New insights and modelling tools for predicting human dynamic thermal perception

Marika Vellei – CNRS Researcher

University of Bordeaux

Context

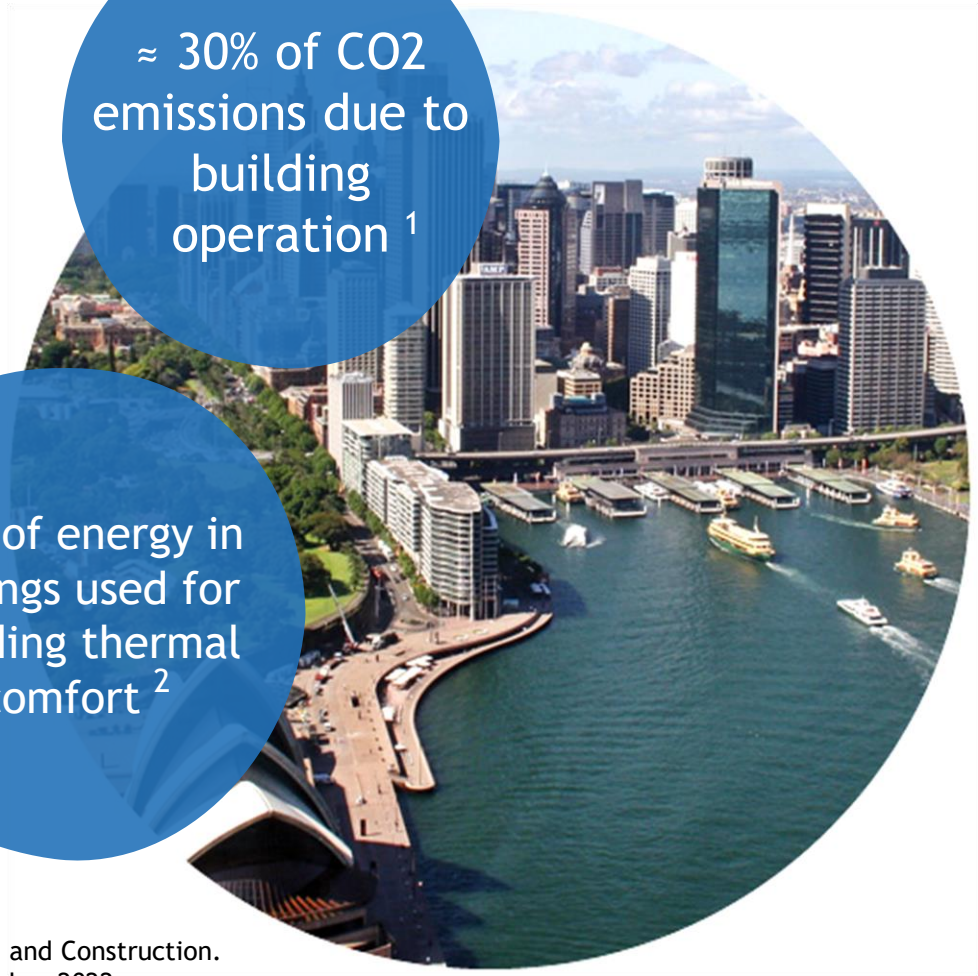
≈ 30% of CO2 emissions due to building operation [1]

[1] GlobalABC - 2022 Global Status Report for Buildings and Construction.
[2] IEA Heating/Space Cooling Tracking report - September 2022.
[3] Graham, L. T., Parkinson, T., & Schiavon, S. (2021). Lessons learned from 20 years of CBE's occupant surveys. Buildings and Cities, 2(1), pp. 166–184.
[4] IPCC - Sixth Assessment Report: Climate Change 2023.

Context

≈ 30% of CO2 emissions due to building operation [1]

≈ 50% of energy in buildings used for providing thermal comfort [2]



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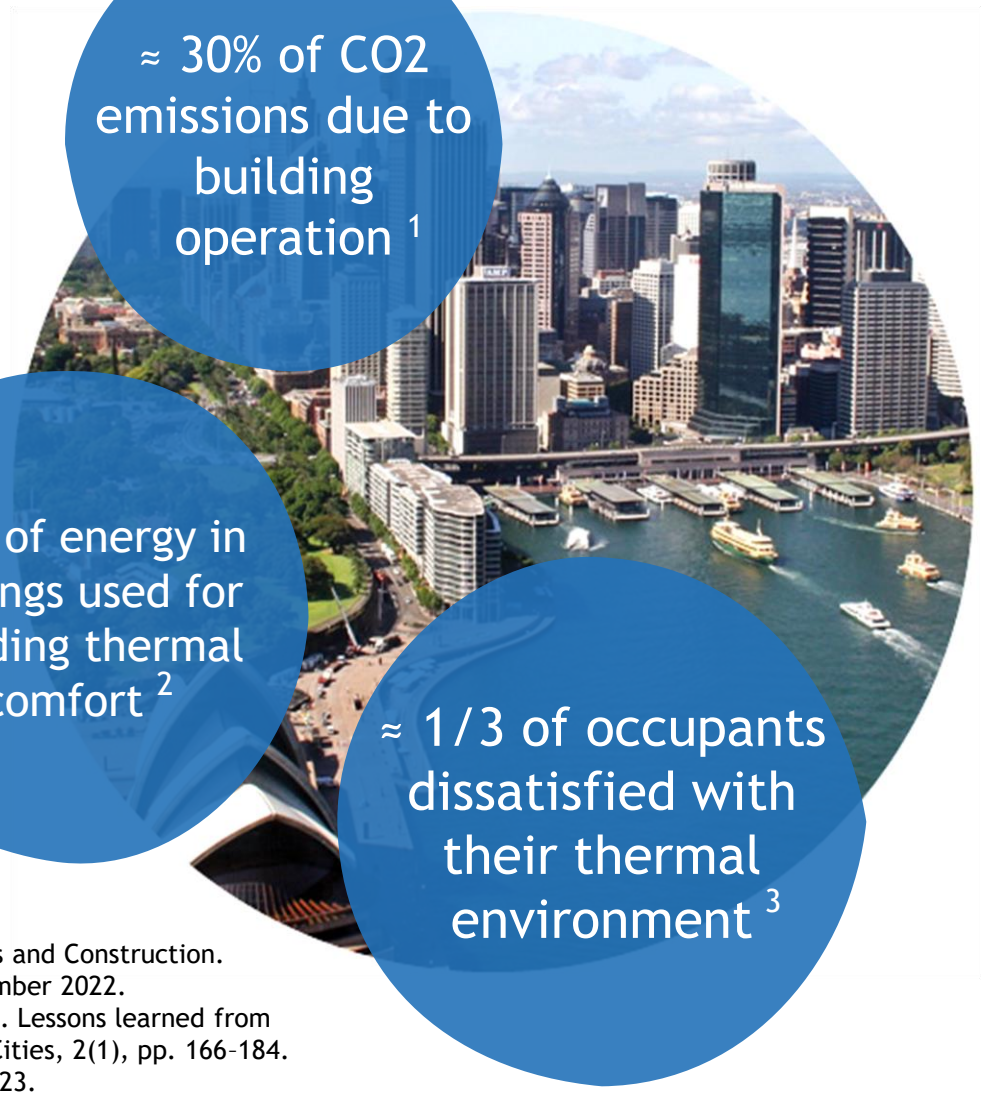

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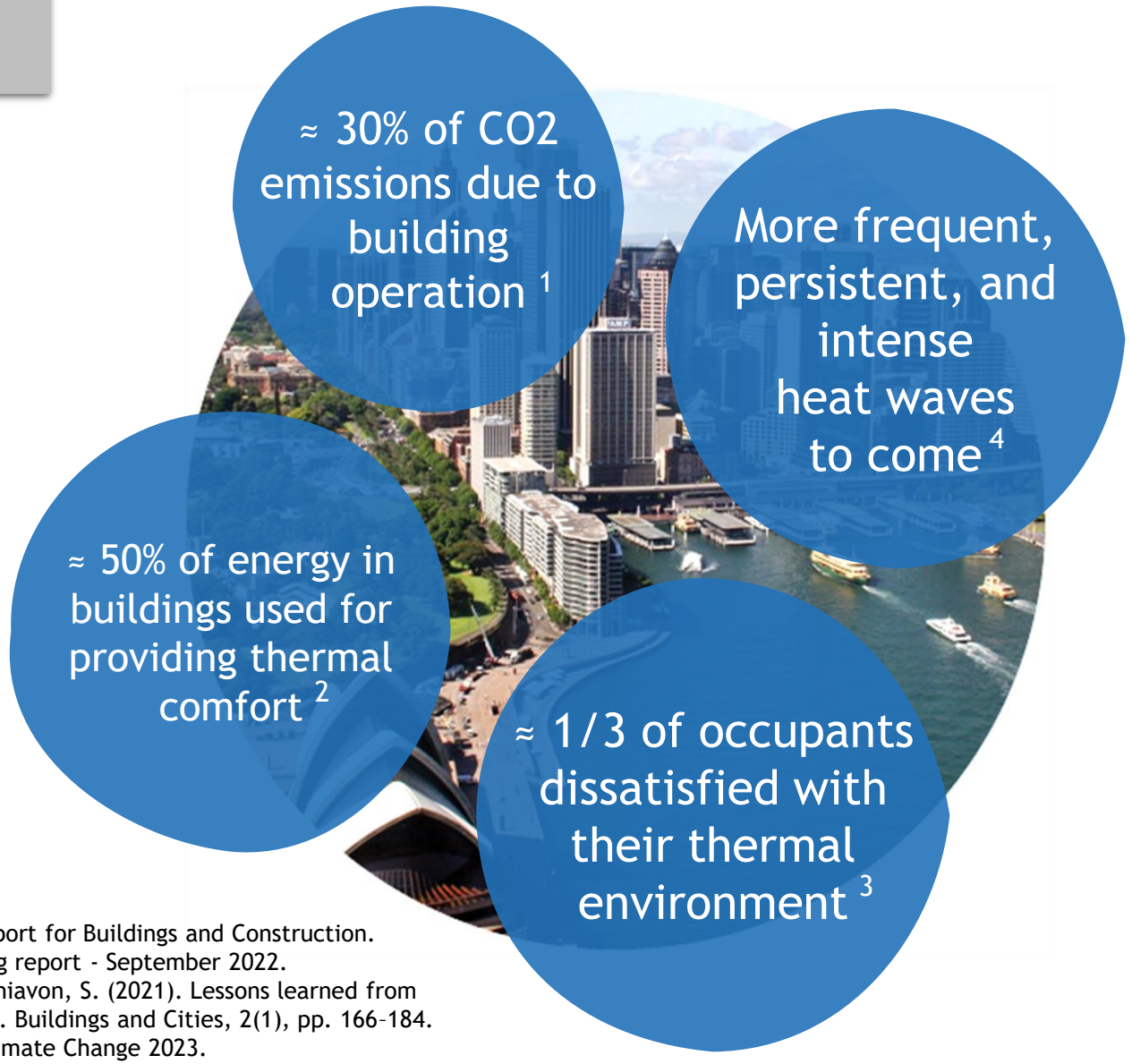

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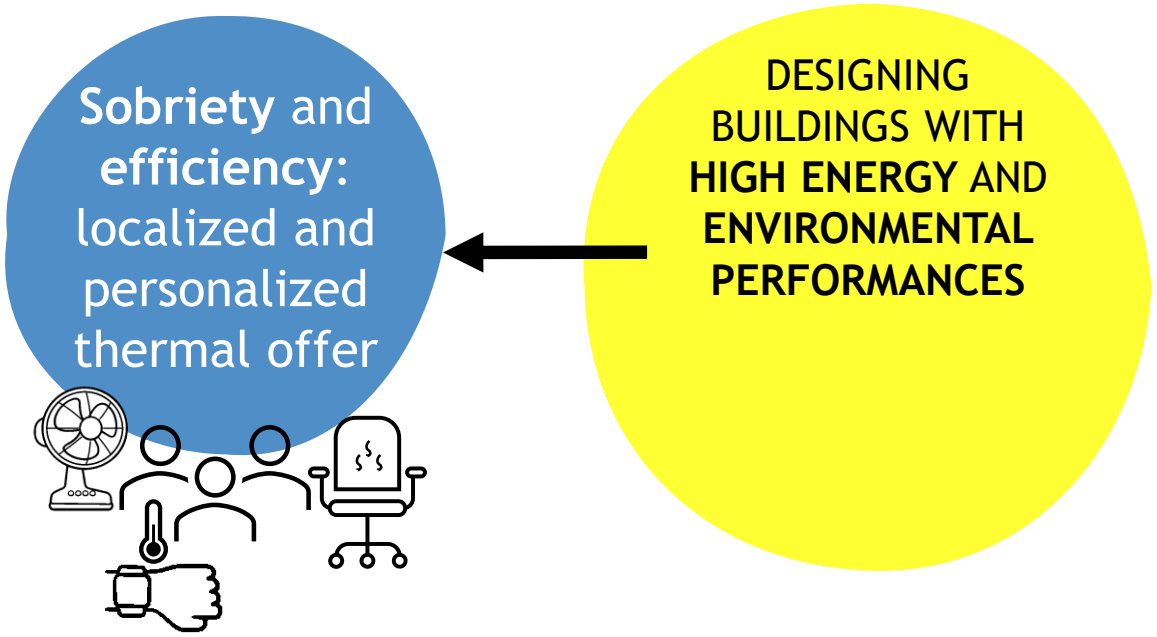
Problem

