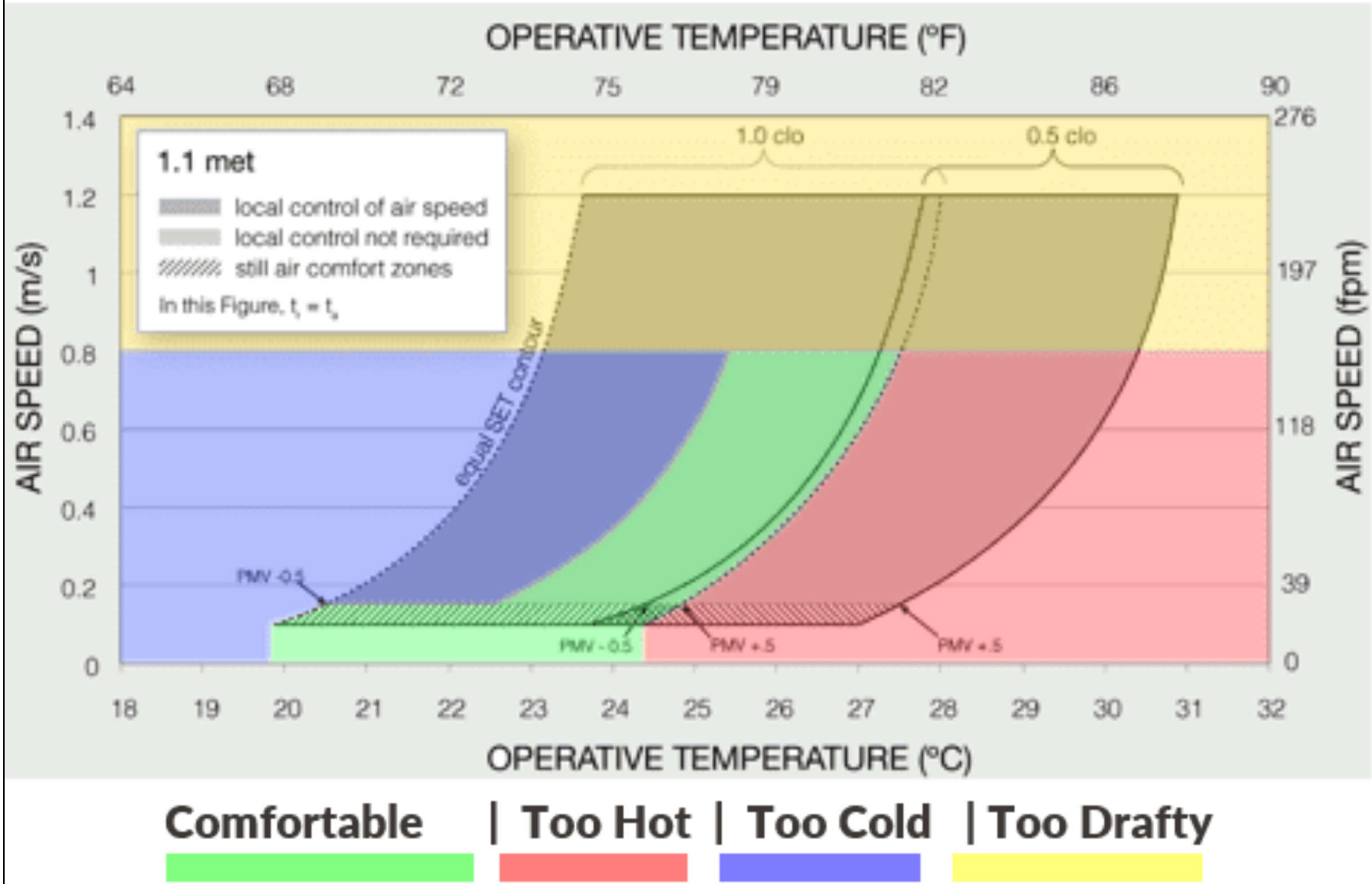
Fig. 5 ASHRAE Summer and Winter Comfort Zones

(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

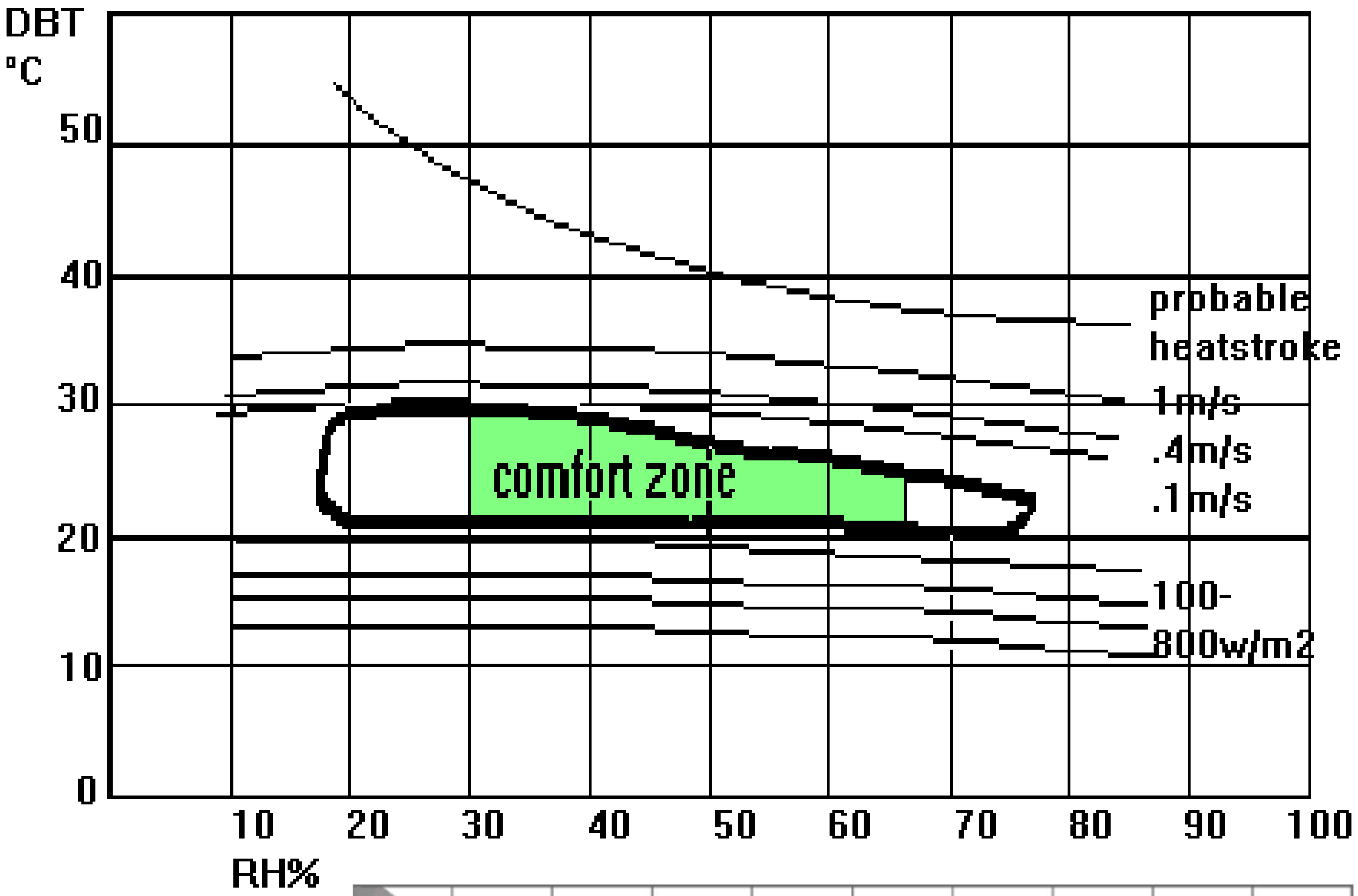
ASHRAE Comfort Zones
(based on 2004 version of ASHRAE Standard 55)

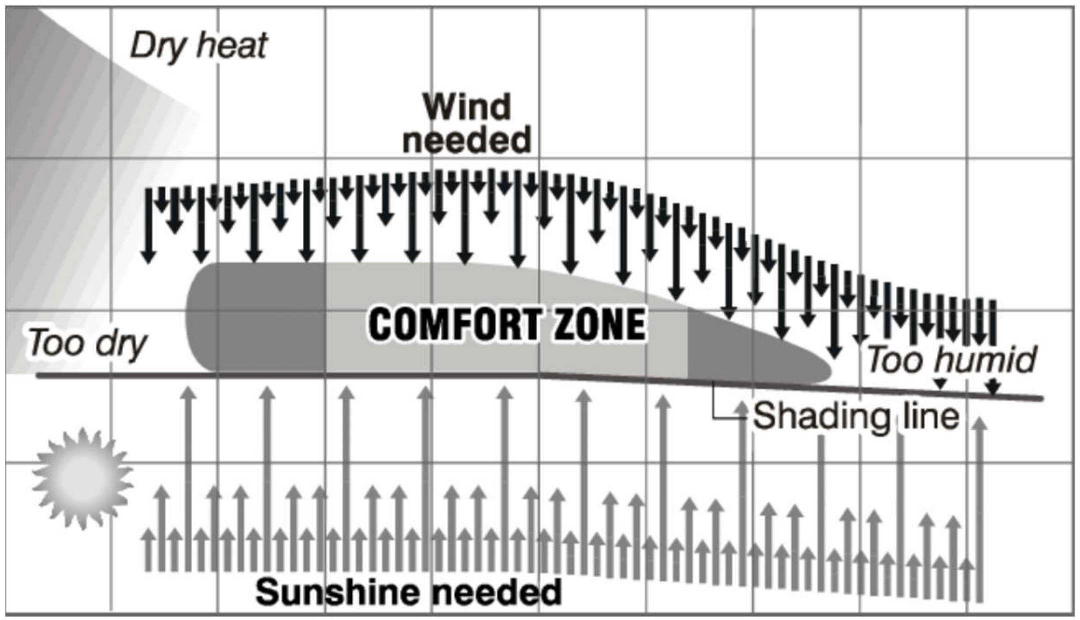


Thermal comfort chart using ASHRAE Standard 55 parameters



(Source: https://www.simscale.com/blog/what-is-ashrae-55-thermal-comfort/)

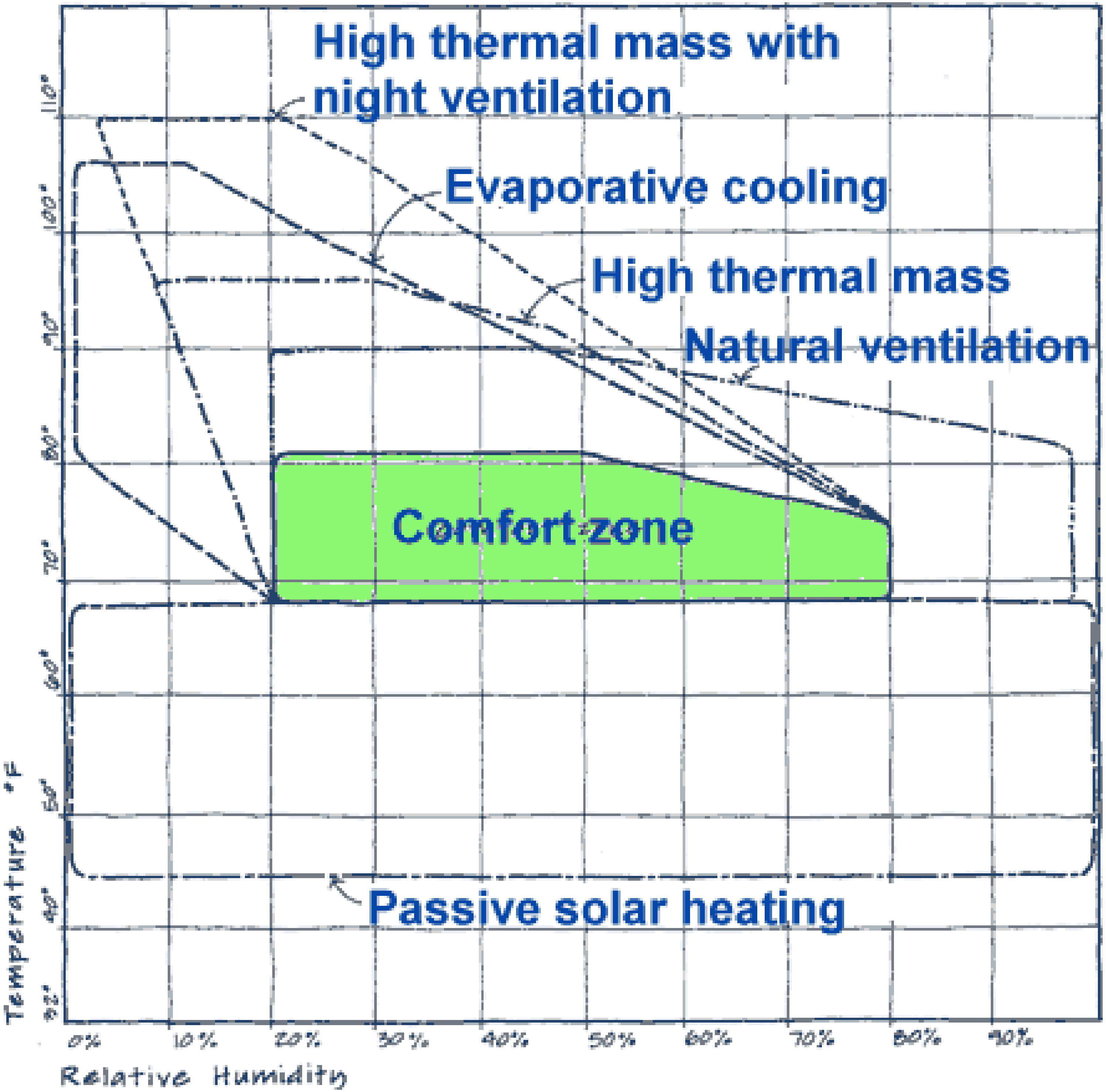




Architecture

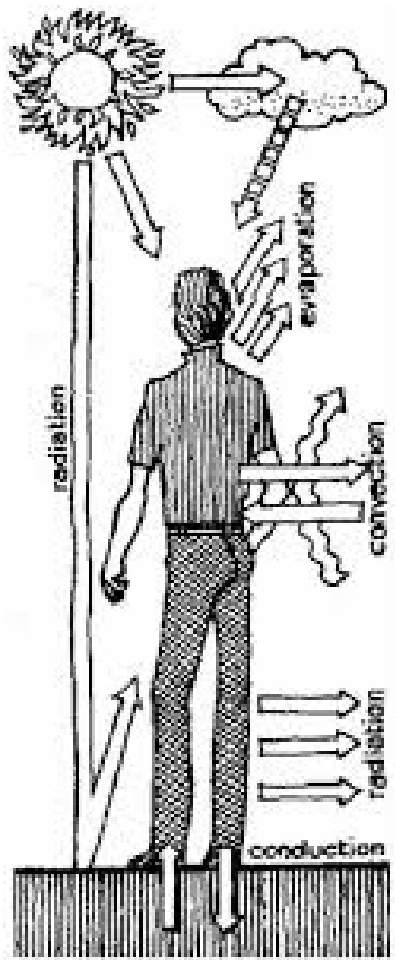
Olgyays bioclimatic chart [developed in the 1950's, was one of the early attempts to specify different zones at different combinations of relative humidity (as abscissa) and dry bulb temperatures (as ordinate)]

Bioclimatic chart with design strategies

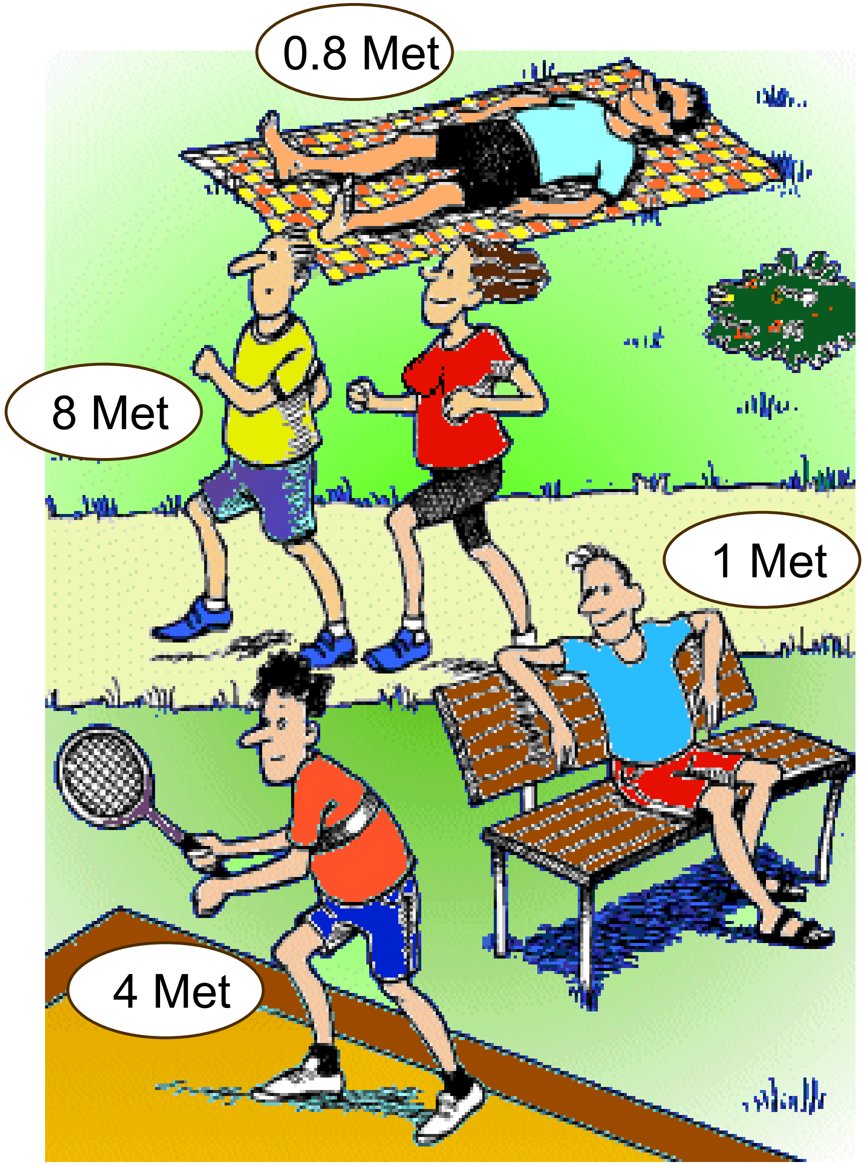


Influencing factors

- Personal factors affecting the comfort level:
  - Age
  - Gender
  - Level of health
  - Clothing worn
  - Type of activity & level of intensity
  - Access to food & drink
  - Acclimatisation
  - Psychological state



Metabolic Rate



Energy released by metabolism depends on muscular activity.

Metabolism is measured in Met (1 Met=58.15 W/m^2 body surface).

Body surface for normal adult is 1.7 m^2.

A sitting person in thermal comfort will have a heat loss of 100 W.

Average activity level for the last hour should be used when evaluating metabolic rate, due to body's heat capacity.

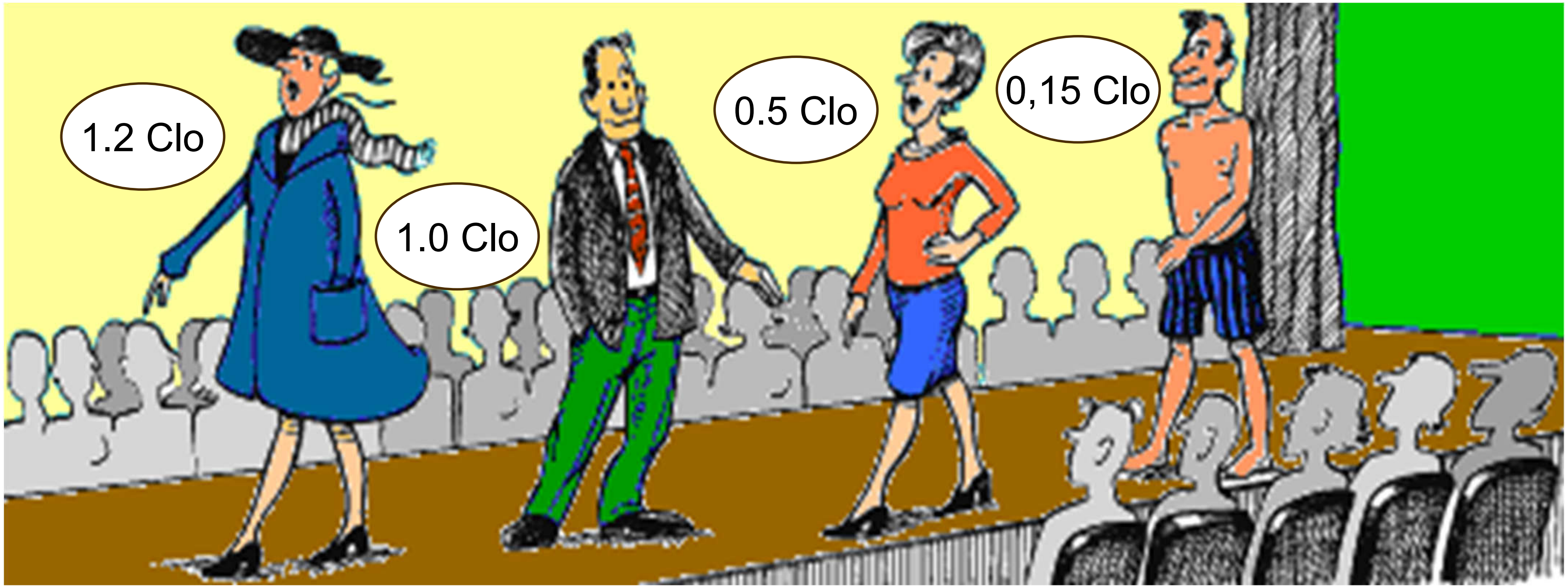
Met Value Table

Activity	Metabolic rates [M]	
Reclining	46 W/m^2	0.8 Met
Seated relaxed	58 W/m^2	1.0 Met
Clock and watch repairer	65 W/m^2	1.1 Met
Standing relaxed	70 W/m^2	1.2 Met
Car driving	80 W/m^2	1.4 Met
Standing, light activity (shopping)	93 W/m^2	1.6 Met
Walking on the level, 2 km/h	110 W/m^2	1.9 Met
Standing, medium activity (domestic work)	116 W/m^2	2.0 Met
Washing dishes standing	145 W/m^2	2.5 Met
Walking on the level, 5 km/h	200 W/m^2	3.4 Met
Building industry	275 W/m^2	4.7 Met
Sports - running at 15 km/h	550 W/m^2	9.5 Met

Met Value Examples

Met Value Examples

Calculation of Insulation in Clothing



- 1 Clo = Insulation value of 0,155 m^2 $^oC/W$

Clo Values Table

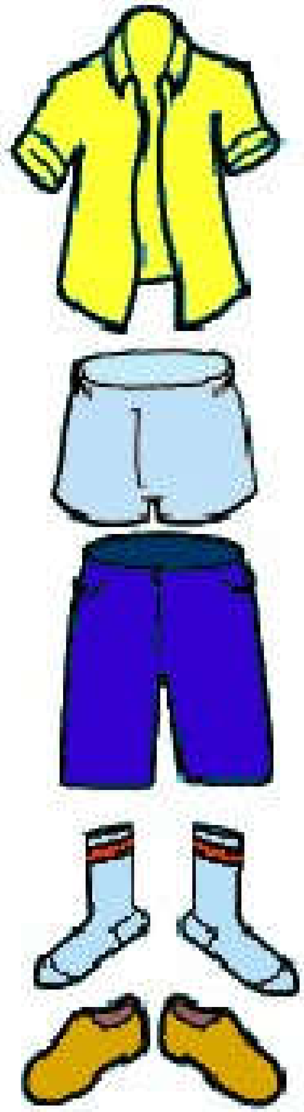
Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Underwear	Pantyhose Briefs Pants long legs	0.02 0.04 0.10	0.003 0.006 0.016
Underwear, shirts	Bra T-shirt Half-slip, nylon	0.01 0.09 0.14	0.002 0.014 0.022
Shirts	Tube top Short sleeves Normal, long sleeves	0.06 0.09 0.25	0.009 0.029 0.039
Trousers	Shorts Normal trousers Overalls	0.06 0.25 0.28	0.009 0.039 0.043
Insulated coveralls	Multi-component filling Fibre-pelt	1.03 1.13	0.160 0.175
Sweaters	Thin sweater Normal sweater Thick sweater	0.20 0.28 0.35	0.031 0.043 0.054

Clo Values Table

Garment description		I_{clu} Clo	I_{clu} m^2 °C/W
Jackets	Vest Jacket	0.13 0.35	0.020 0.054
Coats over-trousers	Coat Parka Overalls	0.60 0.70 0.52	0.093 0.109 0.081
Sundries	Socks Shoes (thin soled) Boots Gloves	0.02 0.02 0.10 0.05	0.003 0.003 0.016 0.008
Skirt, dresses	Light skirt, 15cm above knee Heavy skirt, knee-length Winter dress, long sleeves	0.10 0.25 0.40	0.016 0.039 0.062
Sleepwear	Shorts Long pyjamas Body sleep with feet	0.10 0.50 0.72	0.016 0.078 0.112
Chairs	Wooden or metal Fabric-covered, cushioned Armchair	0.00 0.10 0.20	0.000 0.016 0.032

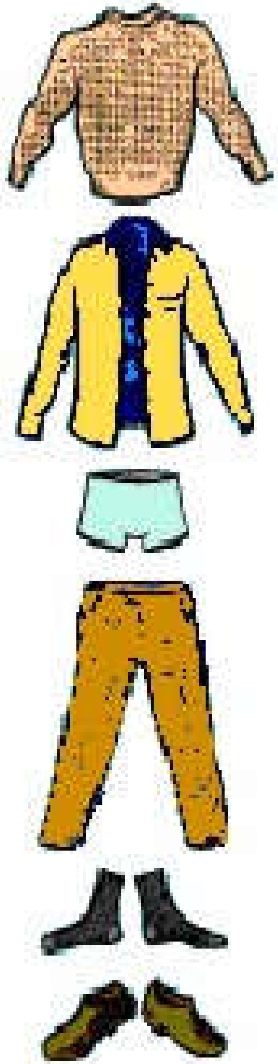
Calculation of Clo-value (Clo)