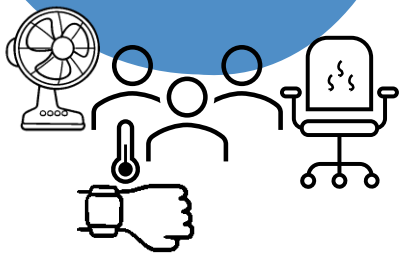
DESIGNING
BUILDINGS WITH
HIGH ENERGY AND
ENVIRONMENTAL
PERFORMANCES

Problem


Sobriety and **efficiency**: localized and personalized thermal offer
DESIGNING BUILDINGS WITH **HIGH ENERGY** AND **ENVIRONMENTAL PERFORMANCES**

Problem

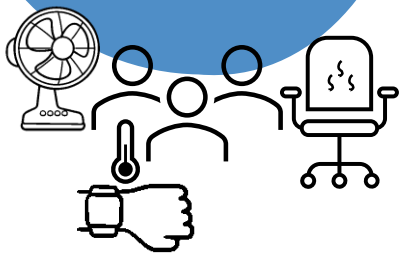
Sobriety and **efficiency:** localized and personalized thermal offer



DESIGNING BUILDINGS WITH **HIGH ENERGY** AND **ENVIRONMENTAL PERFORMANCES** and **INTERACTIVES** WITH THE ELECTRICAL GRID

Problem

Sobriety and **efficiency:** localized and personalized thermal offer



DESIGNING BUILDINGS WITH **HIGH ENERGY** AND **ENVIRONMENTAL PERFORMANCES** and **INTERACTIVES** WITH THE ELECTRICAL GRID

Flexibility: adjustable setpoint temperature

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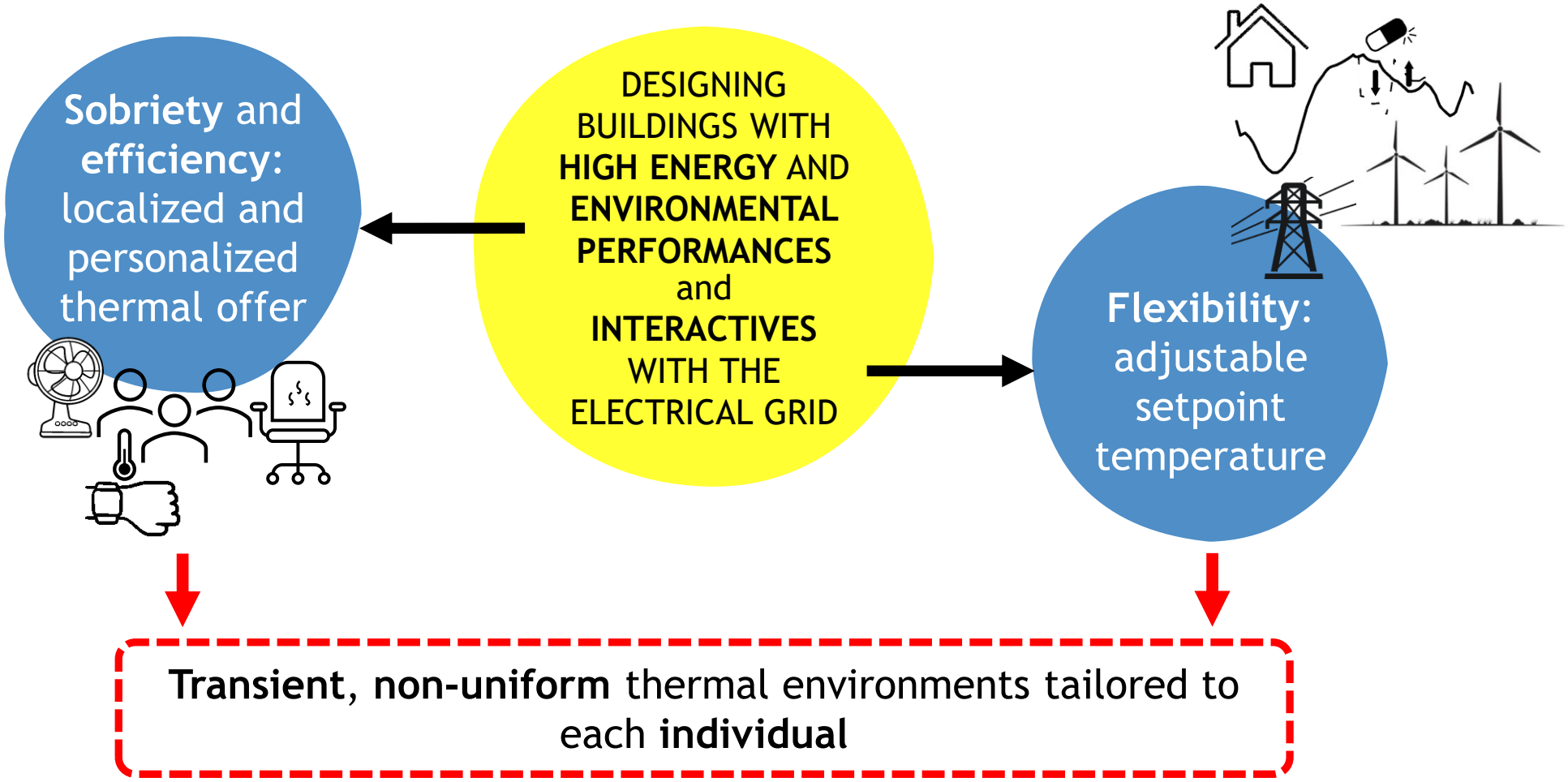
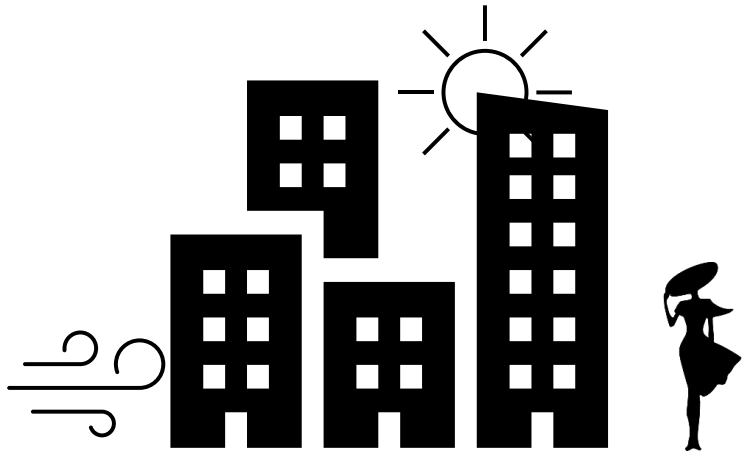

Sobriety and **efficiency:** localized and personalized thermal offer
DESIGNING BUILDINGS WITH **HIGH ENERGY** AND **ENVIRONMENTAL PERFORMANCES** and **INTERACTIVES** WITH THE ELECTRICAL GRID
Flexibility: adjustable setpoint temperature
Transient, non-uniform thermal environments tailored to each **individual**

Problem



- Transient thermal states are already widespread in the built environment;

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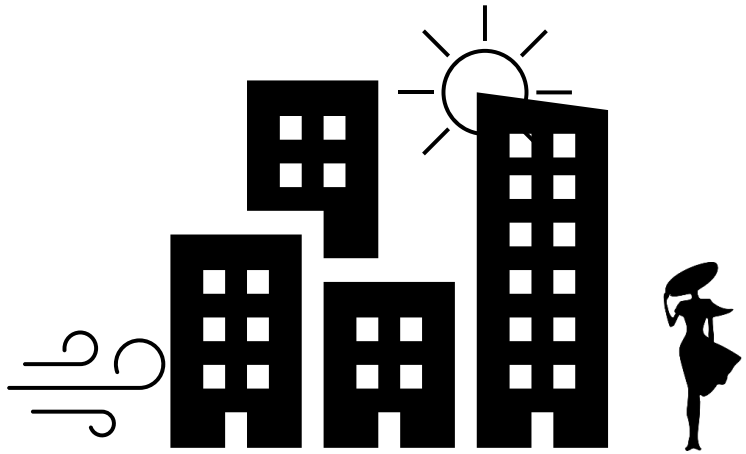

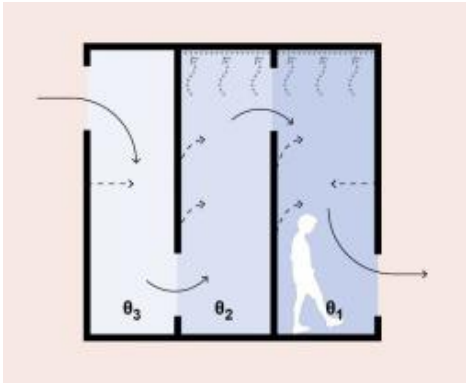

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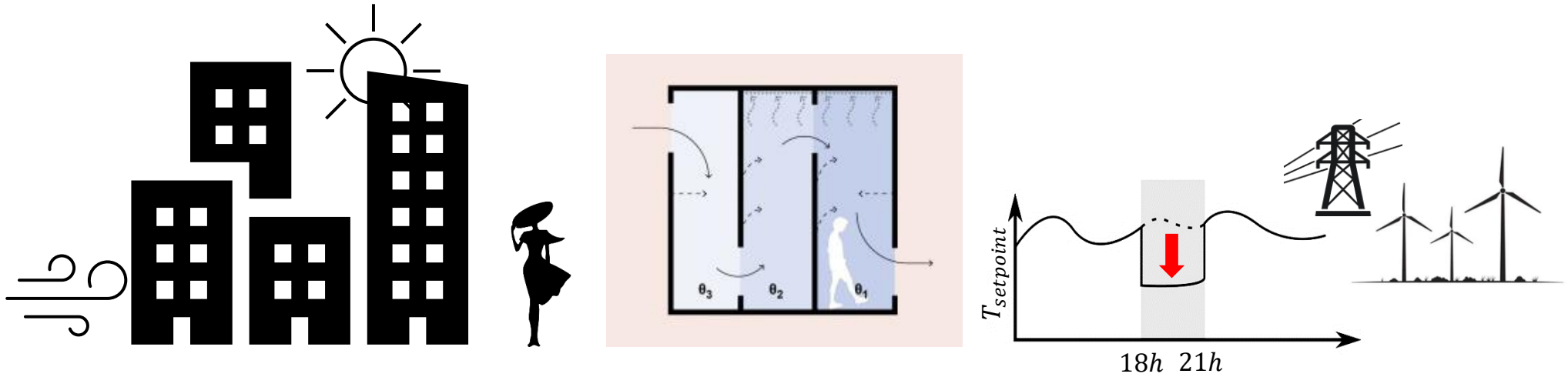

- Transient thermal states are already widespread in the built environment;
- they will become more recurrent as part of demand-management electricity programs;

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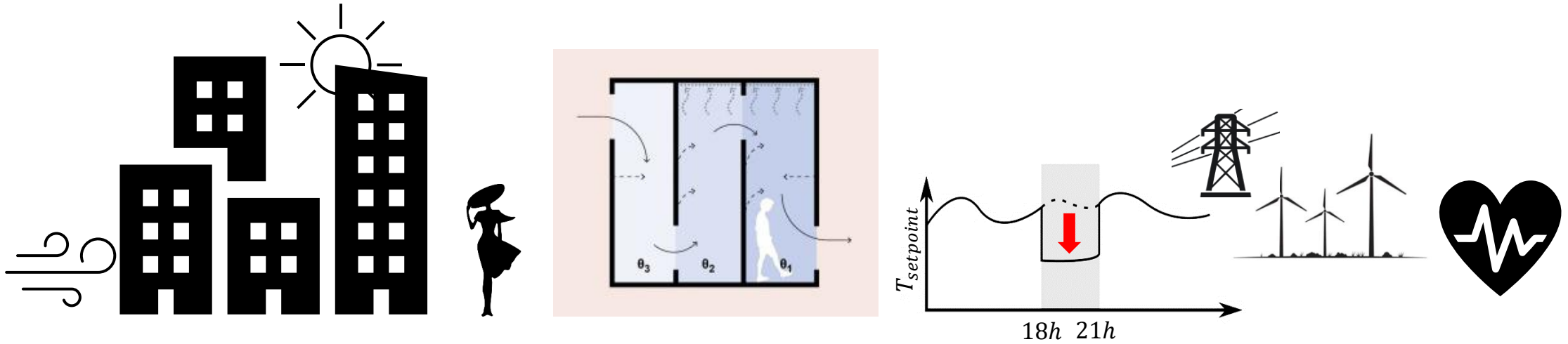
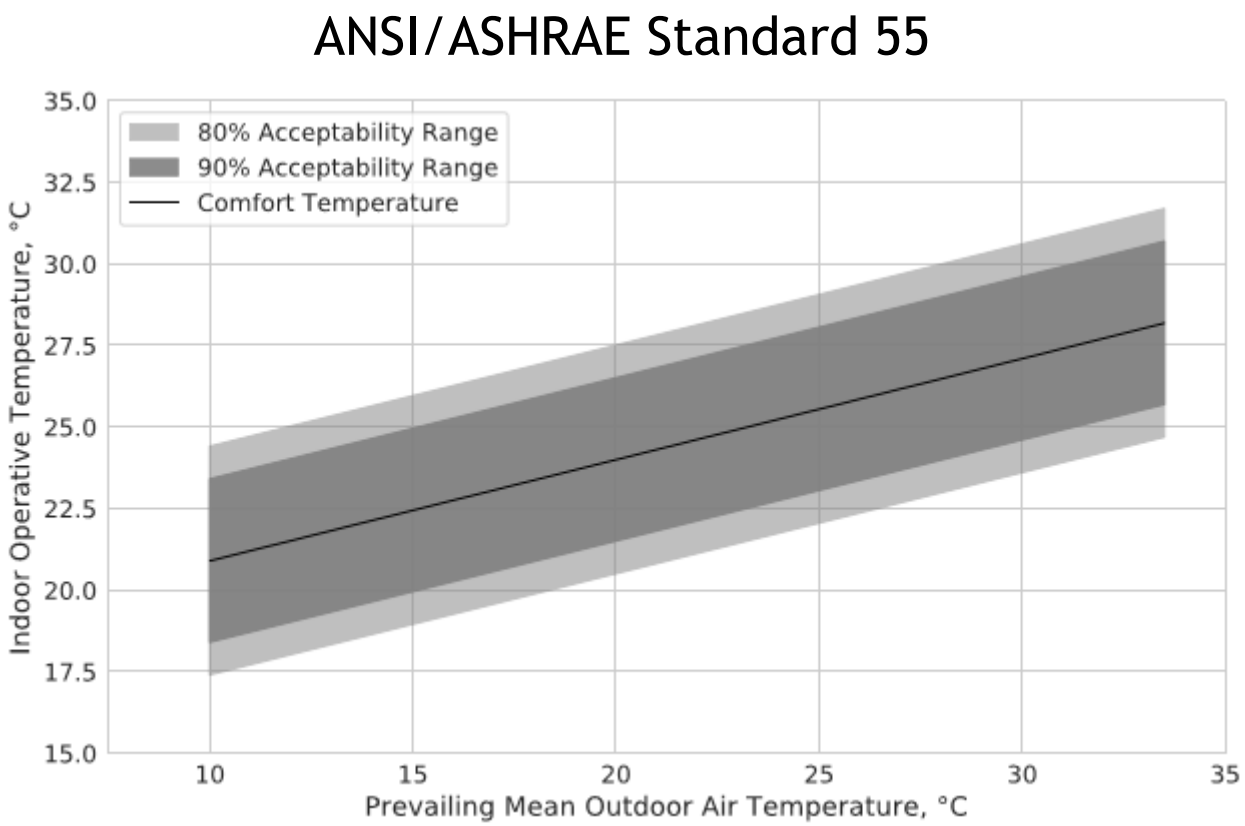


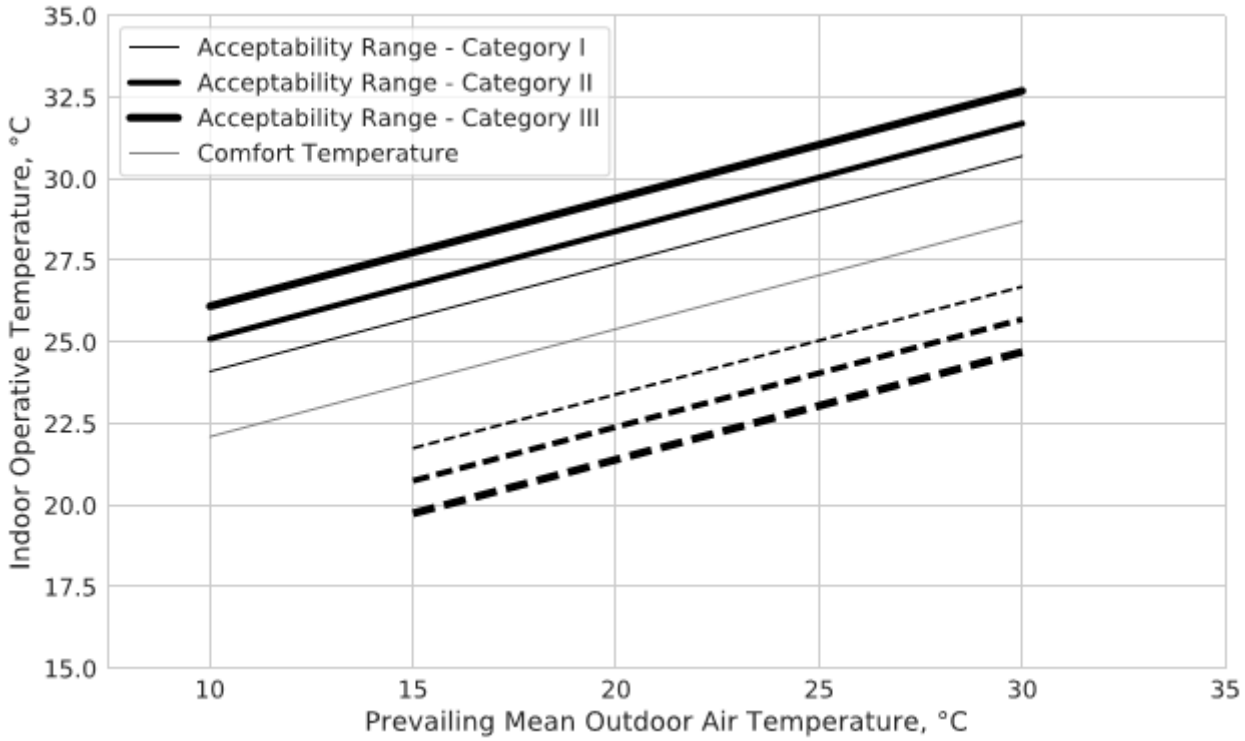
- Transient thermal states are already widespread in the built environment;
- they will become more recurrent as part of demand-management electricity programs;
- they have the potential to create thermal delight and enhance occupants' health.

Adaptive models

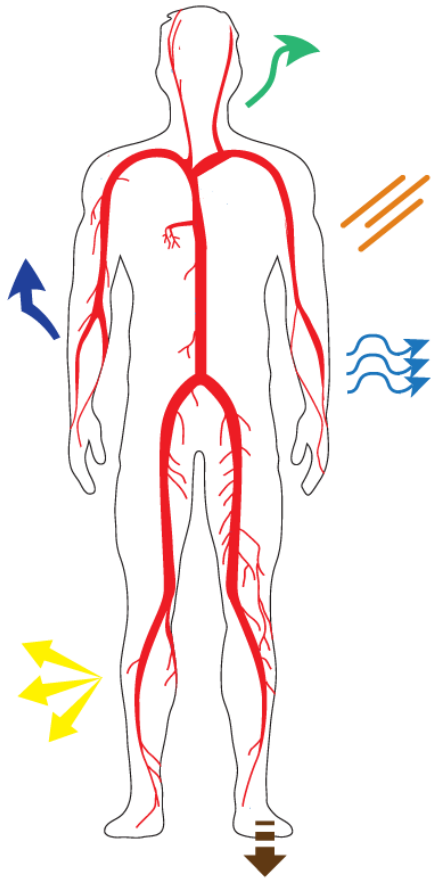


Adaptive models

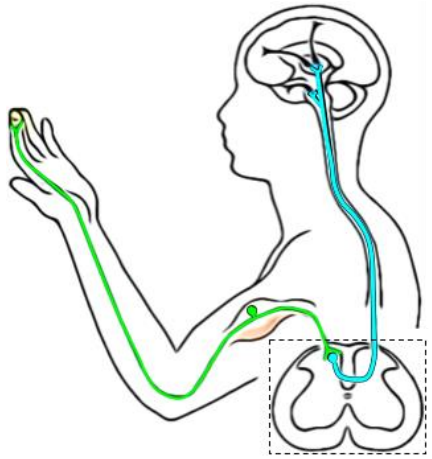
European Standard EN 15251



Processes



@ thanks to
M. Schweiker



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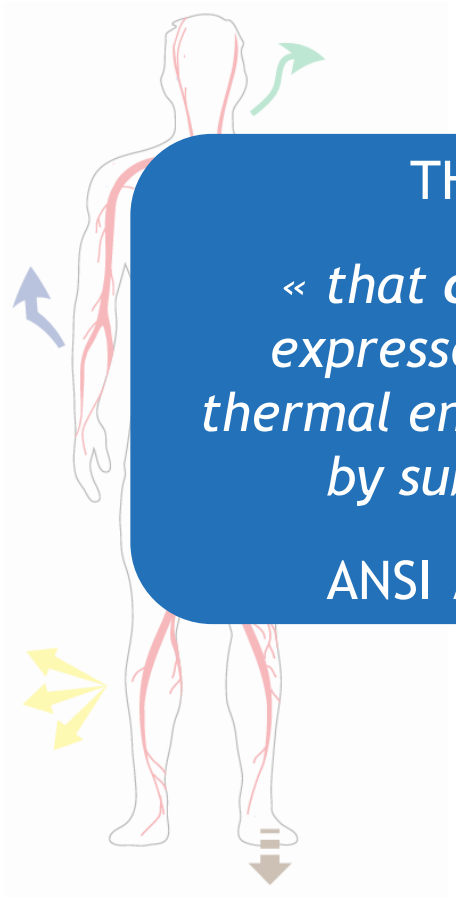
Definition



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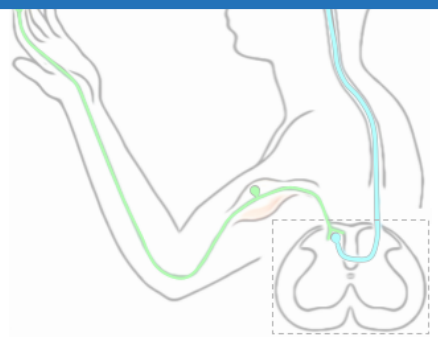
THERMAL COMFORT

« *that* ***condition of mind*** *that expresses satisfaction with the thermal environment and is assessed by subjective evaluation* »

ANSI /ASHRAE Standard 55



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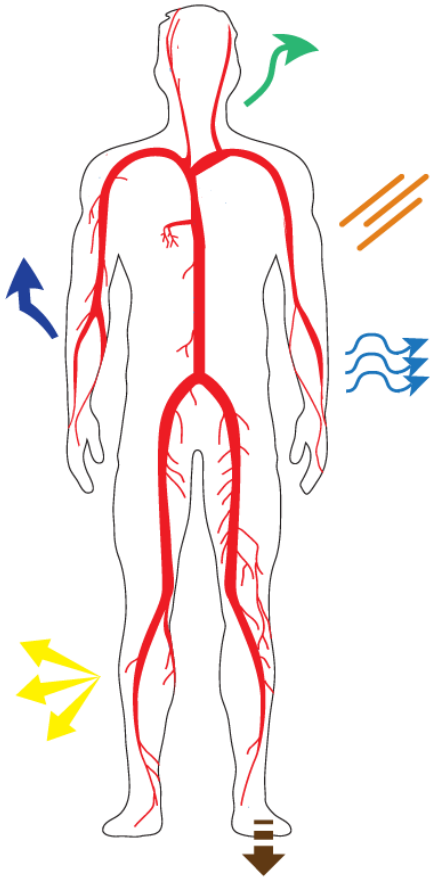
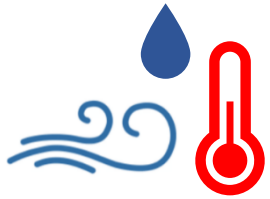


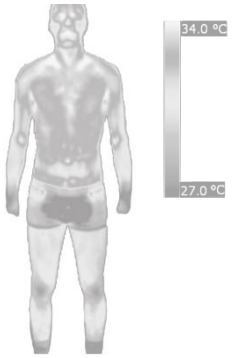


Environment

Thermal Perception

Am I cool … or warm?