Insulation for the entire clothing: $I_{cl} = \sum I_{clu}$



0.19
\+
0.04
\+
0.11
\+
0.02
\+
0.02

0.38



0.28
\+
0.25
\+
0.04
\+
0.25
\+
0.05
\+
0.04

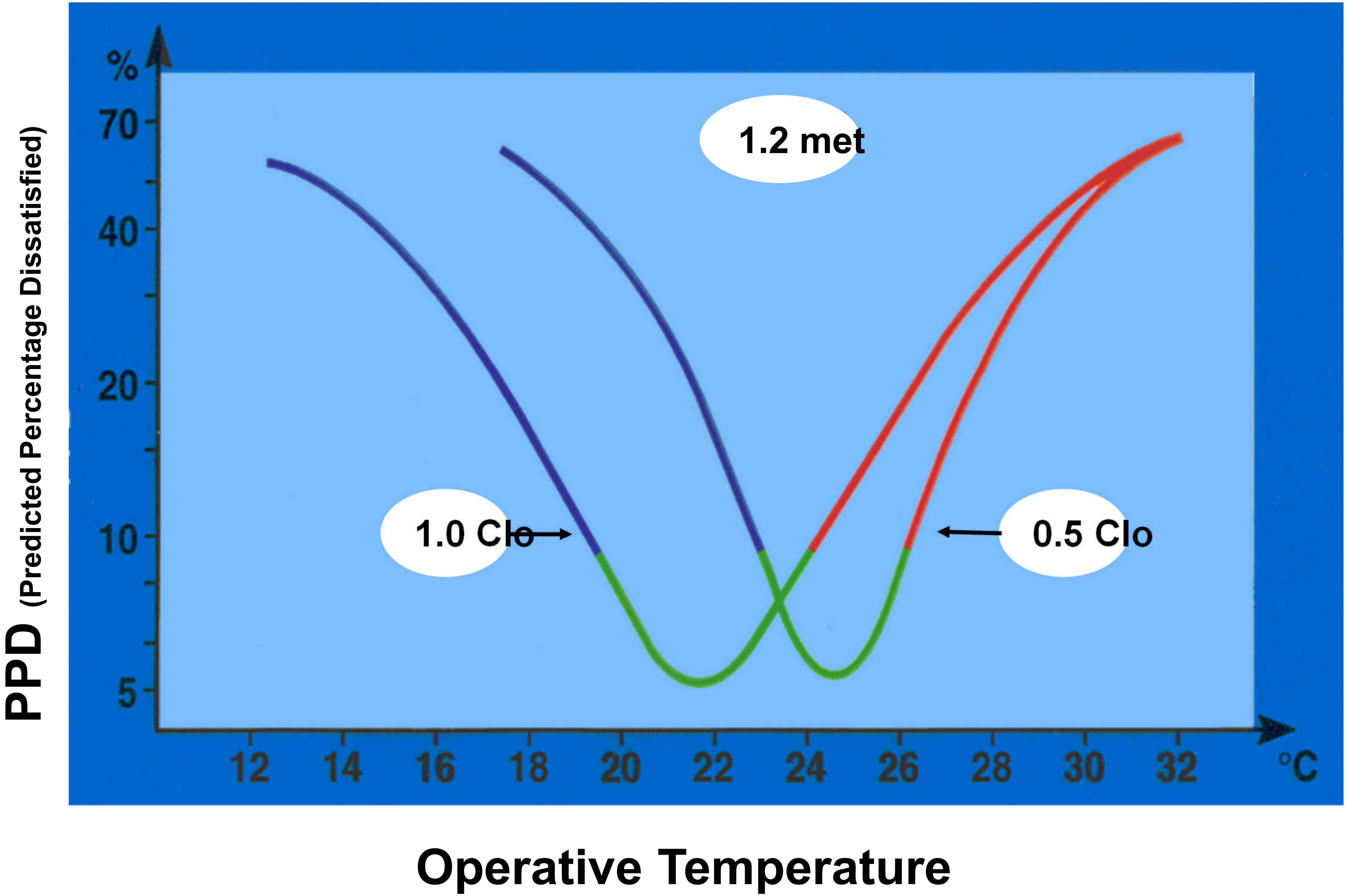
0.91

Things to consider when calculating the CLO value

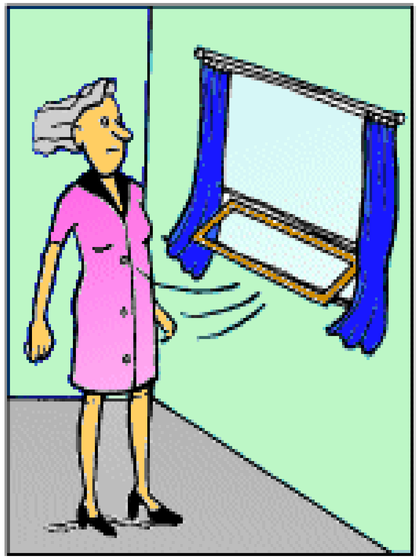
Thermal insulation of chairs

Insulation of wet clothing

Adjustment of Clo Value

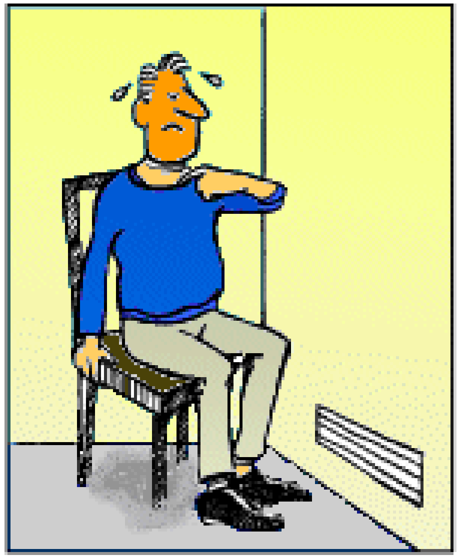


Local Thermal Discomfort

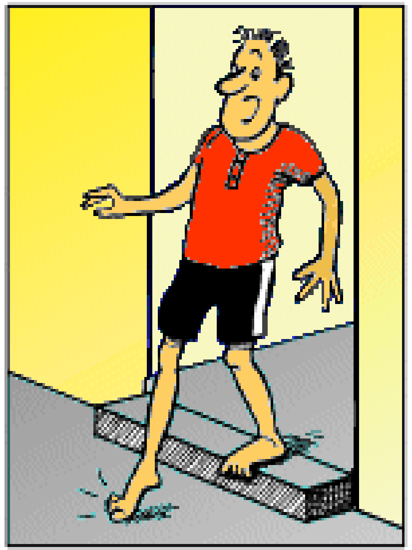


Draught

Radiation Asymmetry

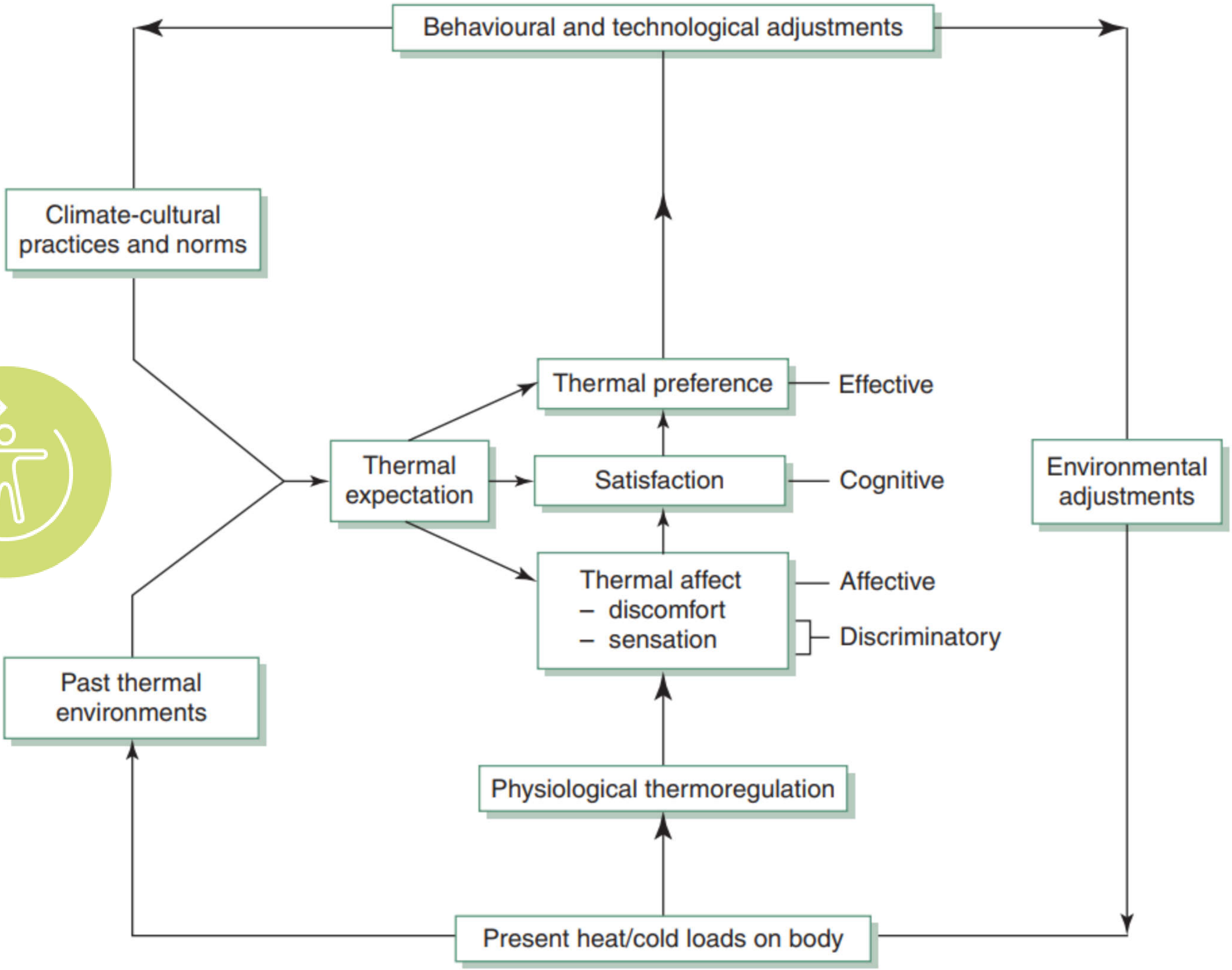


Vertical Air Temperature Differences.



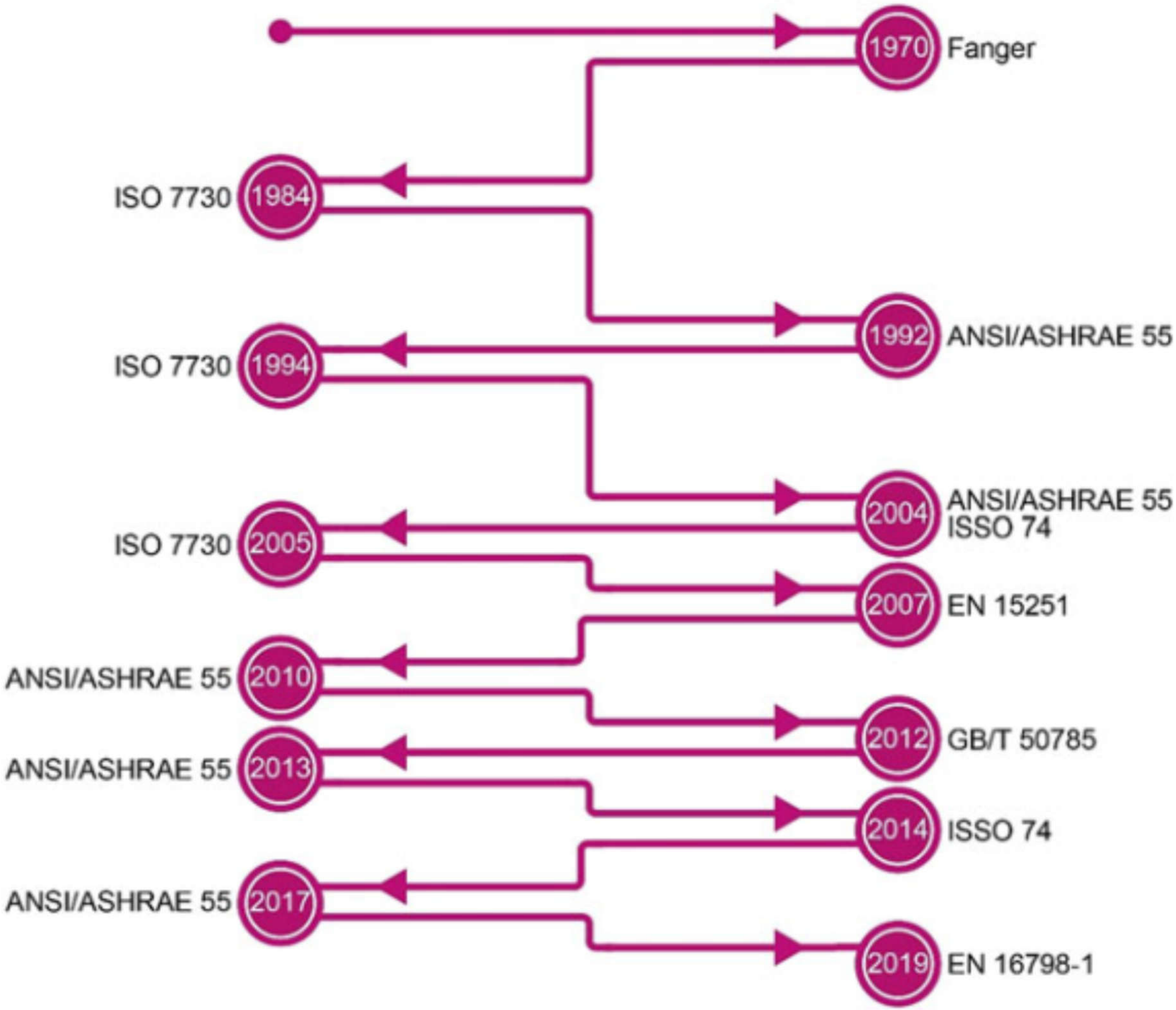
Floor temperature

The psycho-physiological model of thermal perception



(Source: Szokolay S. V., 2008. *Introduction to Architectural Science: the Basis of Sustainable Design*, Second edition.)

Timeline of thermal comfort models



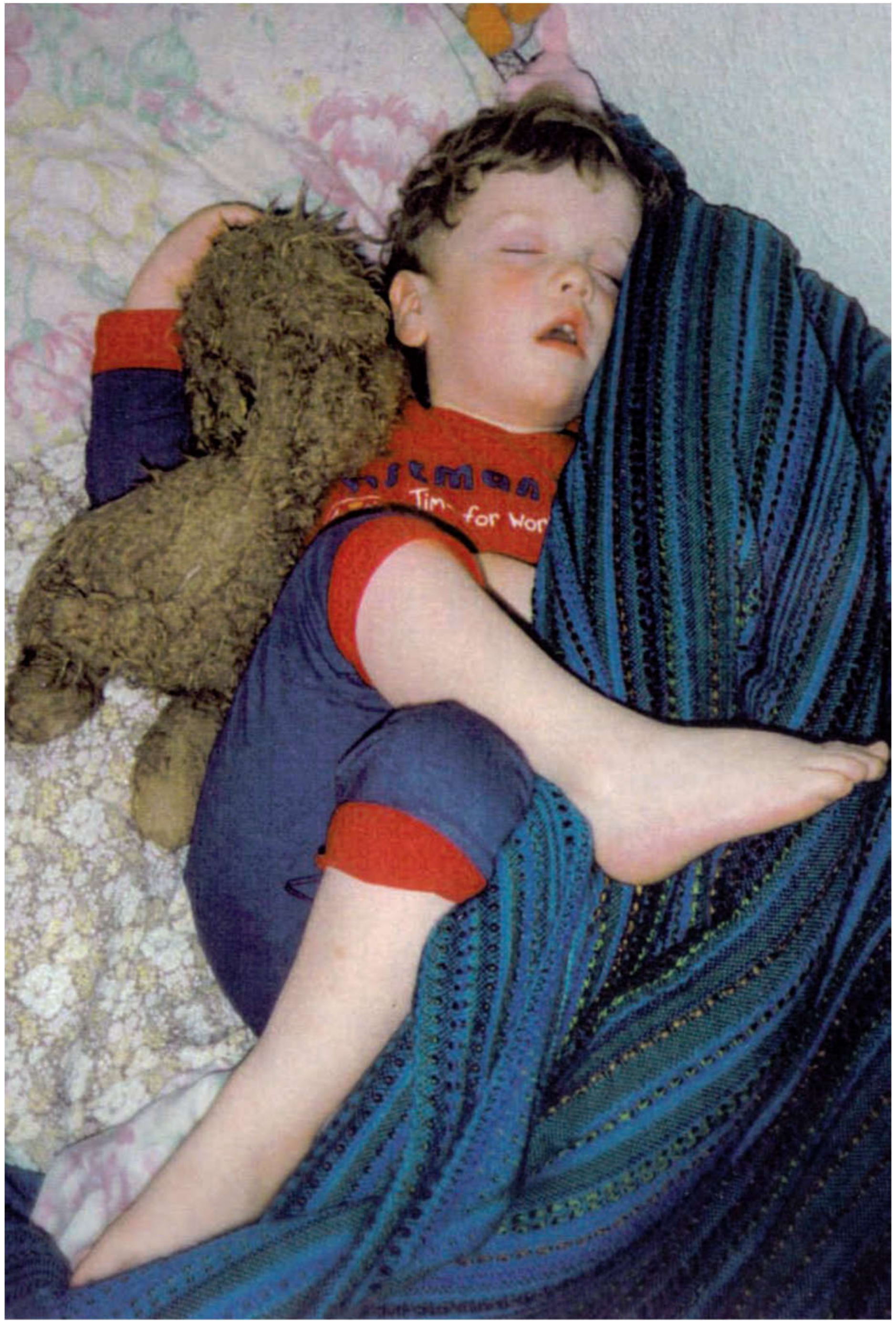
(Source: Bienvenido-Huertas D. & Rubio-Bellido C., 2021. *Adaptive Thermal Comfort of Indoor Environment for Residential Buildings: Efficient Strategy for Saving Energy*, Springer, Singapore.)

Adaptive thermal comfort

- Adaptive thermal comfort
  - People expect different thermal experiences in summer & winter, and modify behaviour accordingly
  - Comfort temperature can vary with changing outdoor conditions (esp. for natural ventilation)
  - Can reduce the average indoor–outdoor temperature difference, and consequently reduces energy requirements
  - Comfort in intermediate & outdoor spaces

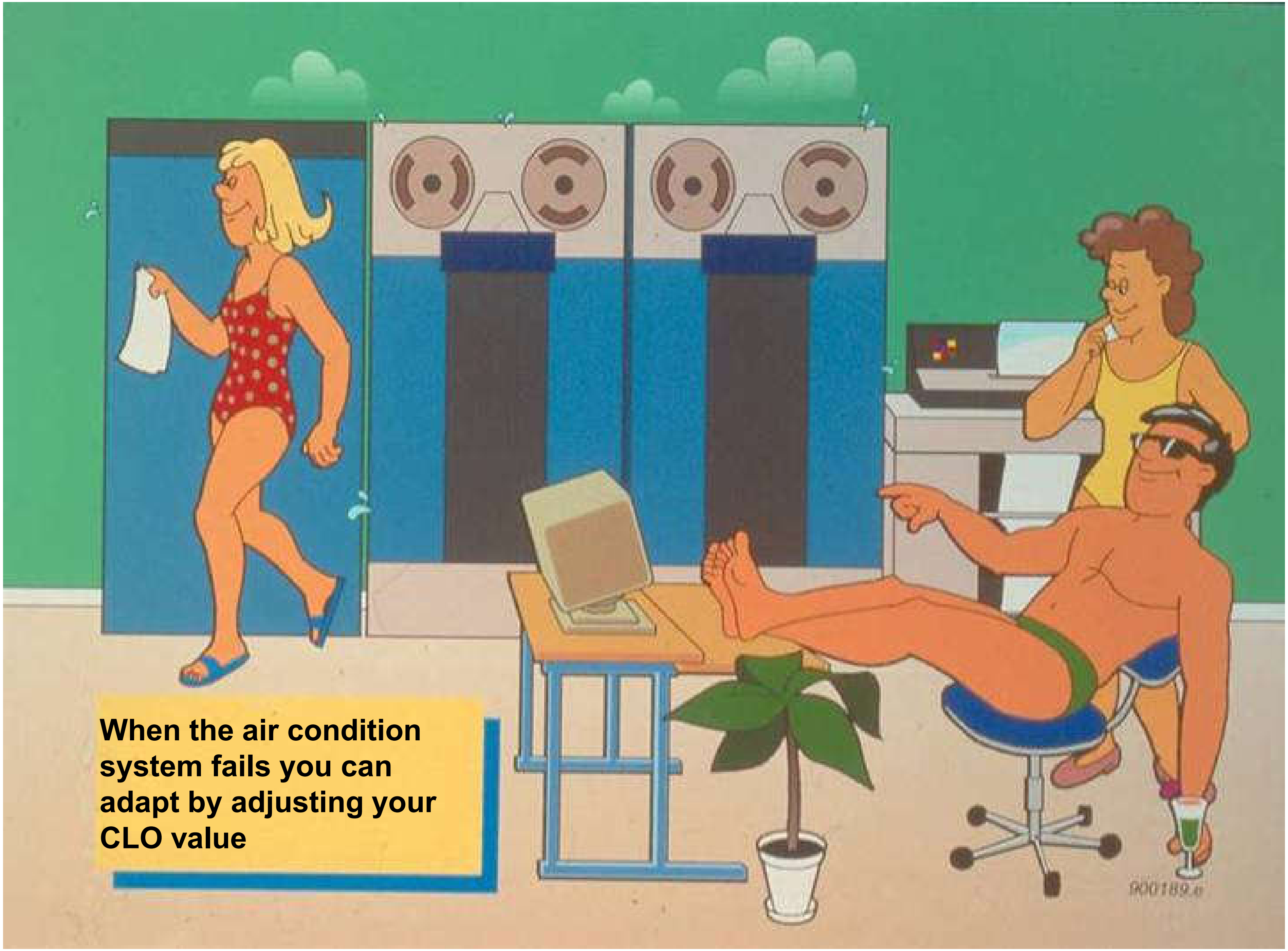
適應性熱舒適度

Adaptation need not be a conscious act, and not only for human

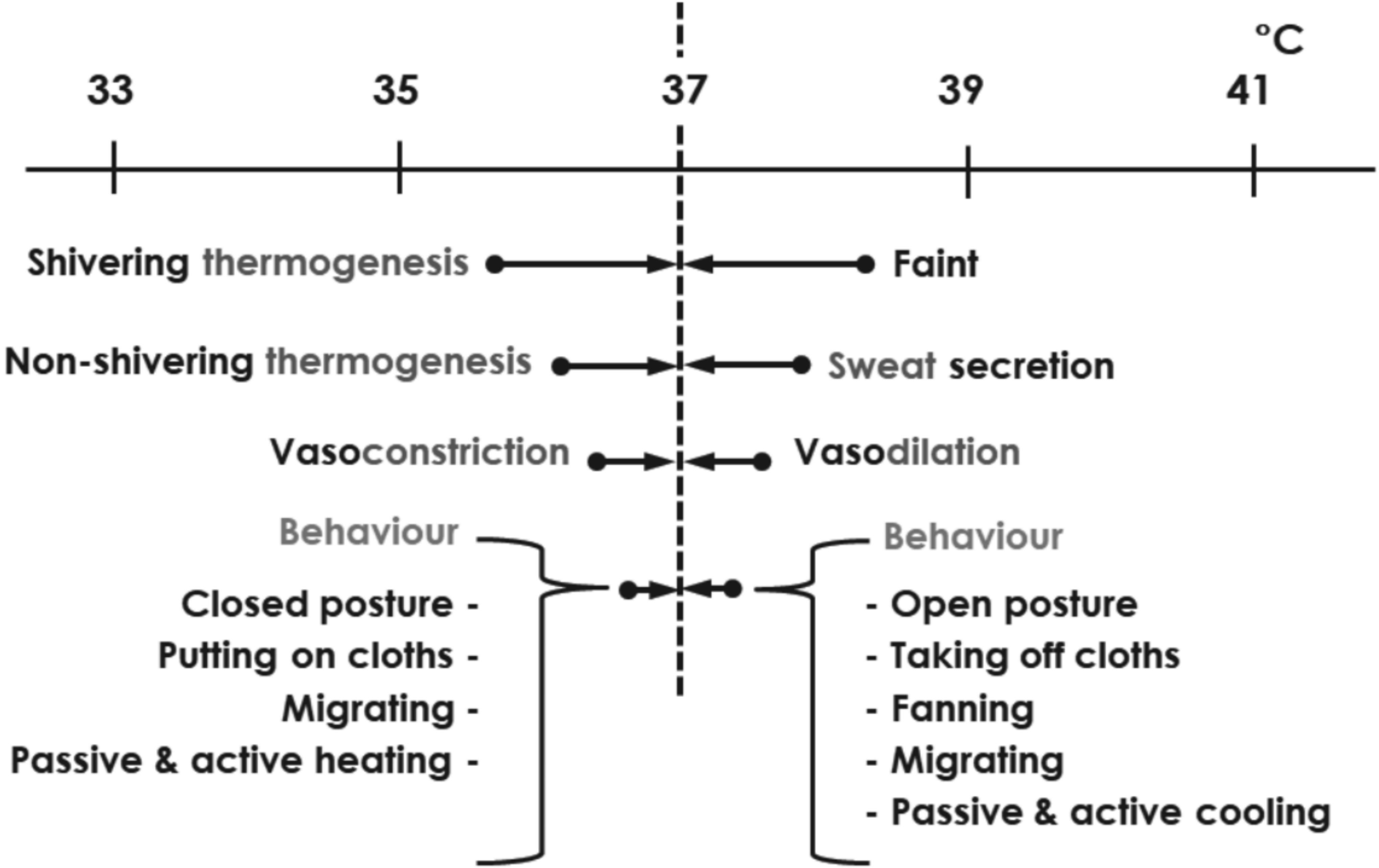


(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Acclimatisation/Adaptation!

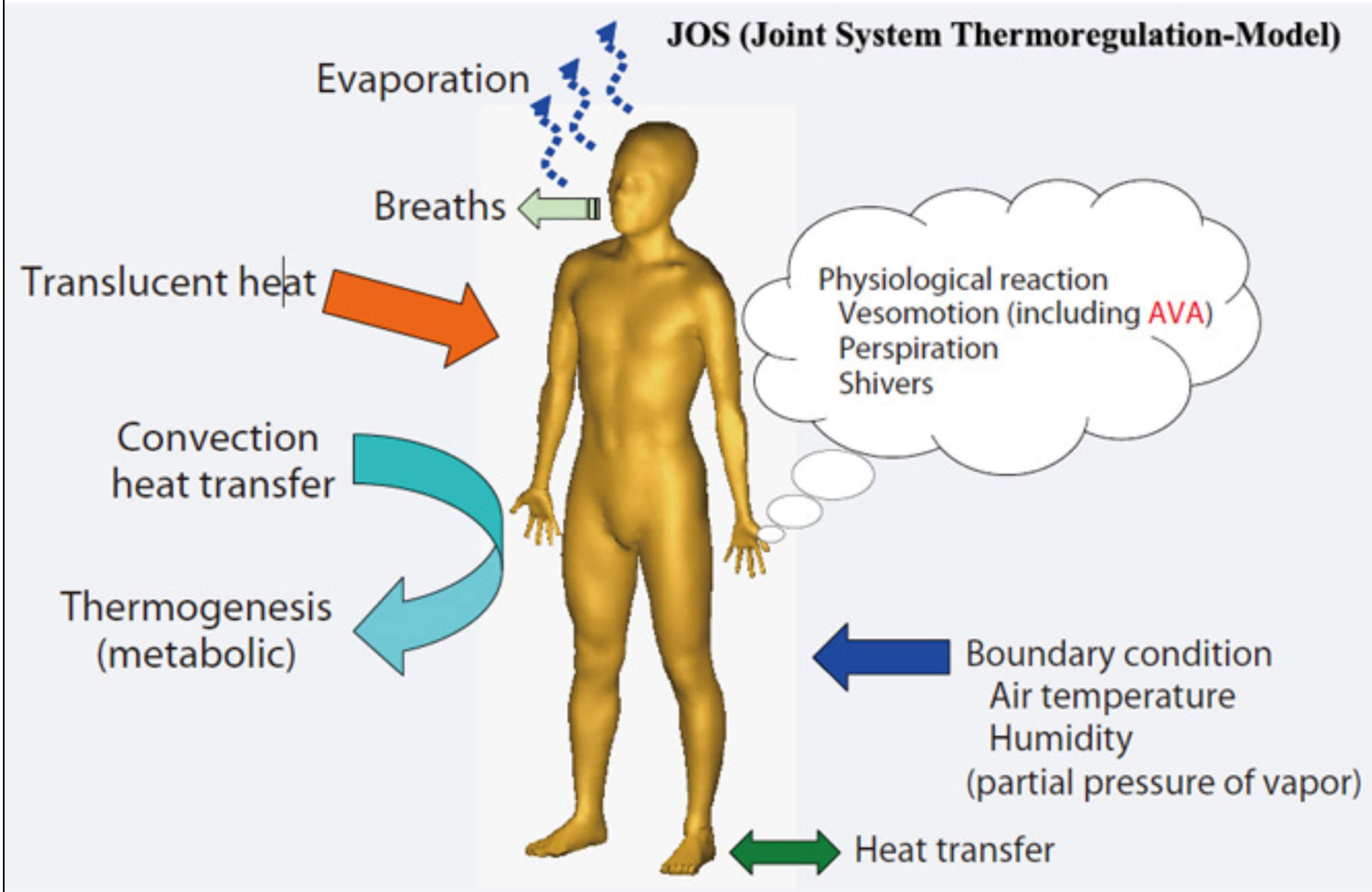


Thermal homeostasis (avoid of discomfort) achieved by a variety of adaptive process



(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

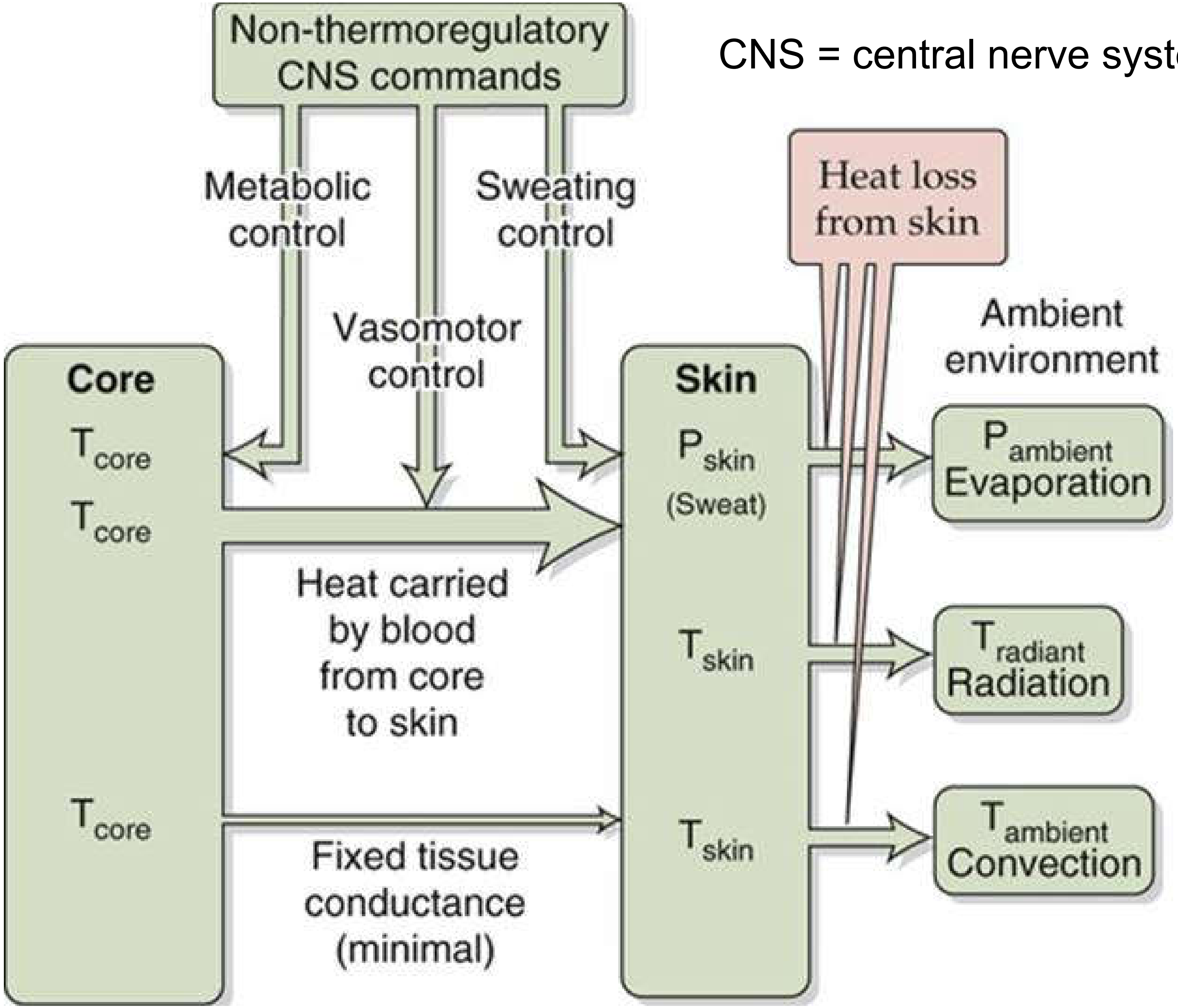
Thermoregulation model of human body



(Source: https://www.designingbuildings.co.uk/wiki/Thermal_comfort_and_wellbeing)