Physiological state



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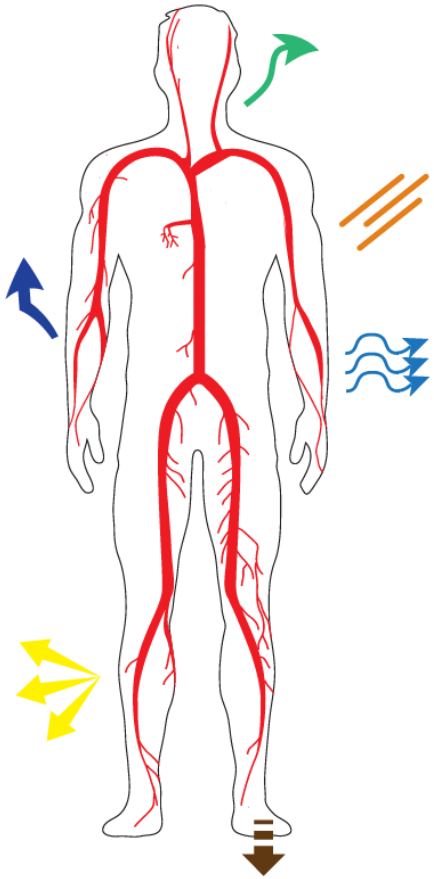

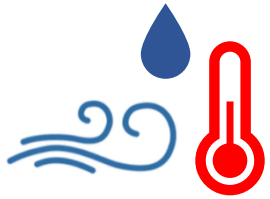

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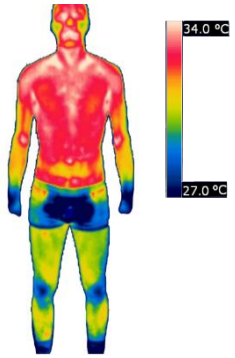

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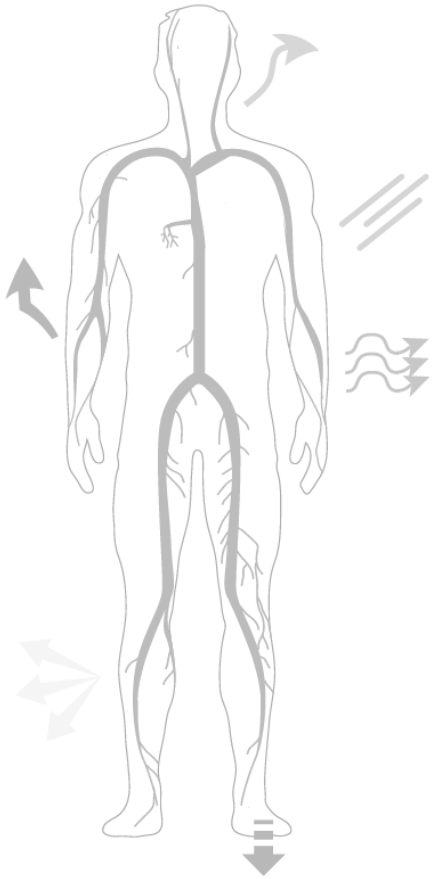

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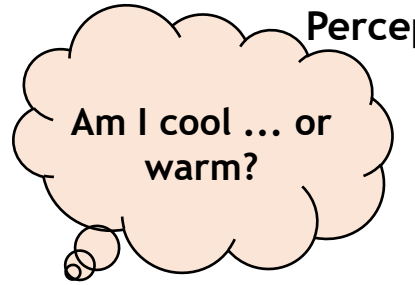

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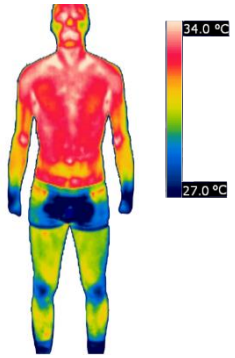

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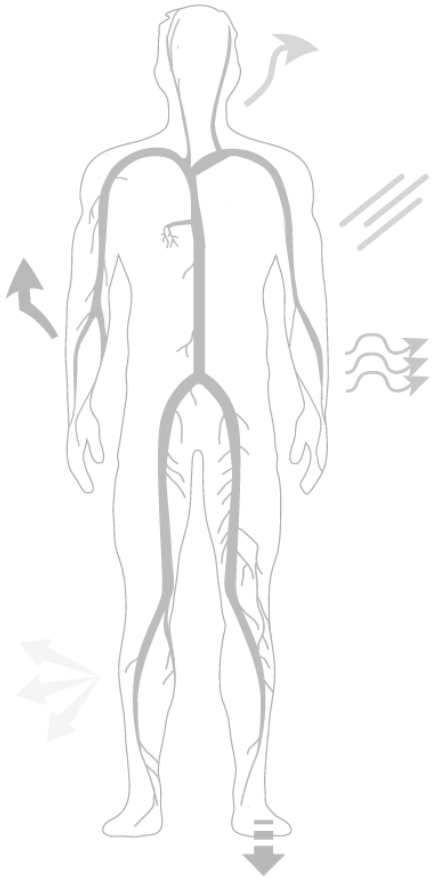

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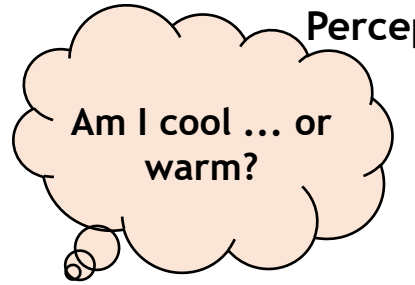

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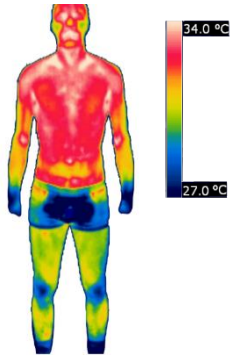

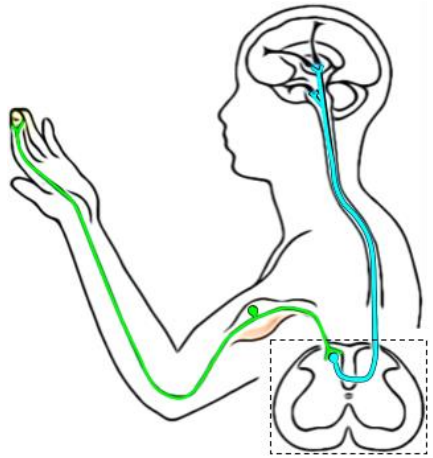

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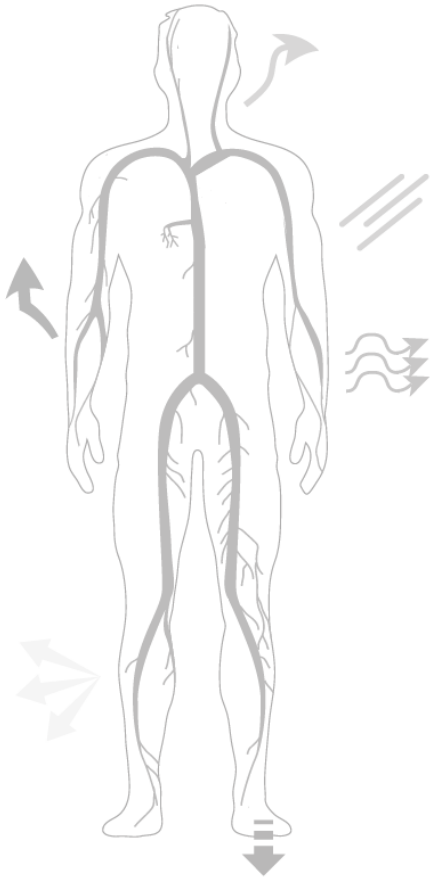

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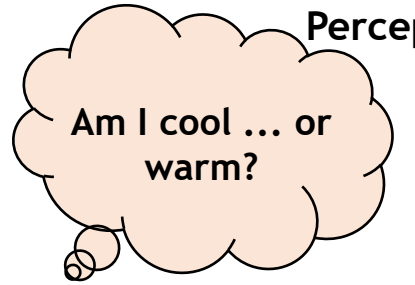

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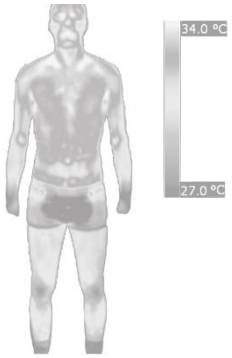

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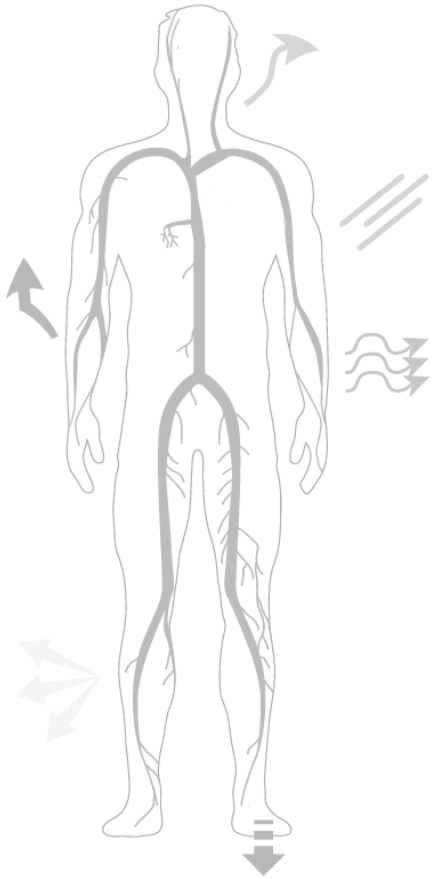

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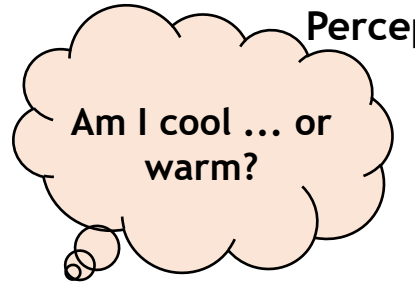

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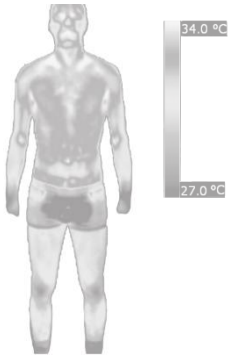

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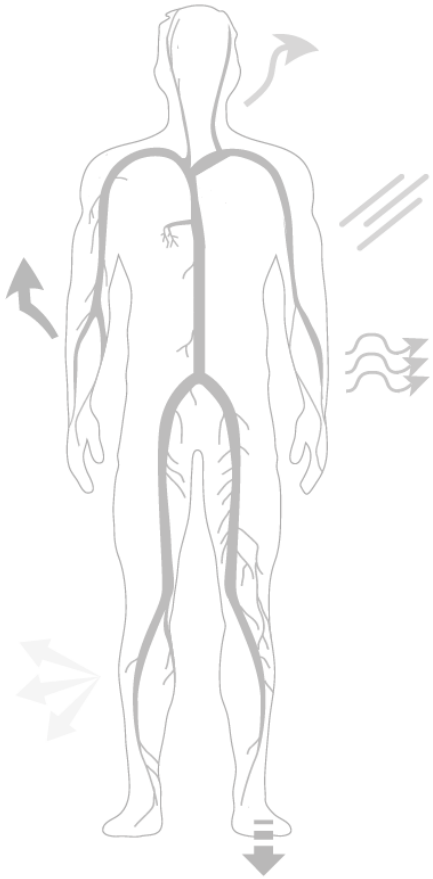

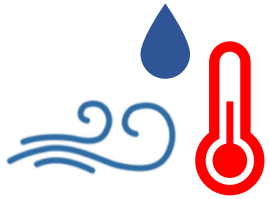

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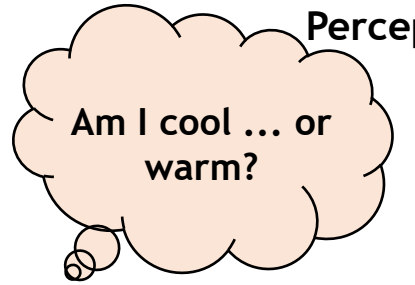

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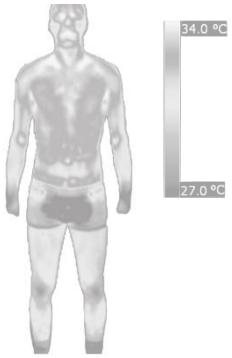

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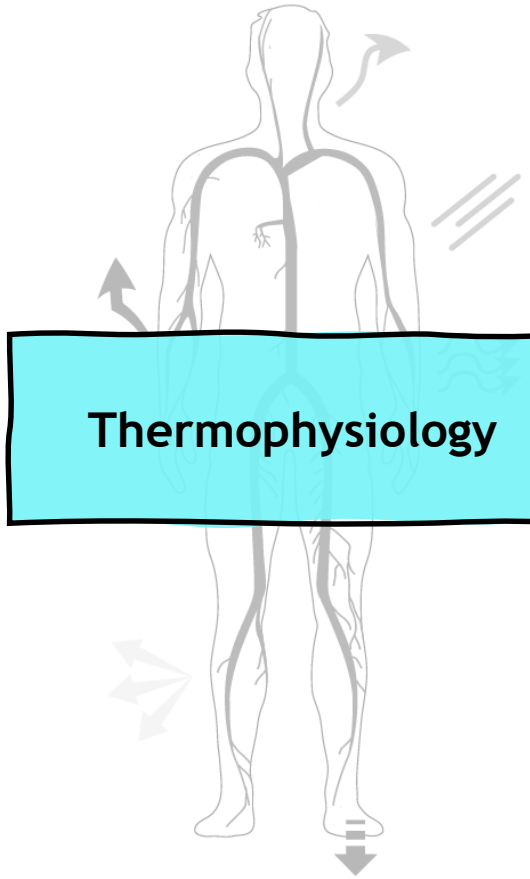
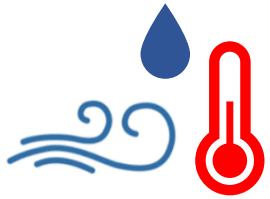