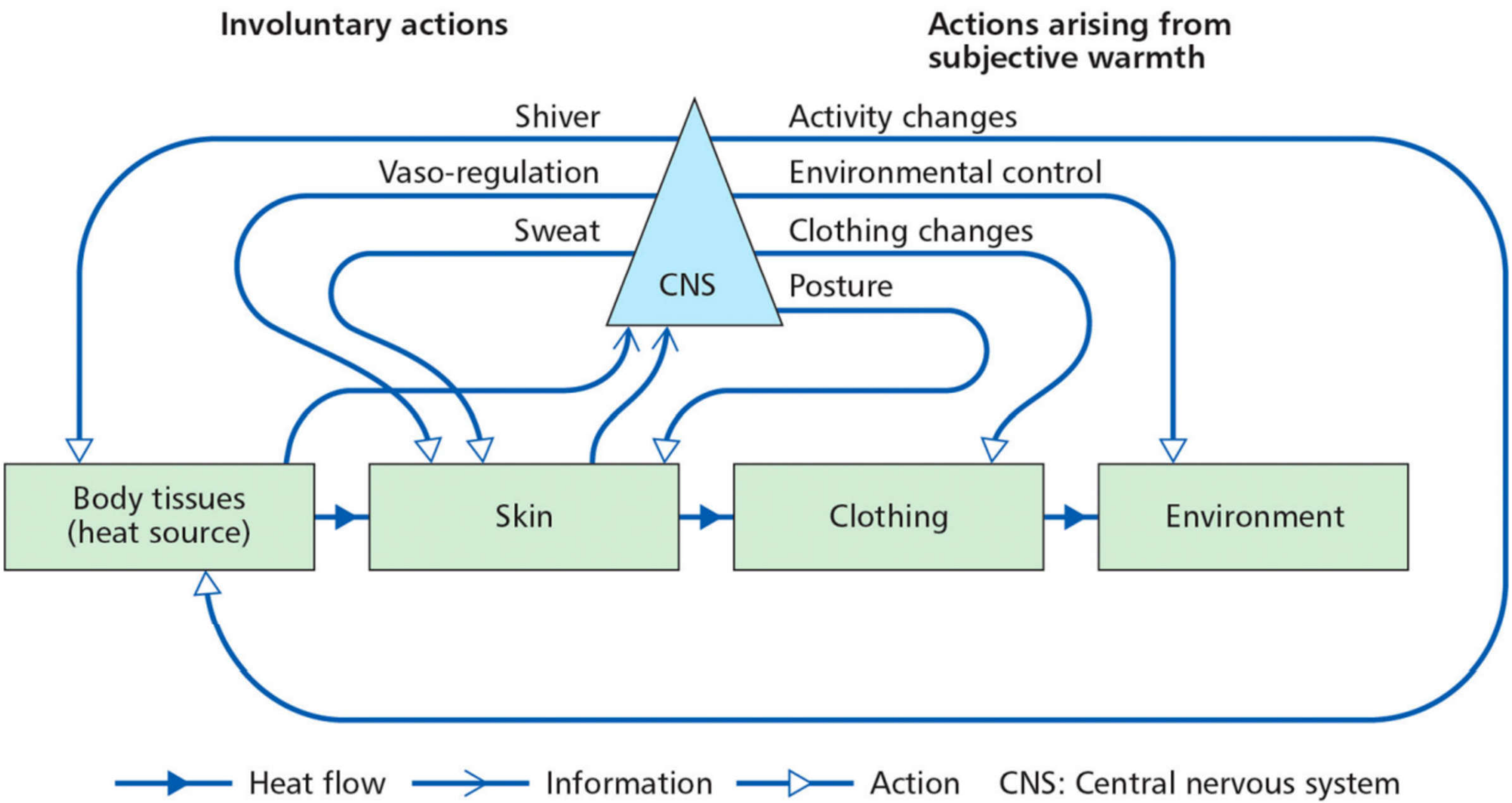
Passive or unregulated heat transfer of human body

CNS = central nerve system



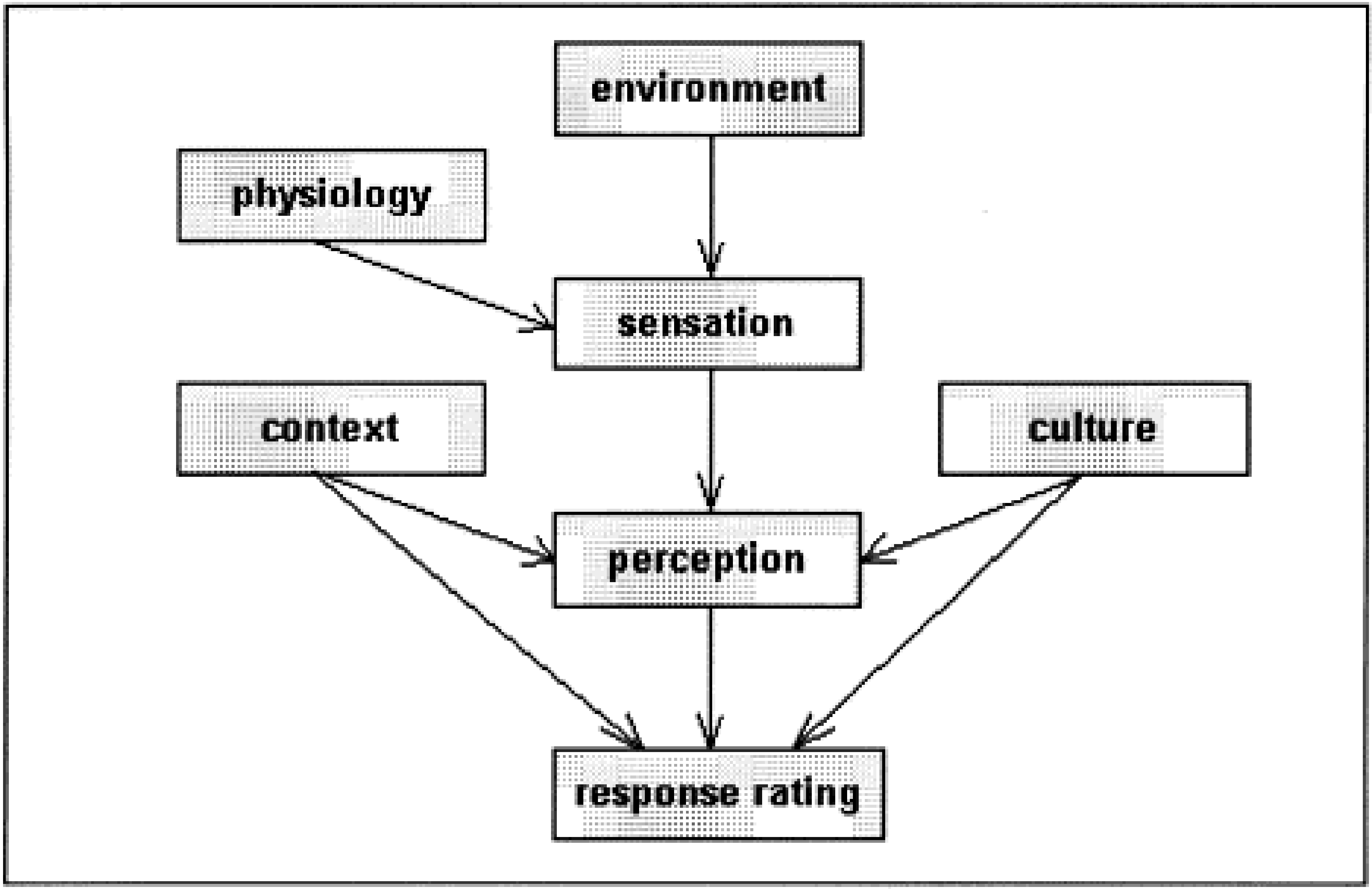
(Source: https://doctorlib.info/physiology/medical/336.html)

Thermal regulatory system



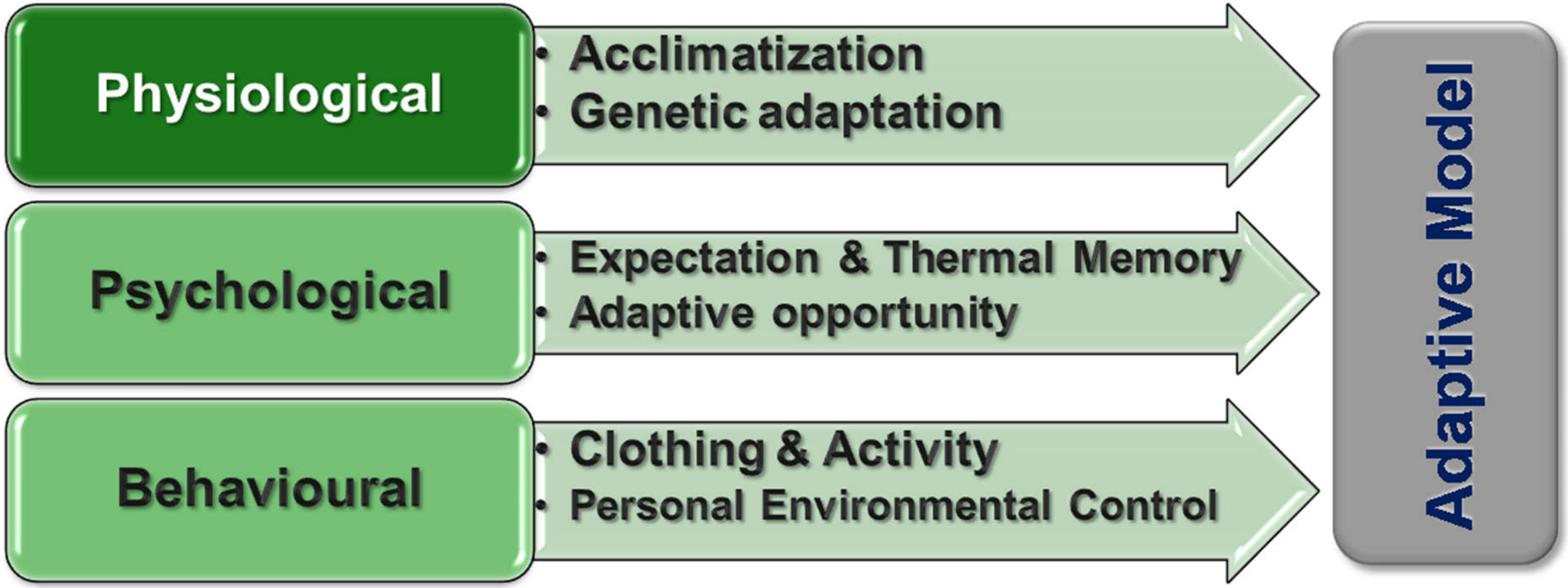
(Source: Nicol J. F. & Roaf S., 2017. Rethinking thermal comfort, *Building Research & Information*, 45 (7) 711-716. https://doi.org/10.1080/09613218.2017.1301698)

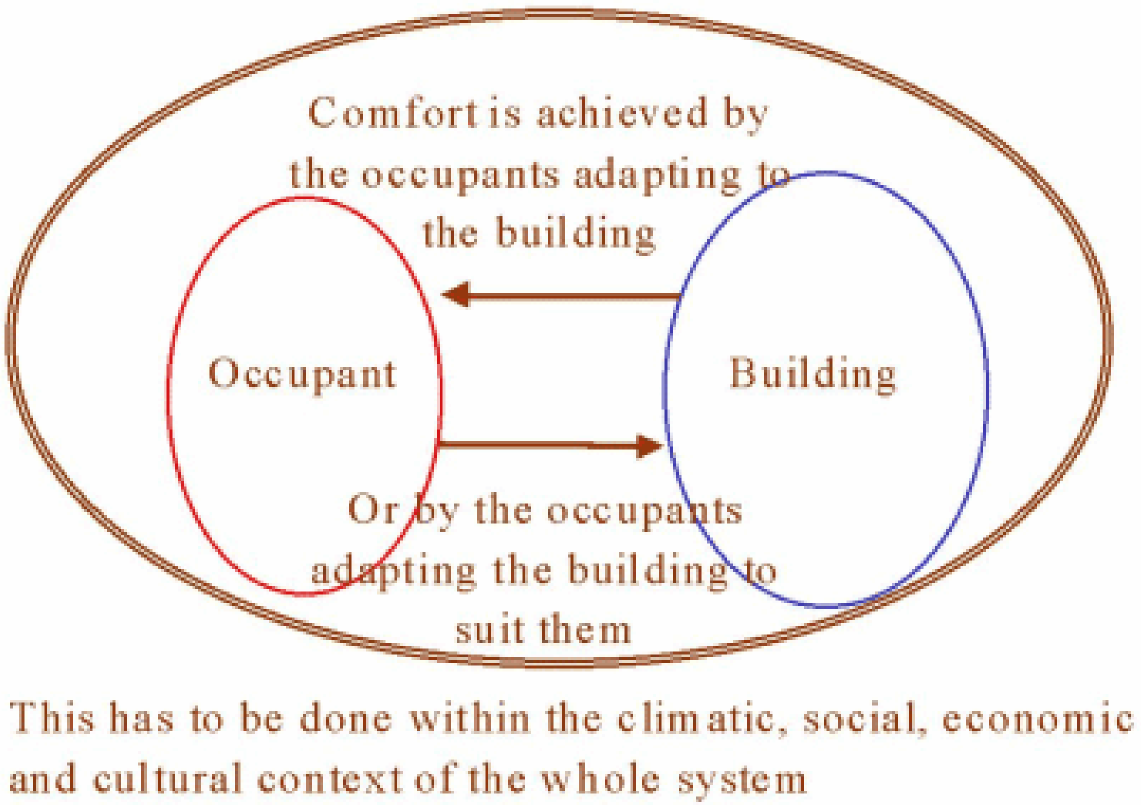
The adaptation model



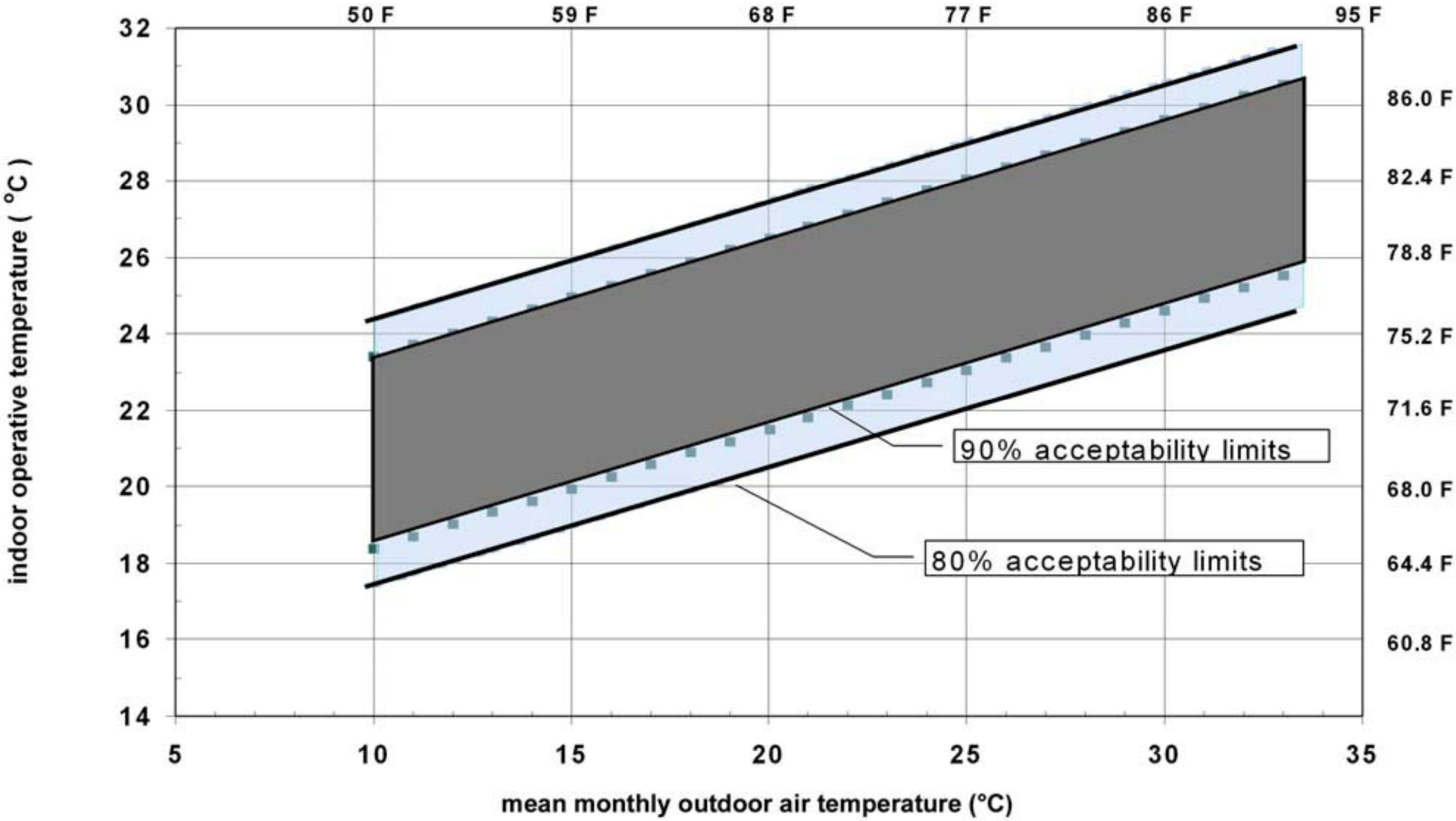
(Source: Butera, F. M., 1998. Principles of thermal comfort, *Renewable and Sustainable Energy Review*, 2 (1-2): 39-66.)