Thermophysiology



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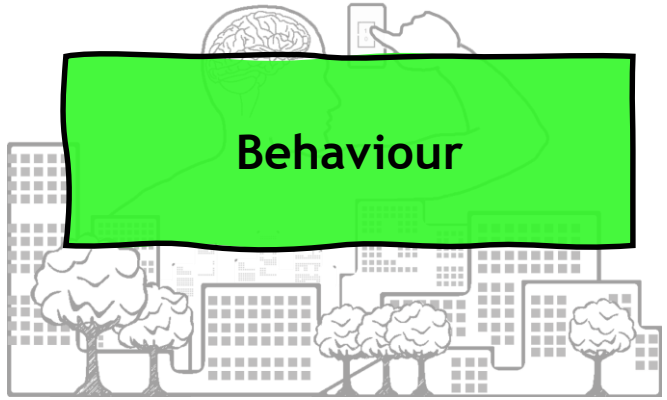
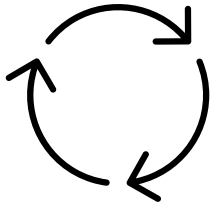


Behaviour



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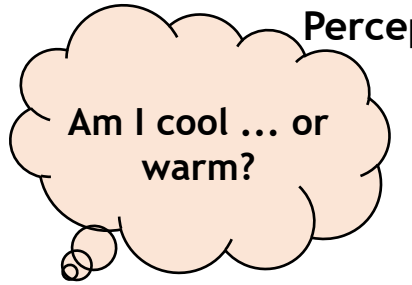

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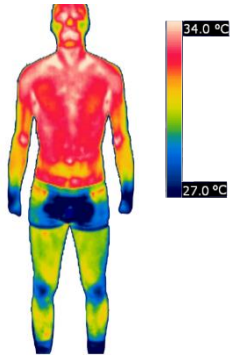
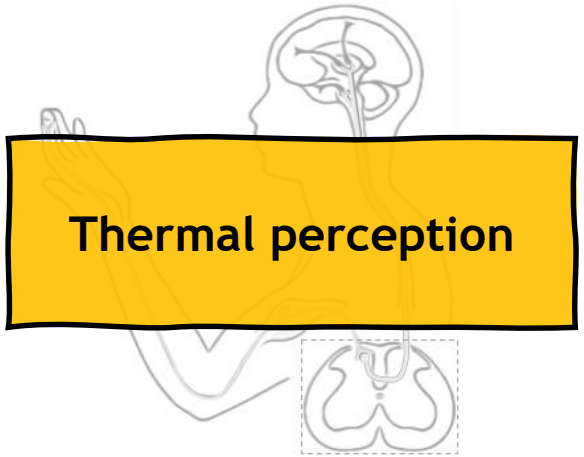
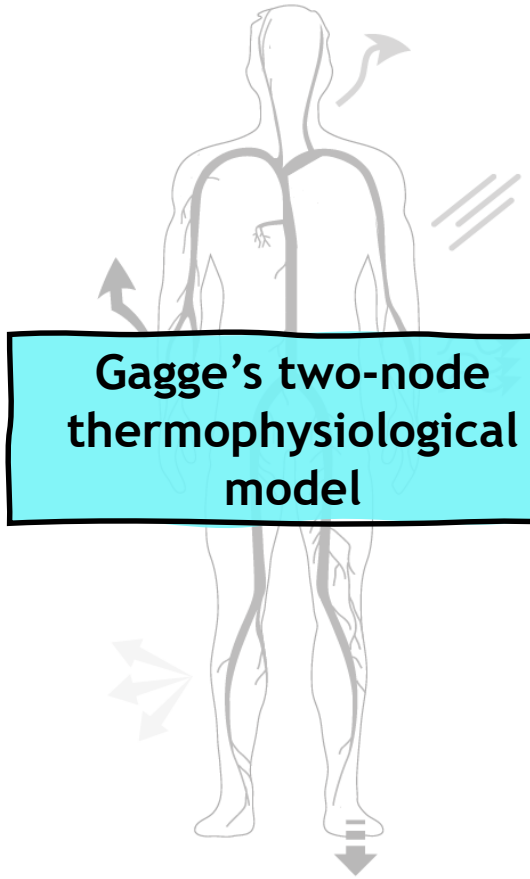
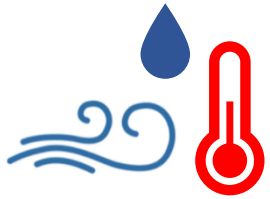




Thermal perception

Modelling

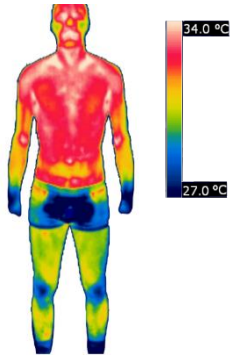




Environment

Gagge's two-node thermophysiological model

Physiological state



Thermal perception

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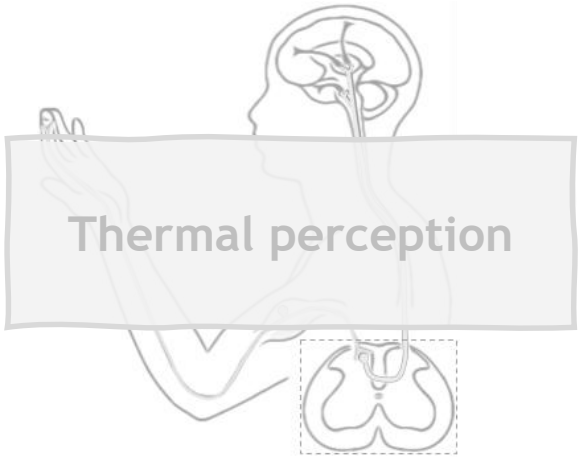
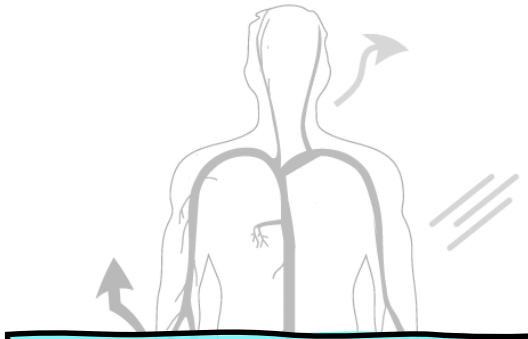
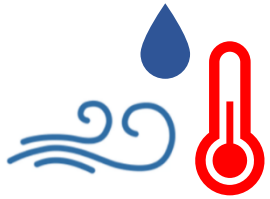


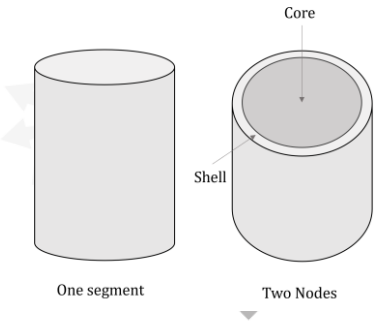
Modelling



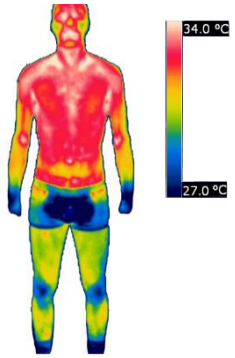


Environment

Gagge's two-node thermophysiological model

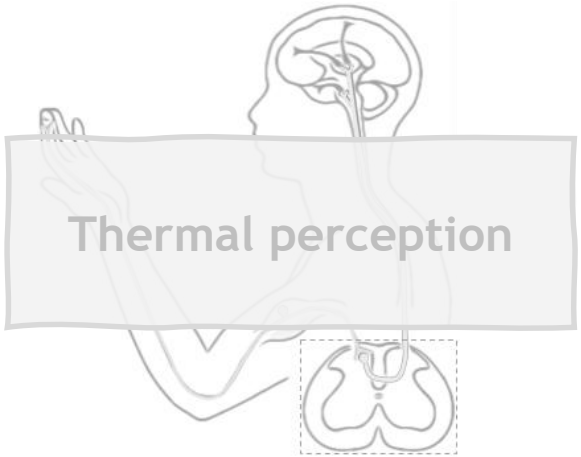


Physiological state

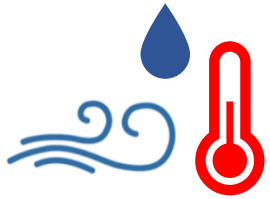


Thermal perception

Am I cool … or warm?

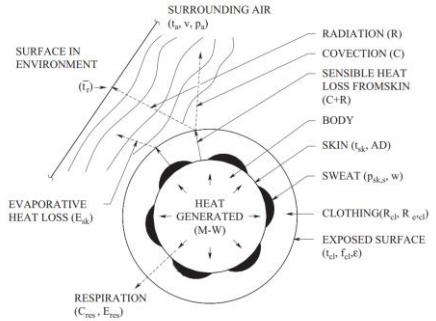


Modelling

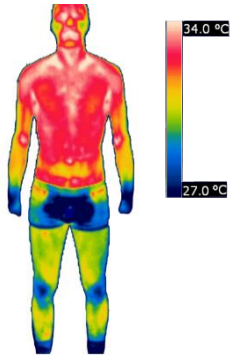


Environment

Gagge's two-node thermophysiological model

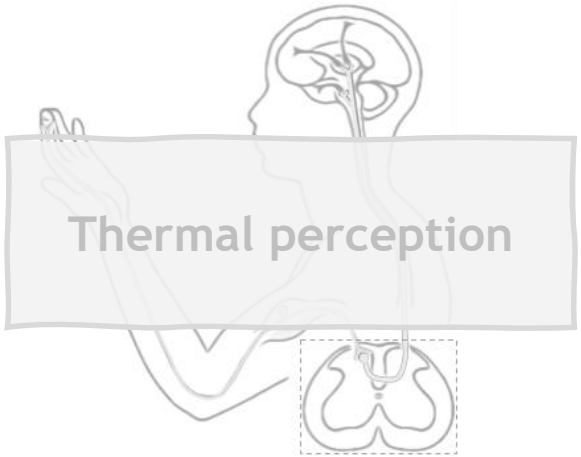


Physiological state

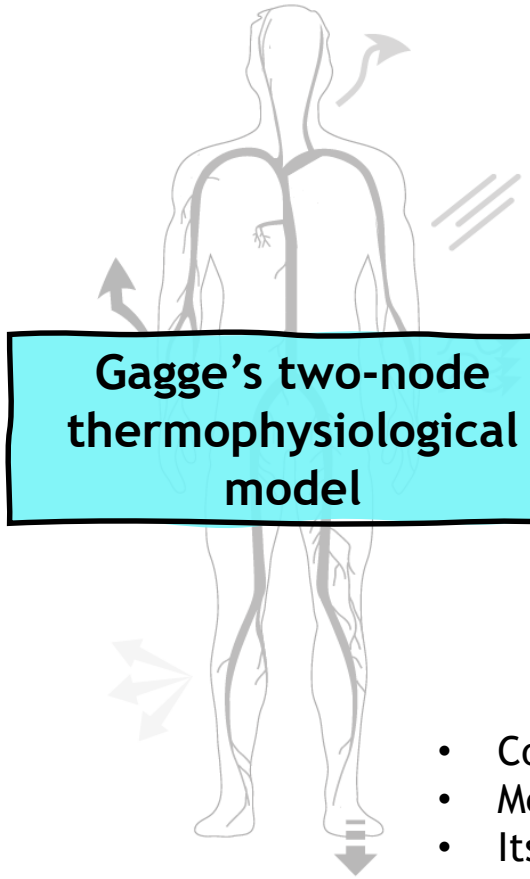


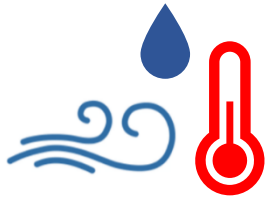
Thermal perception

Am I cool … or warm?



Modelling





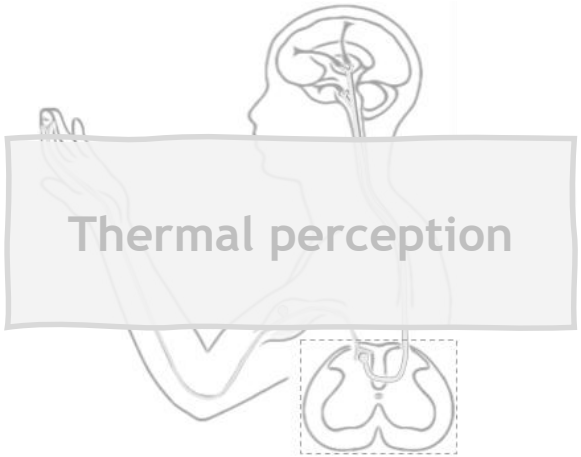
Environment

Gagge's two-node thermophysiological model

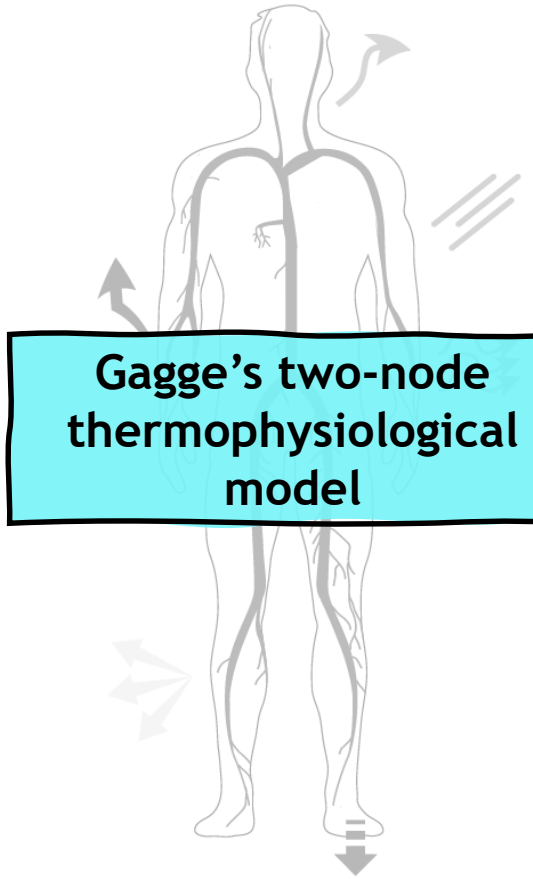
Physiological state

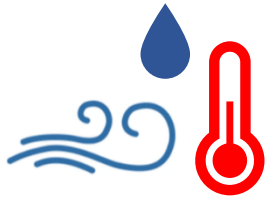
- Core body temperature
- Mean skin temperature
- Its rate of change
- Mean skin wettedness

Thermal perception



Modelling





Environment

Gagge's two-node thermophysiological model

Physiological state

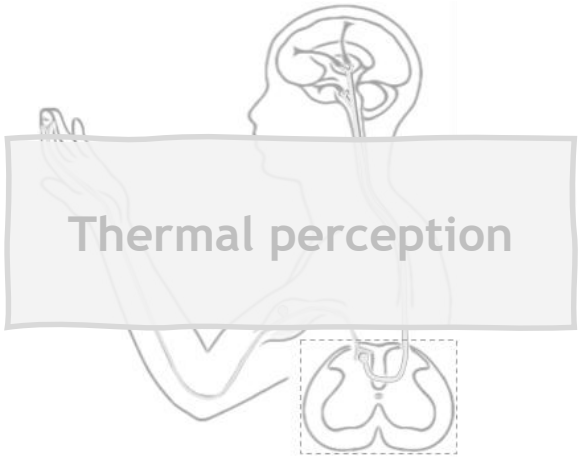
T_{core}

$T_{sk,mean}$

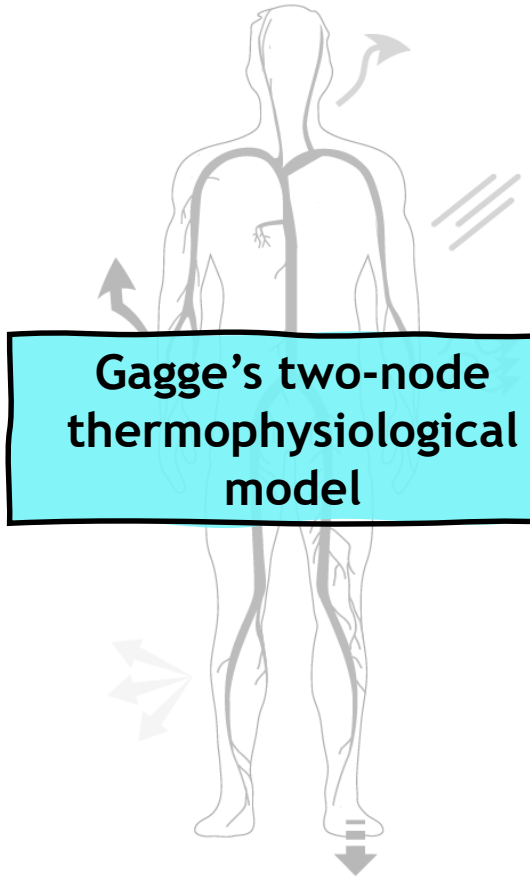
$\frac{\partial T_{sk,mean}}{\partial t}$

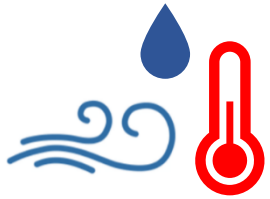
W_{sk}

Thermal perception



Modelling





Environment

Gagge's two-node thermophysiological model

Physiological state

T_{core}

$T_{sk,mean}$

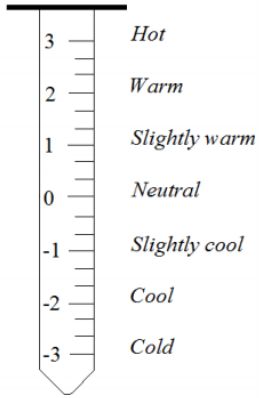
$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

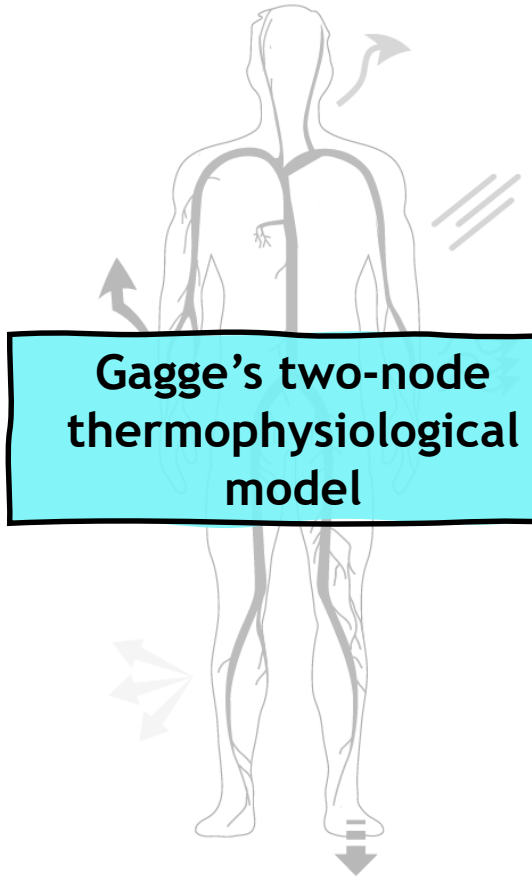
Thermal perception

Am I cool … or warm?

Thermal sensation model



Modelling



Environment

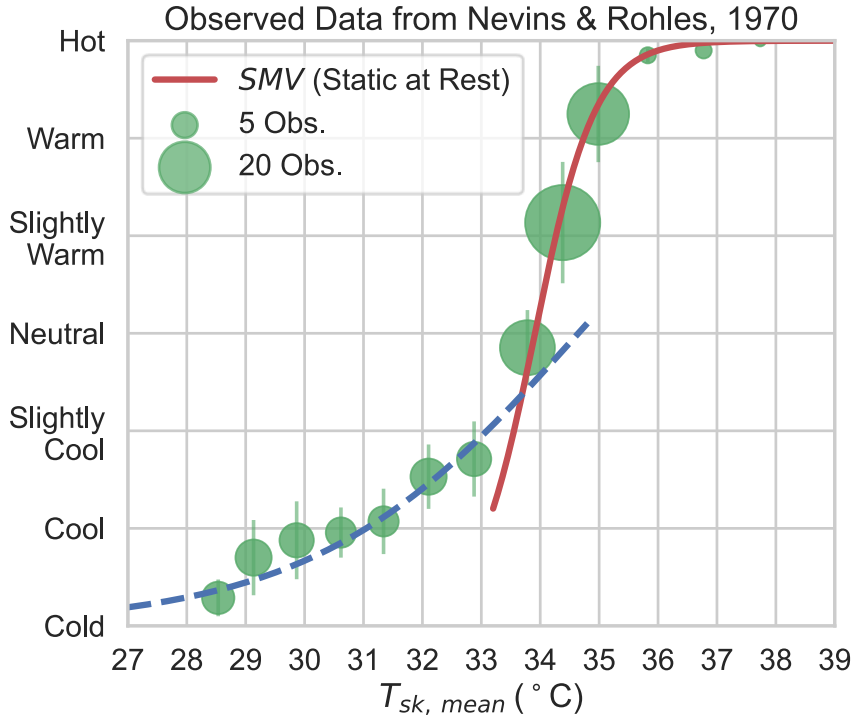
Gagge's two-node thermophysiological model

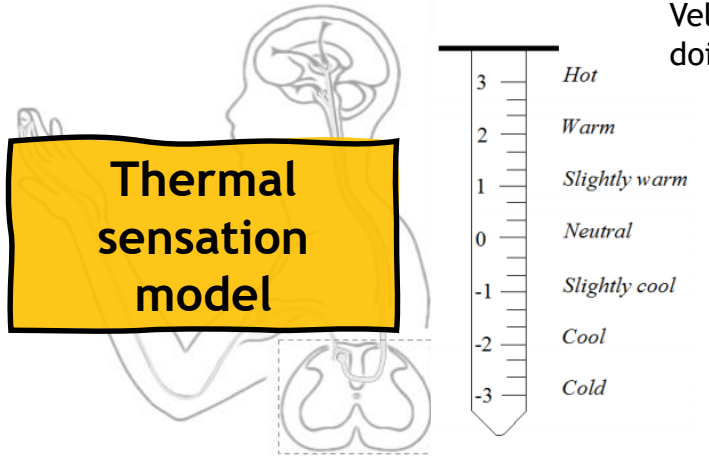
Physiological state

$$T_{core}$$
$$T_{sk,mean}$$
$$\frac{\partial T_{sk,mean}}{\partial t}$$
$$W_{sk}$$

Thermal sensation model

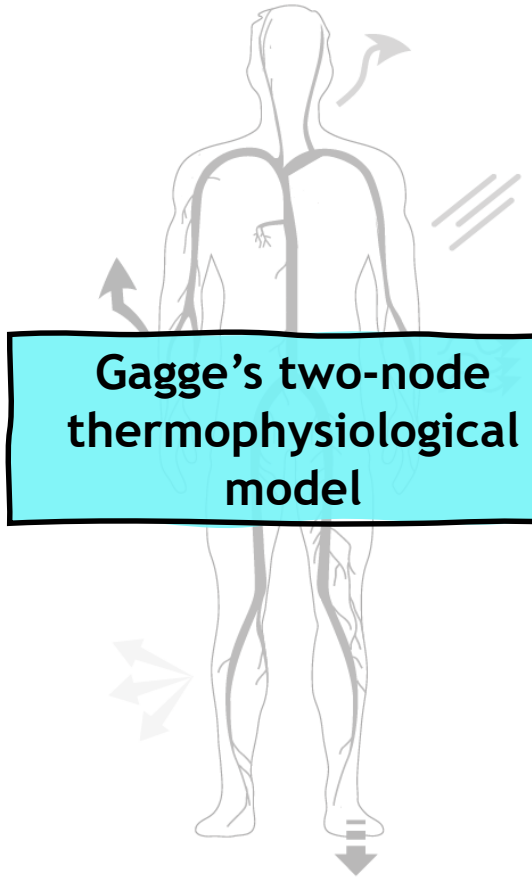
Data from 160 steady-state thermal exposures at rest





Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Modelling



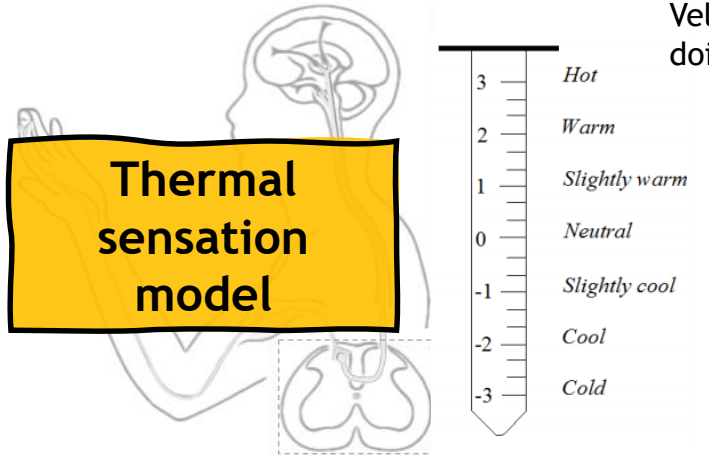
Environment

Gagge's two-node thermophysiological model

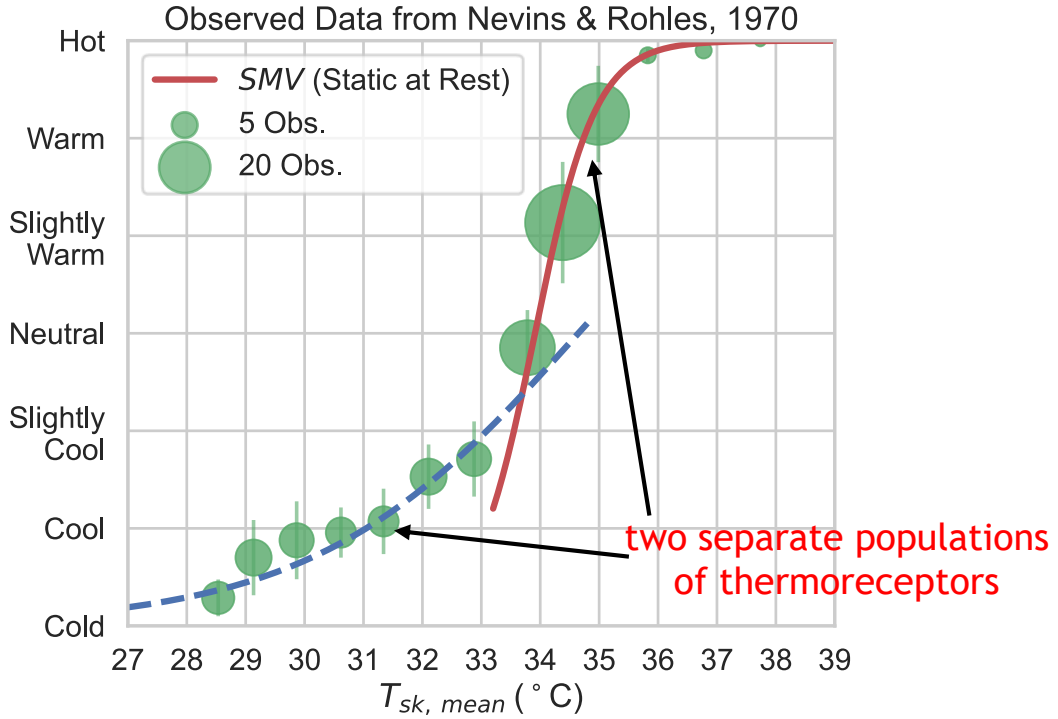
Physiological state

$$T_{core}$$
$$T_{sk,mean}$$
$$\frac{\partial T_{sk,mean}}{\partial t}$$
$$W_{sk}$$

Thermal sensation model



Data from 160 steady-state thermal exposures at rest



Vellei, 2024
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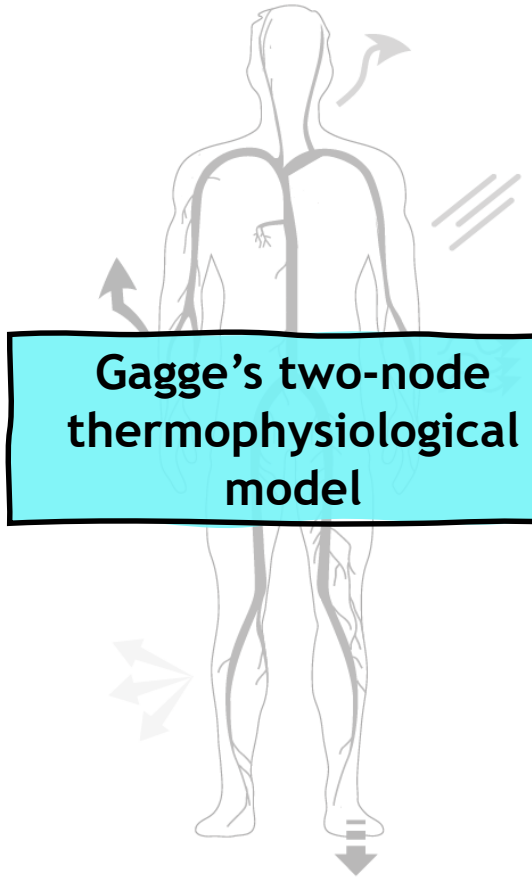
Modelling



Environment

Gagge's two-node thermophysiological model

Physiological state

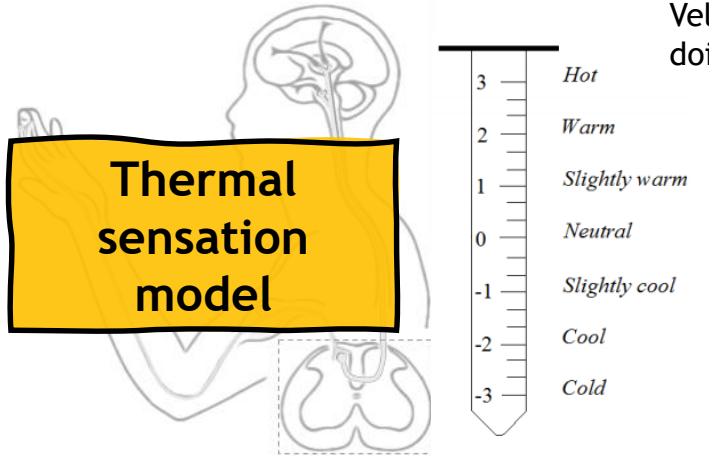
T_{core}

$T_{sk,mean}$

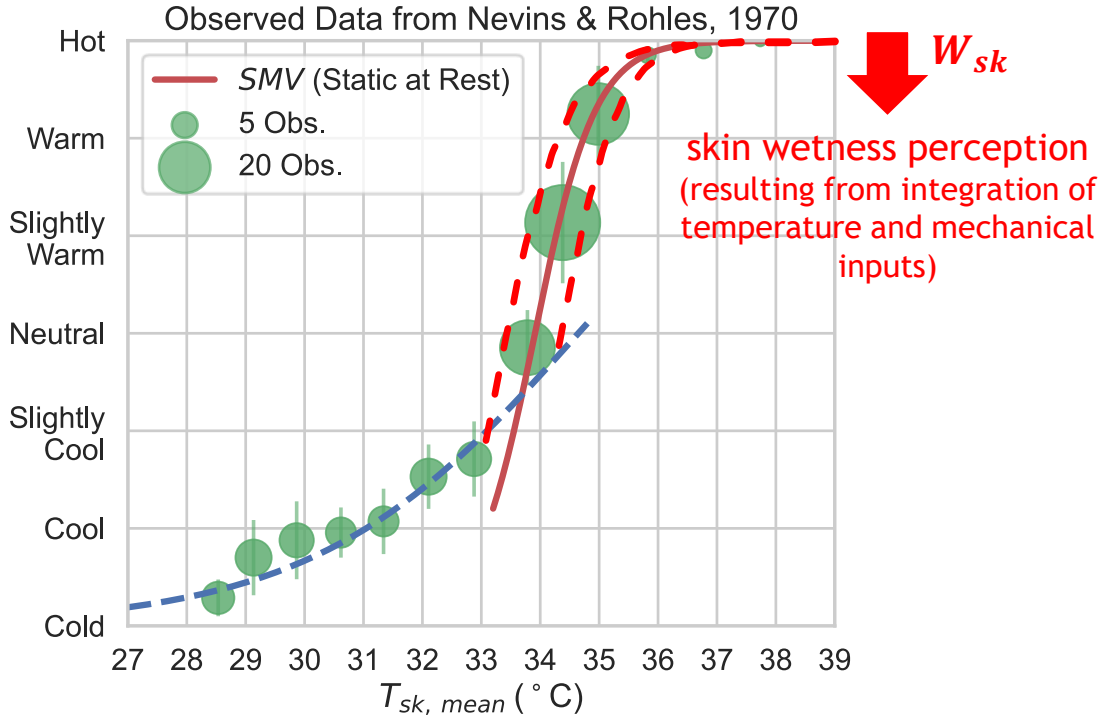
$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Thermal sensation model



Data from 160 steady-state thermal exposures at rest



W_{sk}

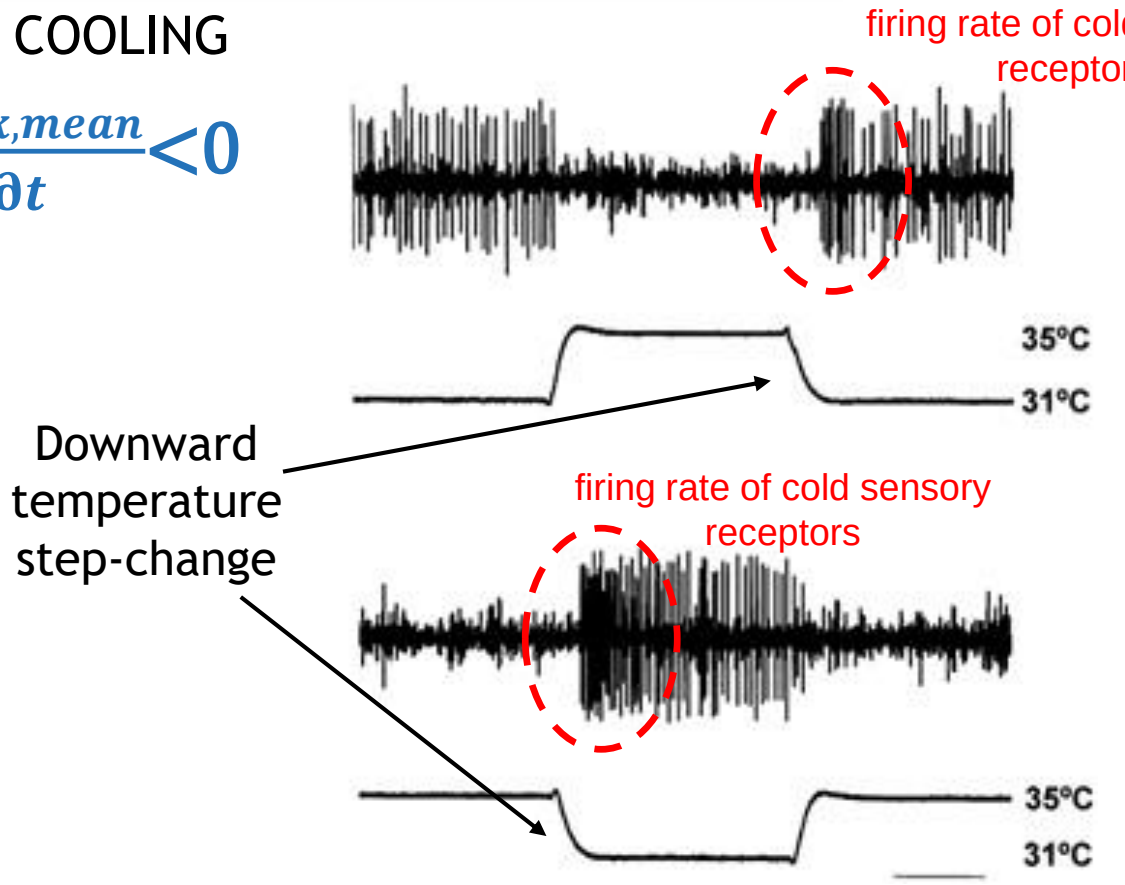
skin wetness perception (resulting from integration of temperature and mechanical inputs)

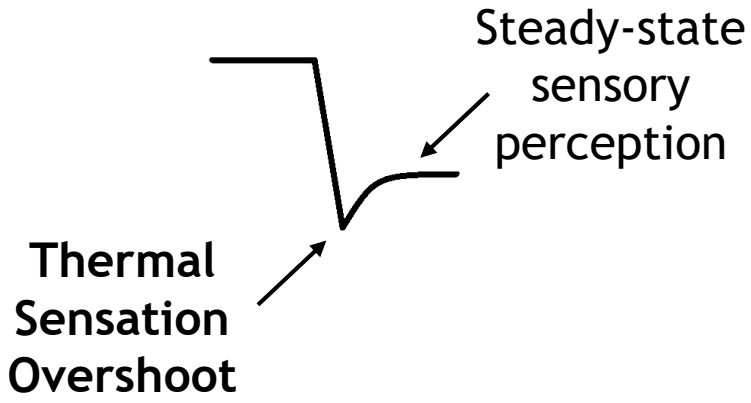
Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Thermal overshoot

SKIN COOLING

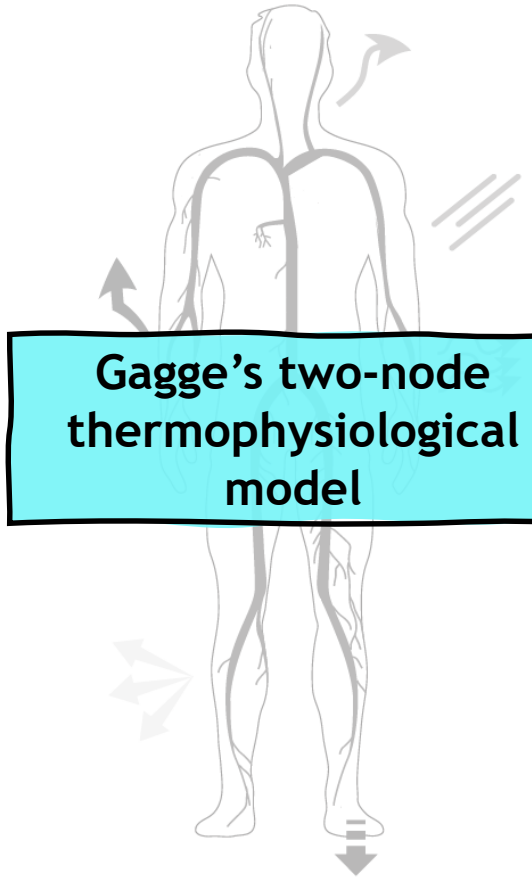
$$\frac{\partial T_{sk,mean}}{\partial t} < 0$$