Basic concepts of adaptive thermal comfort



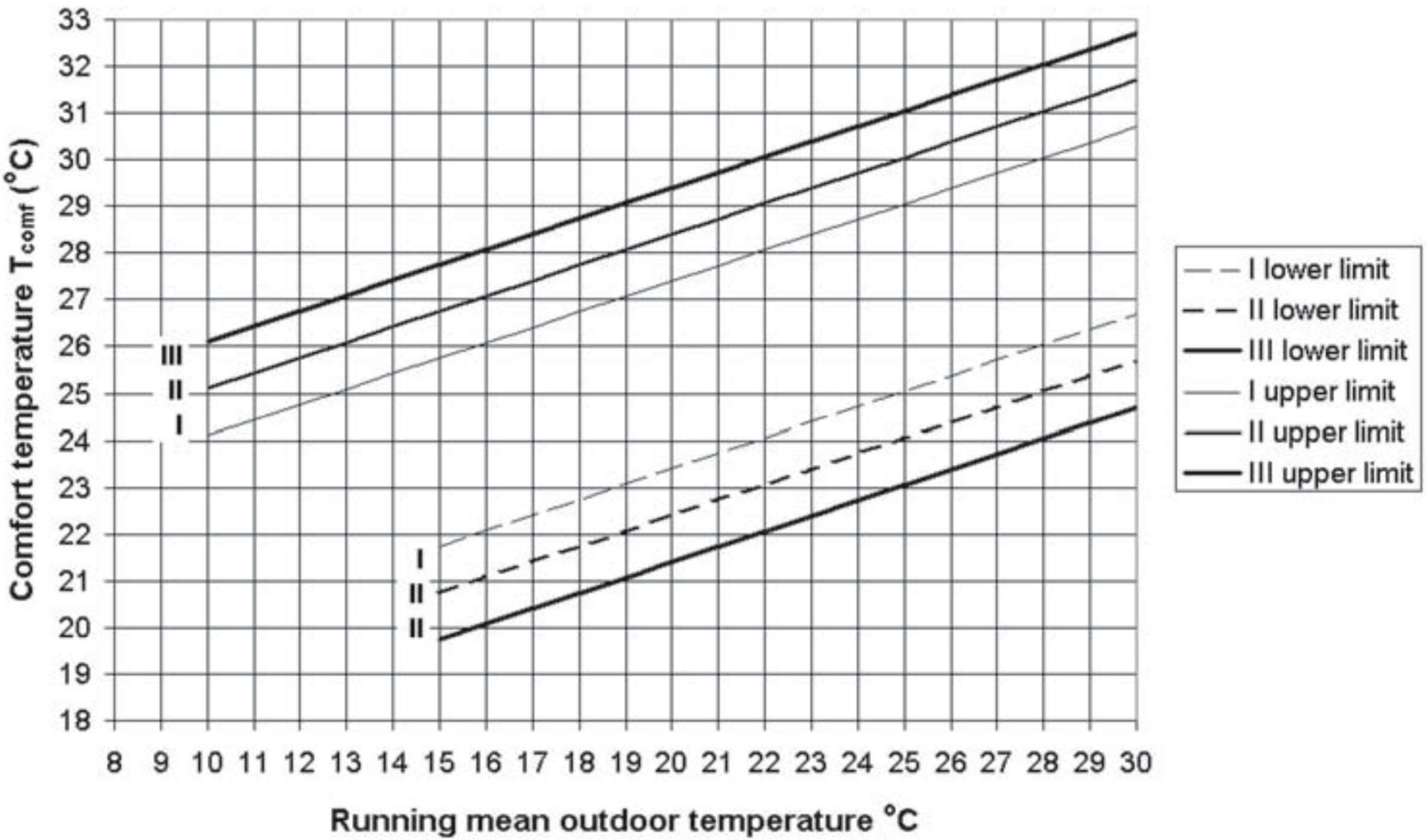


Acceptable operative temperature ranges for naturally conditioned spaces



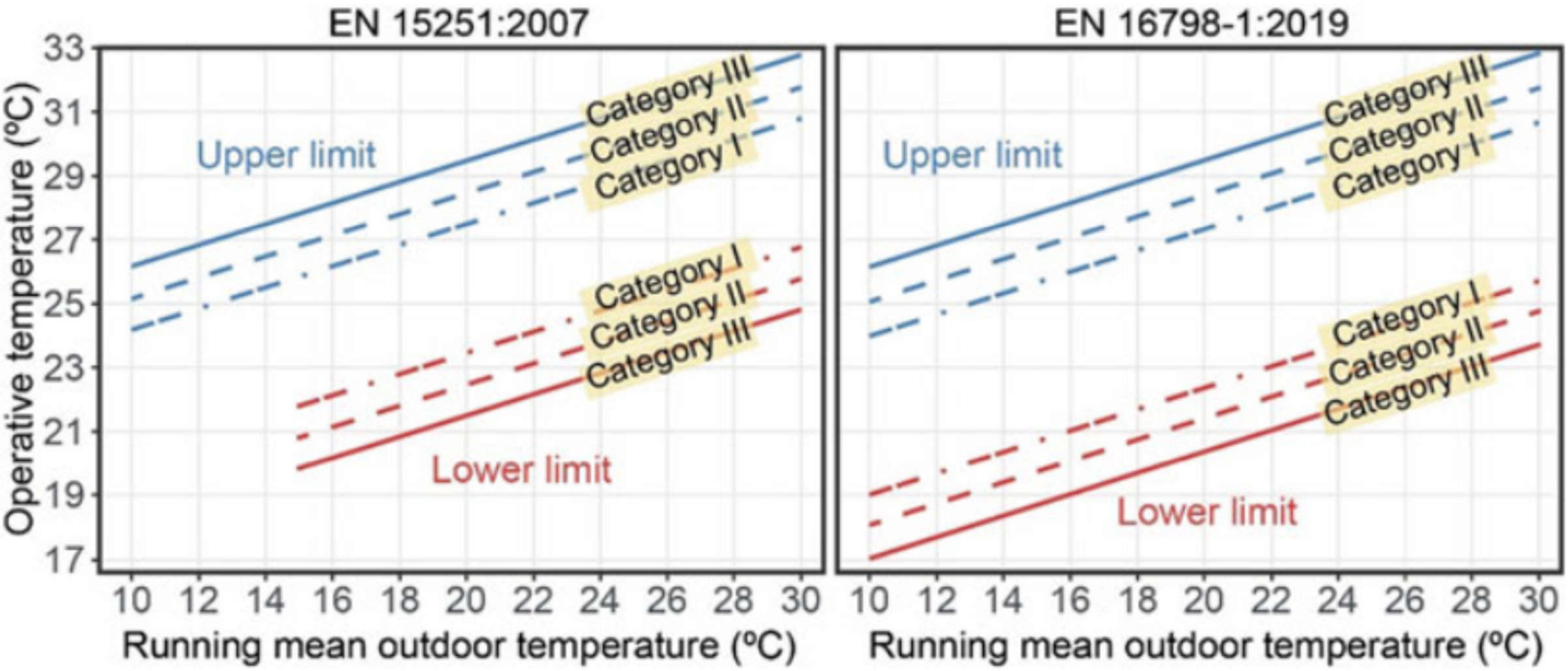
(Source: ASHRAE Standard 55-2010)

Acceptable operative temperature ranges for free-running naturally conditioned spaces (after standard EN15251)



(Source: Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*)

Upper and lower limits of the categories of the adaptive model of EN 15251:2007 and EN 16798-1:2019



(Source: Bienvenido-Huertas D. & Rubio-Bellido C., 2021. *Adaptive Thermal Comfort of Indoor Environment for Residential Buildings: Efficient Strategy for Saving Energy*, Springer, Singapore.)

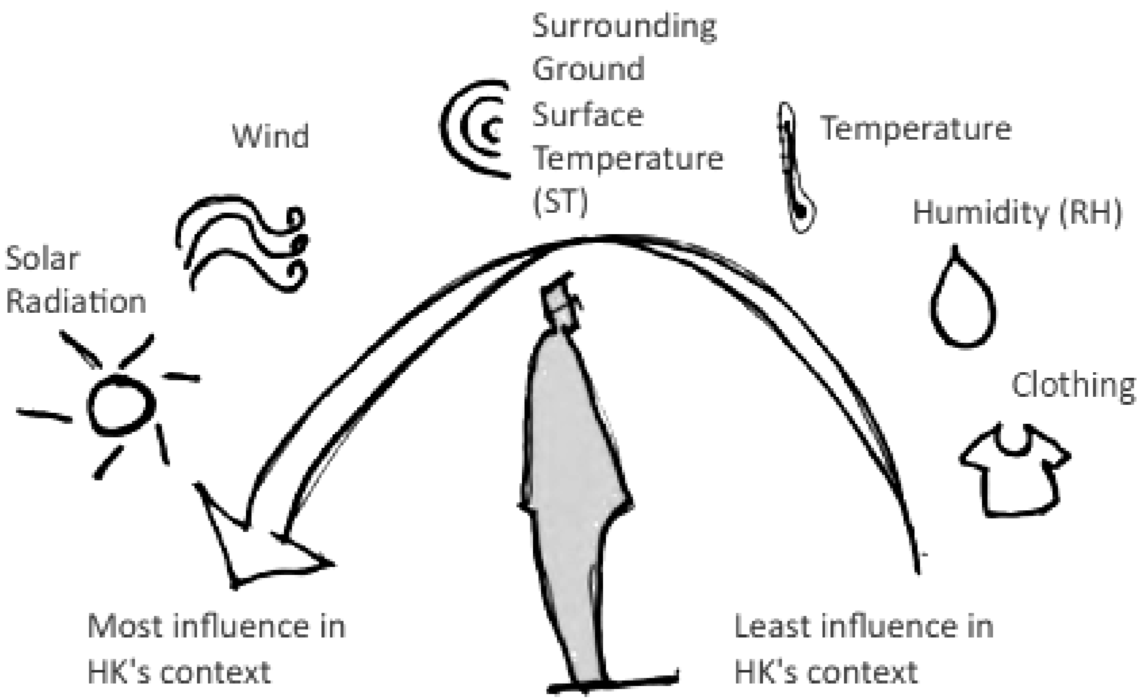
Adaptive thermal comfort

- Outdoor human thermal comfort
  - To evaluate the urban microclimate of an outdoor space
  - A thermally comfortable outdoor space can be achieved through careful architectural & landscape considerations
  - Two methods to measure outdoor thermal comfort:
    - Thermal Sensation Index (TSI)
    - Physiological Equivalent Temperature (PET)

Thermal Sensation Index (TSI)

$$TSI = 1.7 + 0.1118Ta + 0.0019SR - 0.322WS - 0.0073RH + 0.0054ST$$

Where,
Ta = air temperature (˚C)
SR = horizontal solar radiation (W/m^2)
WS = wind speed (m/s)
RH = relatively humidity (%)
ST = surrounding ground surface temperature (˚C), assumed to be Ta+3˚C for TSI calculation



TSI	Thermal sensation	
1	Cold	Too cold
2	Slightly cold	
3	Acceptably cool	Thermally acceptable range
4	Neutral	
5	Acceptably warm	
6	Slight hot	Too hot
7	Hot	

(Source: HKGBC Guidebook on Urban Microclimate Study https://www.hkgbc.org.hk/eng/engagement/file/UMC_Guidebook_amended_reduced.pdf)

Physiological Equivalent Temperature (PET)

PET = 1.2Ta – 2.2v + 0.52(Tmrt – Ta)

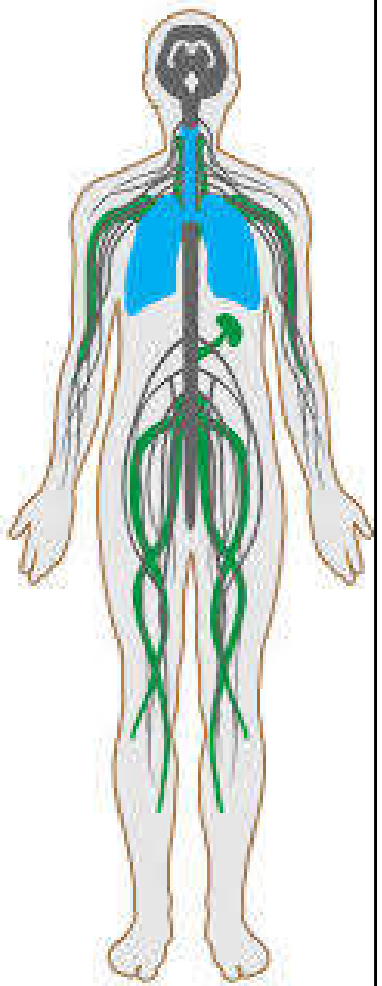
Where,
Ta = air temperature (°C)
v = wind speed (m/s)
Tmrt = mean radiant temperature (°C), assumed 0-3°C under shade, 10°C under cloudy sky and 40-60°C under direct sun
* In Hong Kong, the classification for sub-tropical region is used, where a PET between 22°C and 34°C is considered comfortable.

Thermal Perception	TPC for sub-tropical region	Range of thermal comfort
Very cold	<14	Too cold
Cold	≥14 to <18	
Cool	≥18 to <22	
Slightly cool	≥22 to <26	Range of thermal comfort
Neutral	≥26 to <30	
Slightly warm	≥30 to <34	
Warm	≥34 to <38	Too hot
Hot	≥38 to <42	
Very hot	≥42	

(Source: HKGBC Guidebook on Urban Microclimate Study https://www.hkgbc.org.hk/eng/engagement/file/UMC_Guidebook_amended_reduced.pdf)

Human factors

- Impacts of thermal comfort, stresses & strain on human body
  - Age, diet, health, work efficiency & acclimatization
- Comfort & the risk for human health
  - Indoor environmental quality (IEQ) factors
- Effects of the environment on human performance



Impacts of thermal comfort, stresses & strain on human body

The desire of women for slightly warmer conditions in both winter and summer is due to differences in clothing.

Age: The elderly are particularly sensitive to extremes in temperature.

Diet: Very high and very low calorie diets appear to slightly reduce heat tolerance.

Health: Any infection will reduce the ability to resist thermal stress.

Work Efficiency: The amount of muscular activity is directly related to individual heat tolerance. This is the most important factor contributing to individual differences.

Acclimatization: Appears to be due to behavioral adjustments (e.g., greater work efficiency) and not due to physiological changes.

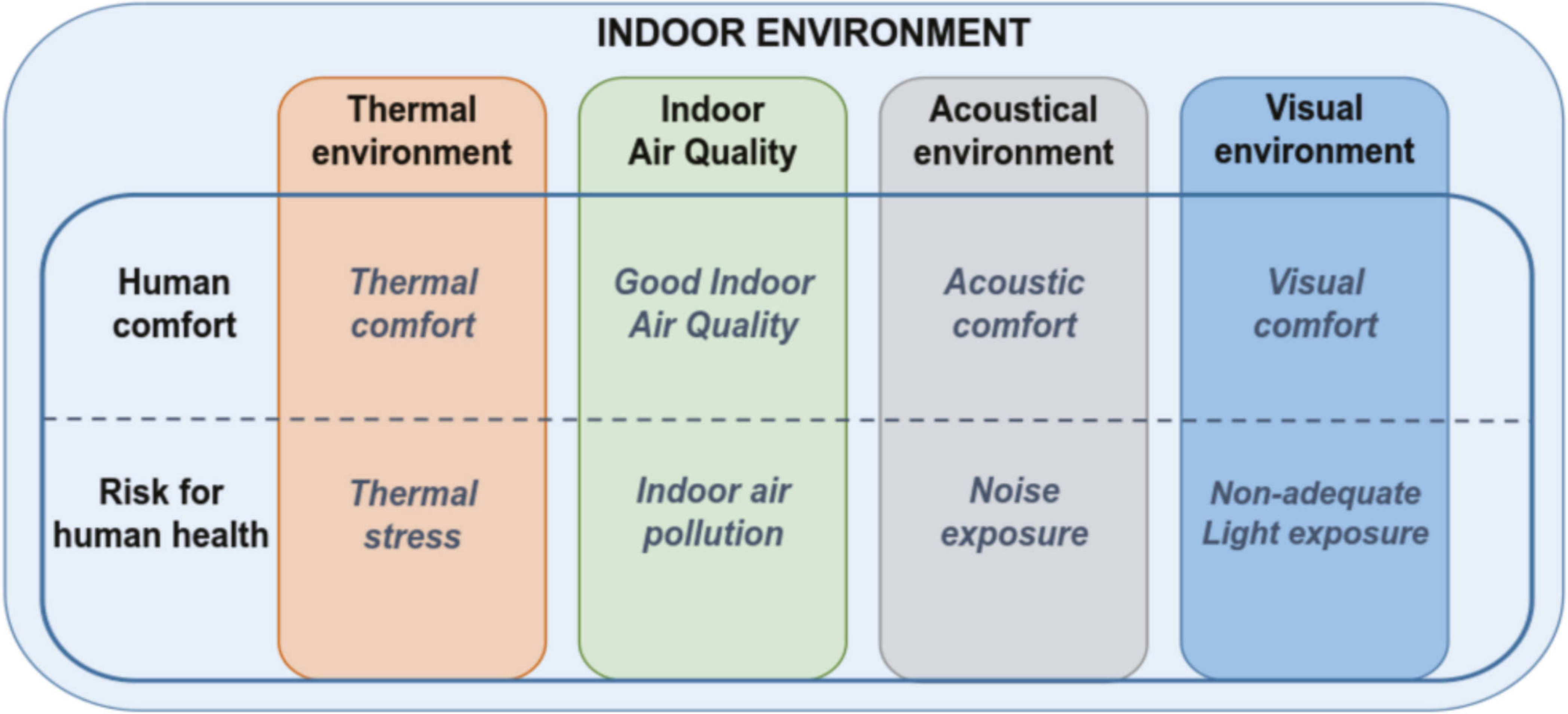
According to Hooke's law, strain (e.g., physiological reactions) is proportional to stress (e.g., temperature).

- Stresses are usually cumulative (e.g., temperature, noise, glare, distractions) so that even low levels of a number of environmental stresses may cause discomfort, even though any one of these factors by itself may be quite tolerable.

- Strain is the physiological reaction of the human body to any imposed stress (e.g., shivering, perspiration, pulse rate, blood pressure, headache).

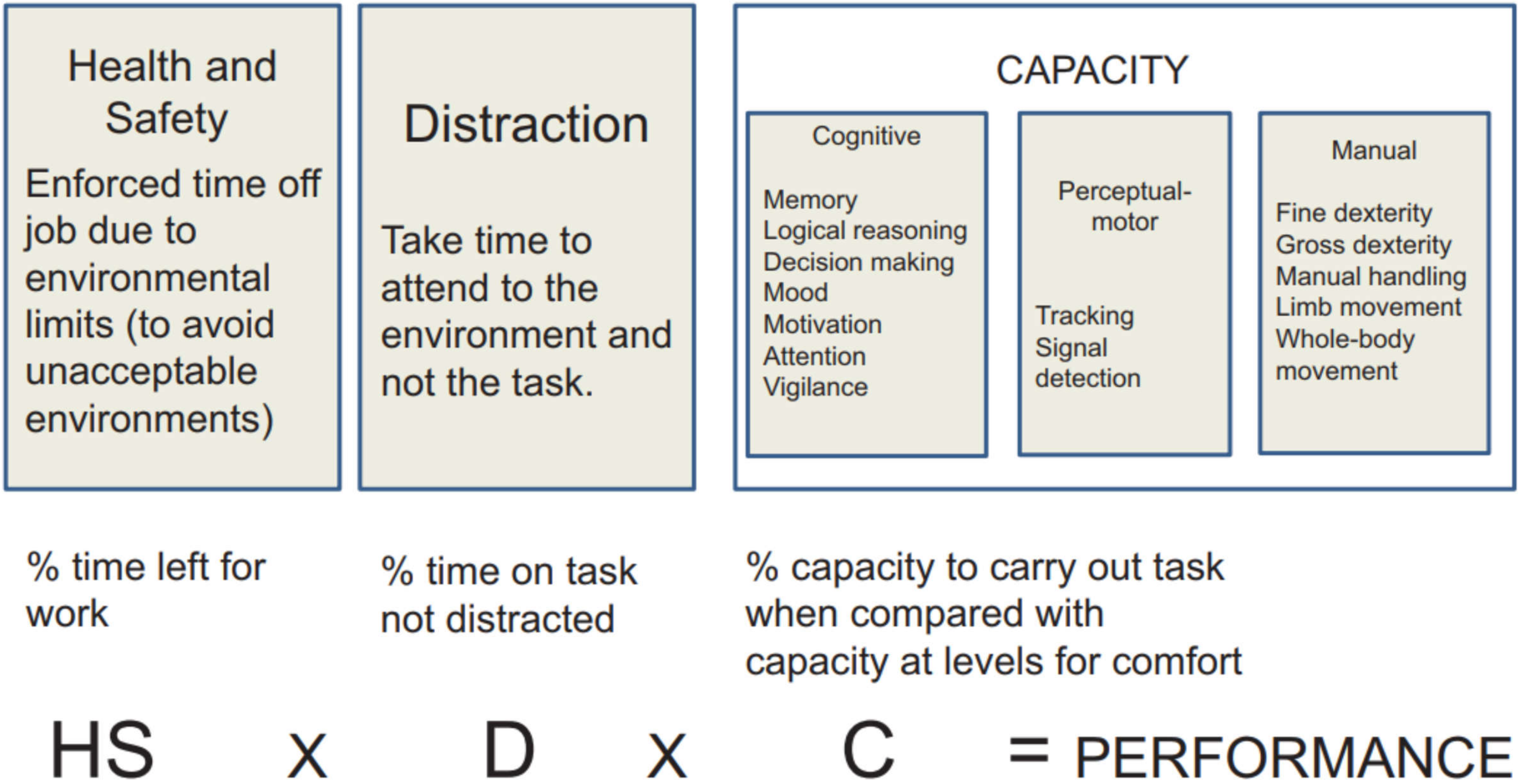
(Source: Pohl J., 2011. *Building Science: Concepts and Application*, 1st ed., Wiley-Blackwell.)

Main aspects related to the comfort and to the risk for human health for the four indoor environmental quality (IEQ) factors



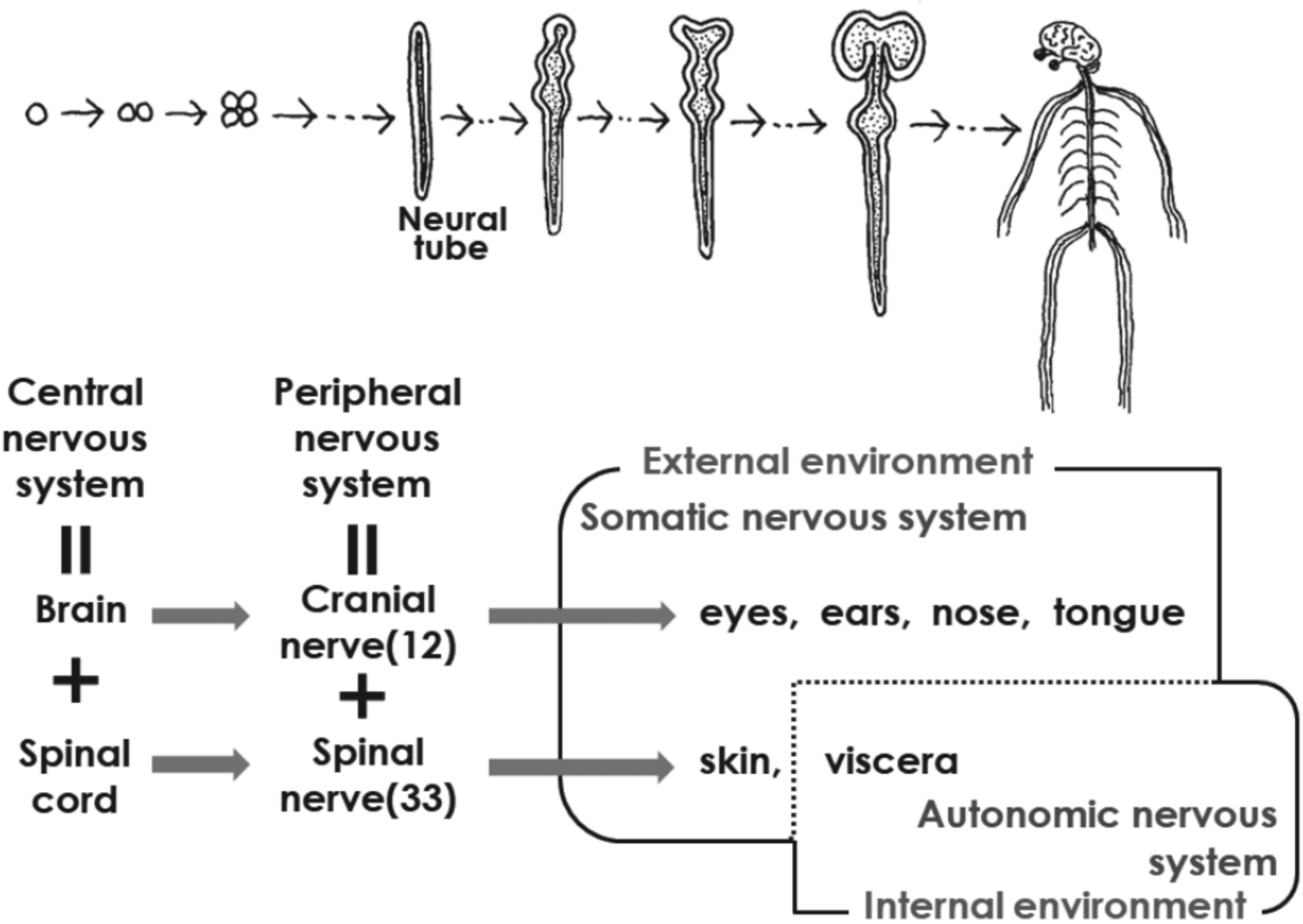
(Source: D'Ambrosio F. R. & Palella B. I. (eds.), 2020. *Indoor Thermal Comfort*, Multidisciplinary Digital Publishing Institute (MDPI), Basel, Switzerland. https://doi.org/10.3390/books978-3-03943-528-9)

HSDC model for predicting the effects of the environment on human performance



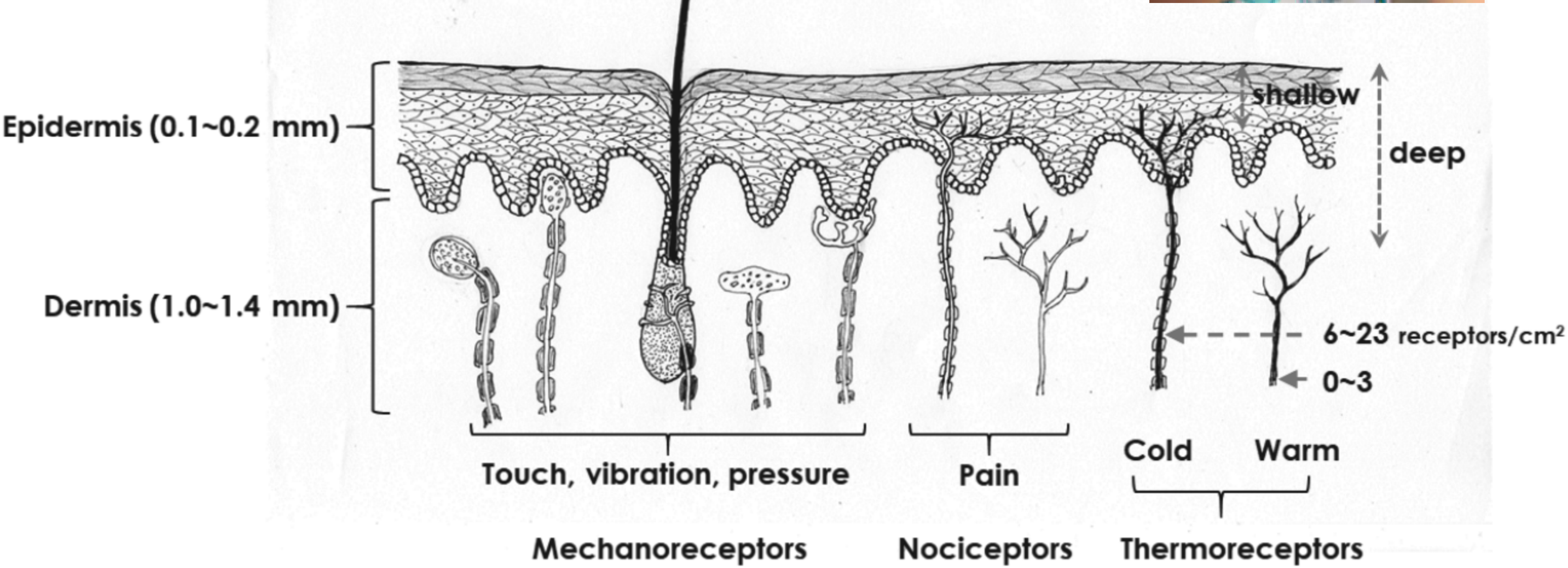
(Source: Parsons K. C., 2020. *Human Thermal Comfort*, CRC Press/Taylor & Francis Group, Boca Raton, FL.)

Human nervous system and its relation to environment



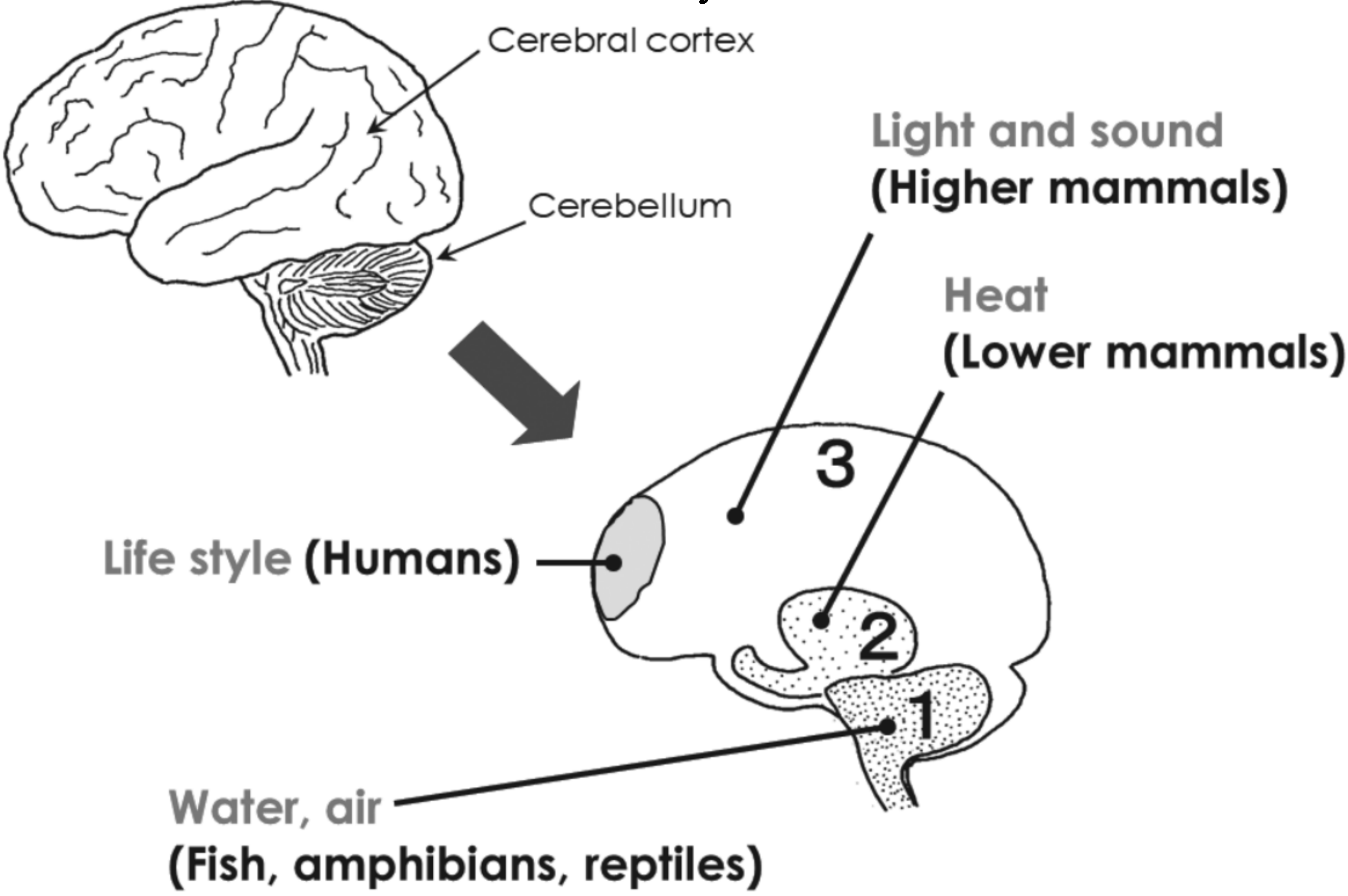
(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

Sensory portals near the skin surface



(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

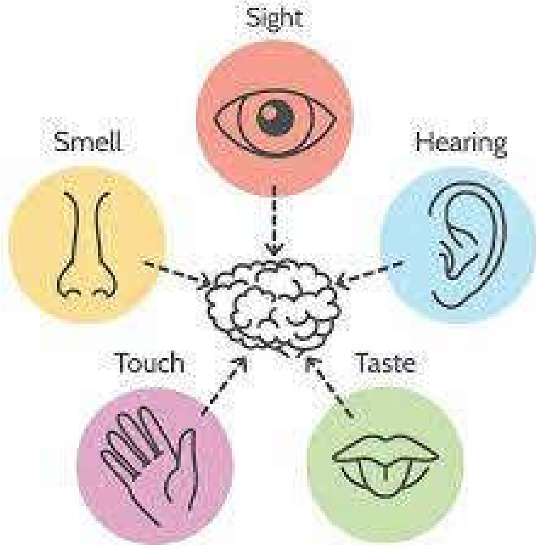
Brain as nested structure and its relation to environmental factors & lifestyle



(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

Nerves, sensory portals and information

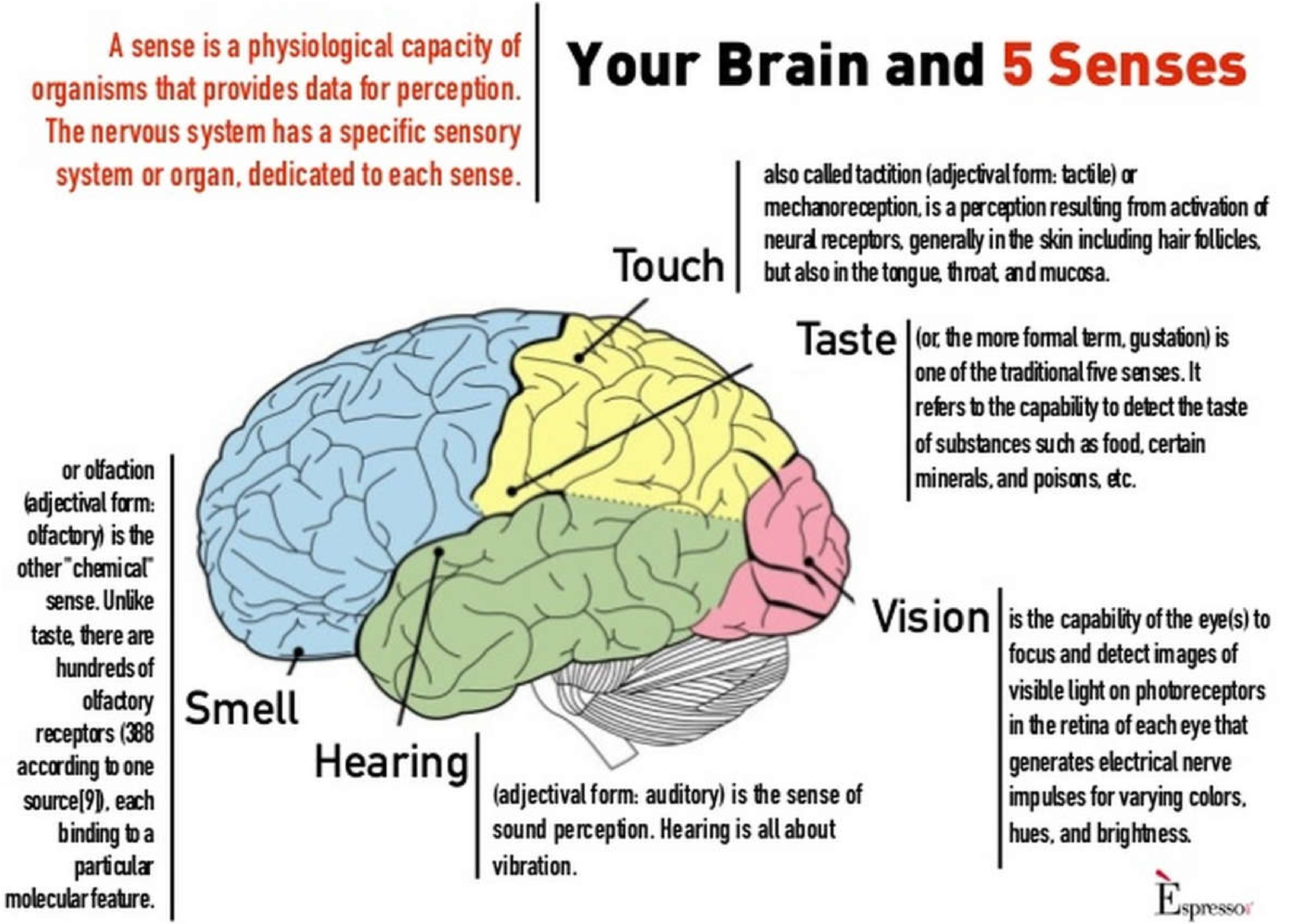
Nerve	Sensory portal	Information	
Cranial	Eyes	Visual	
	Ears	Auditory	
		Equilibratory	
	Nose	Olfactory	
	Tongue	Gustatory	
Spinal	Skin	Fine touch	Somatic (voluntary)
		Pressure	
		Pain	
		Warmth	
		Coldness	
		Kinesthesia	
	Viscera	Existence	Visceral* (involuntary)
		Pain	



* Visceral is also called autonomic. Viscera = the large organs inside the human body

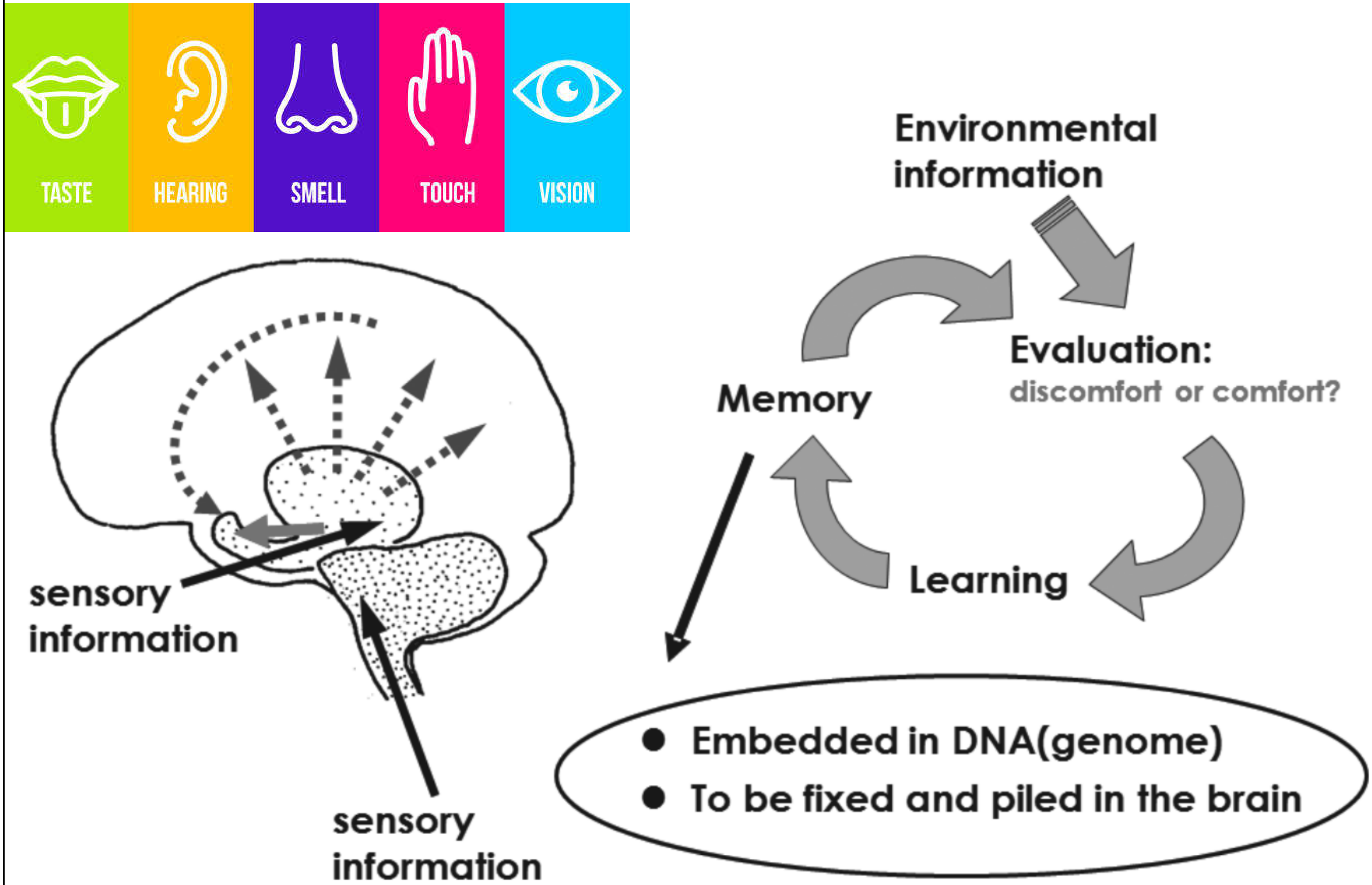
(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

The five senses that help us perceive the world



(Source: https://www.re-thinkingthefuture.com/rtf-fresh-perspectives/a1440-psychological-impact-of-landscape-design/)

Cycle of evaluation, learning, and memory

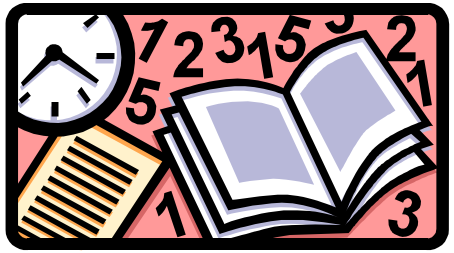


(Source: Shukuya M., 2019. *Bio-Climatology for the Built Environment*, Chapman and Hall/CRC, Milton.)

Interaction of our mind with physical reality (experience & perception)

(Source: https://www.re-thinkingthefuture.com/rtf-fresh-perspectives/a1440-psychological-impact-of-landscape-design/)

Further Reading



- Thermal comfort - Wikipedia https://en.wikipedia.org/wiki/Thermal_comfort
- Thermal comfort in buildings - Designing Buildings Wiki https://www.designingbuildings.co.uk/wiki/Thermal_comfort_in_buildings
- CBE Thermal Comfort Tool for ASHRAE-55 https://comfort.cbe.berkeley.edu/