Campero et al., 2001
doi: 10.1111/j.1469-7793.2001.t01-1-00855.x

Modelling



Environment

Gagge's two-node thermophysiological model

Physiological state

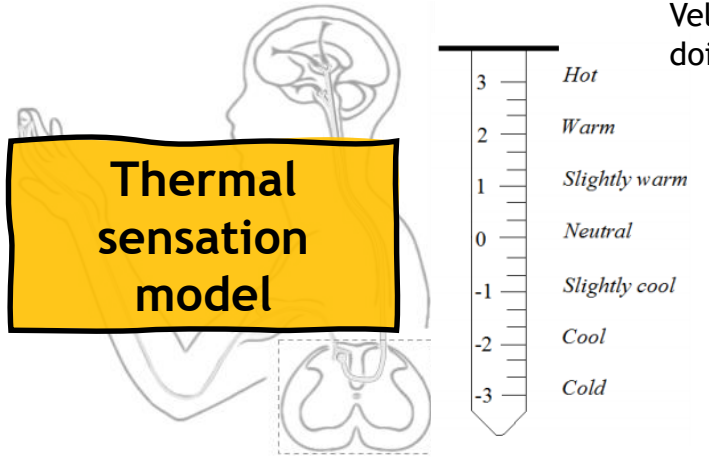
T_{core}

$T_{sk,mean}$

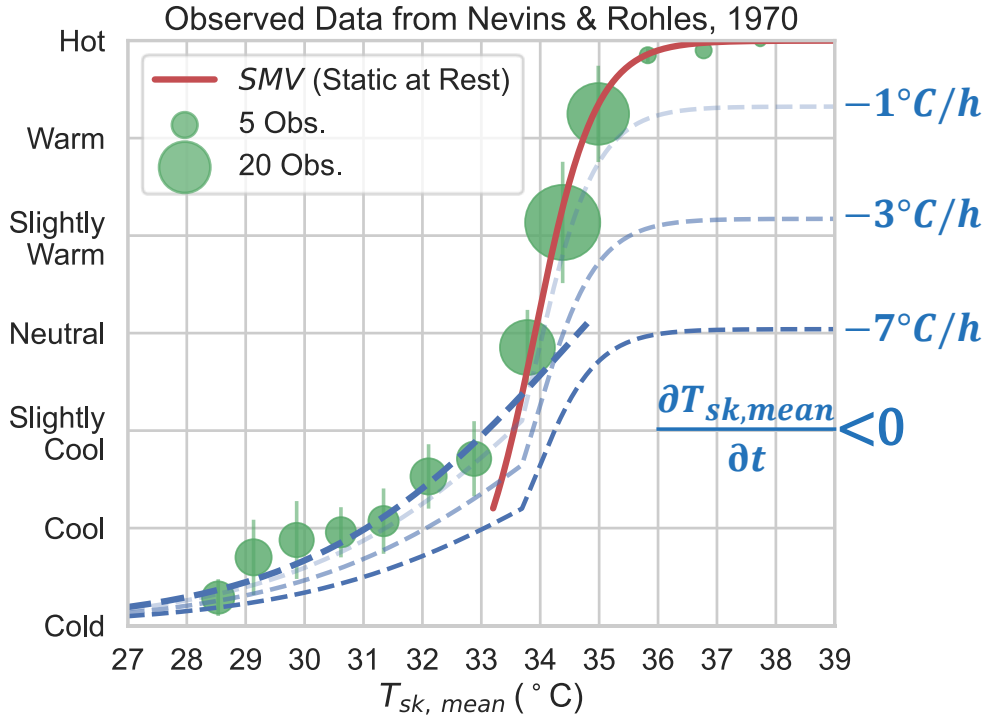
$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Thermal sensation model



Data from 60 transient thermal conditions at rest

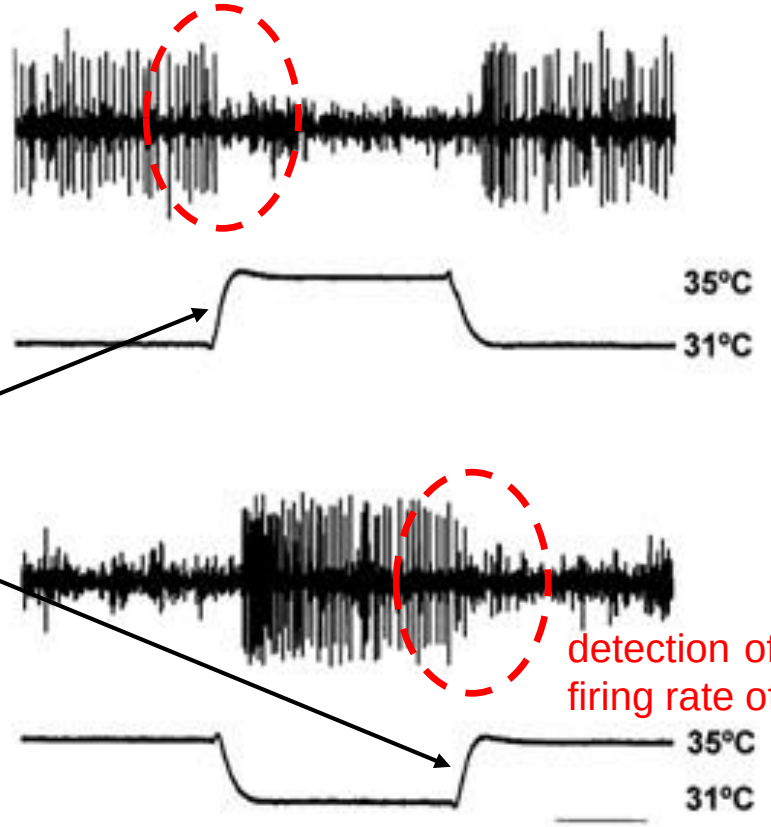


Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Thermal overshoot

SKIN WARMING

$$\frac{\partial T_{sk,mean}}{\partial t} > 0$$



Upward temperature step-change

Thermal Sensation Overshoot

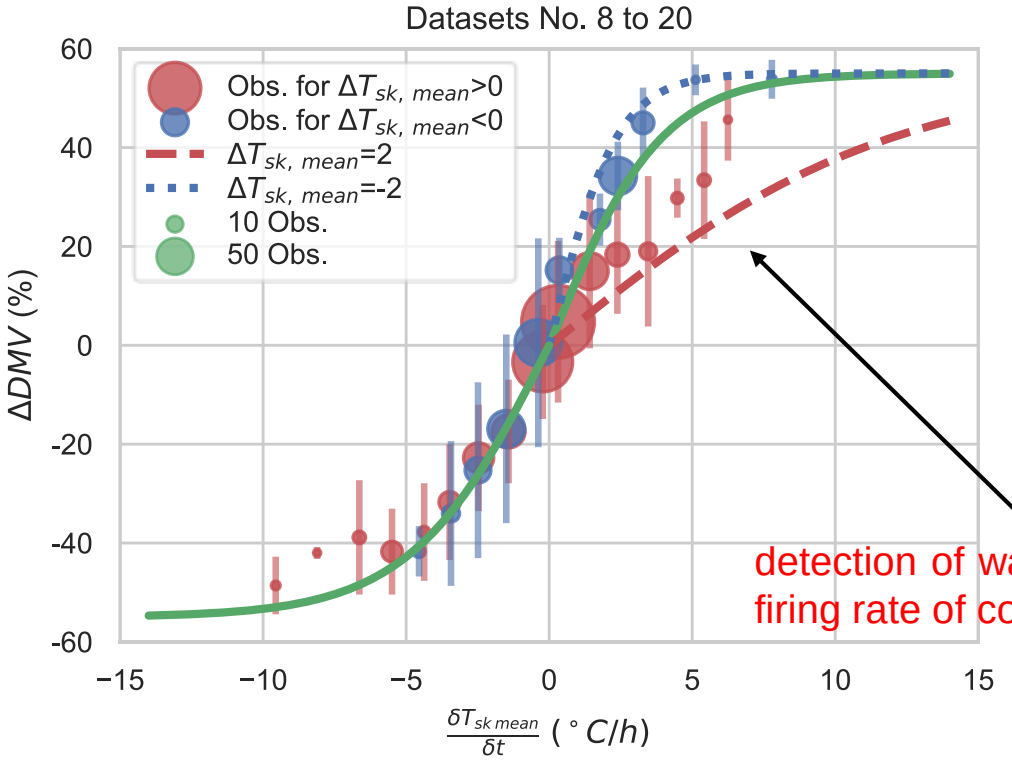
Steady-state sensory perception

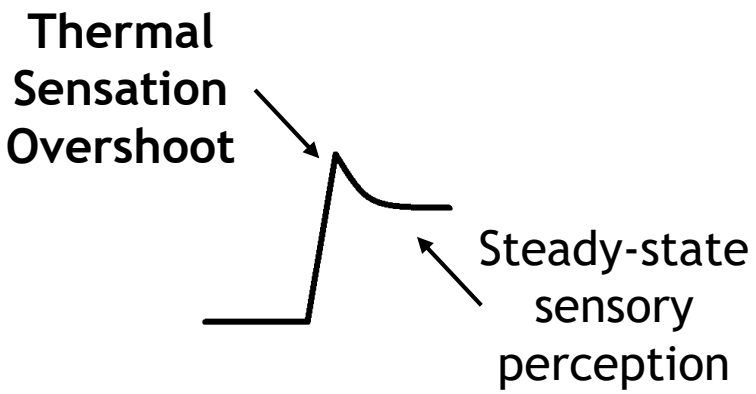
detection of warming rate related to inhibition of firing rate of cold sensory receptors…

Campero et al., 2001
doi: 10.1111/j.1469-7793.2001.t01-1-00855.x

Thermal overshoot

Data from 60 transient thermal conditions at rest



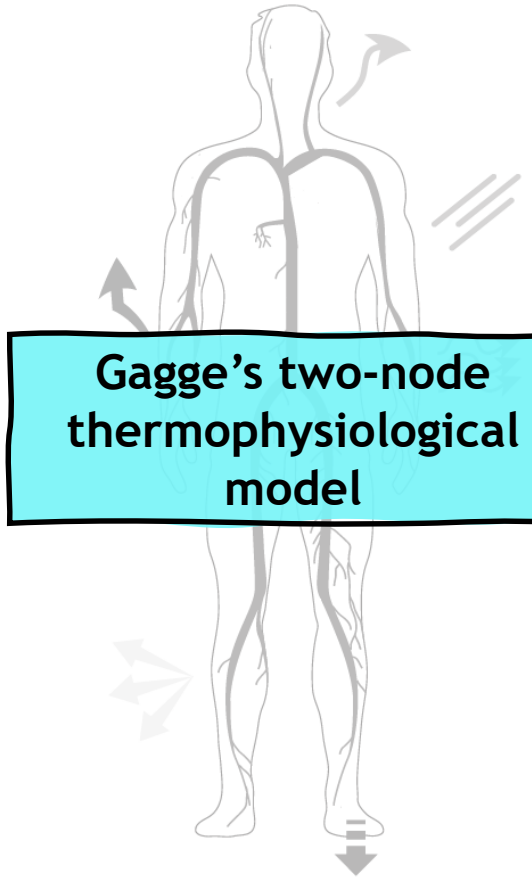


detection of warming rate related to inhibition of firing rate of cold sensory receptors…

… thus more acute at lower skin temperatures!

Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Modelling



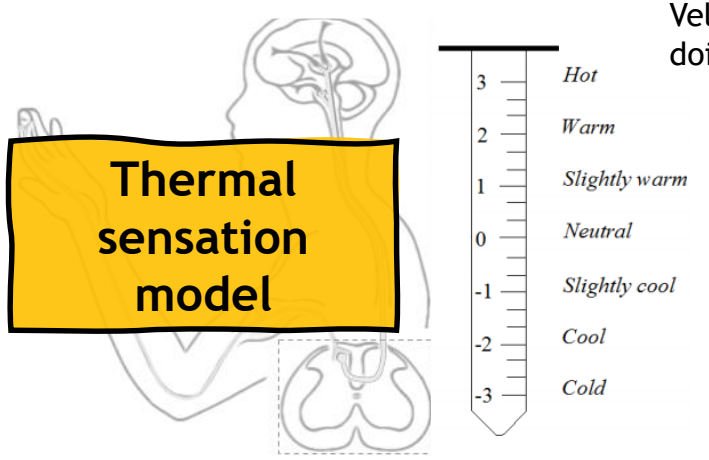
Environment

Gagge's two-node thermophysiological model

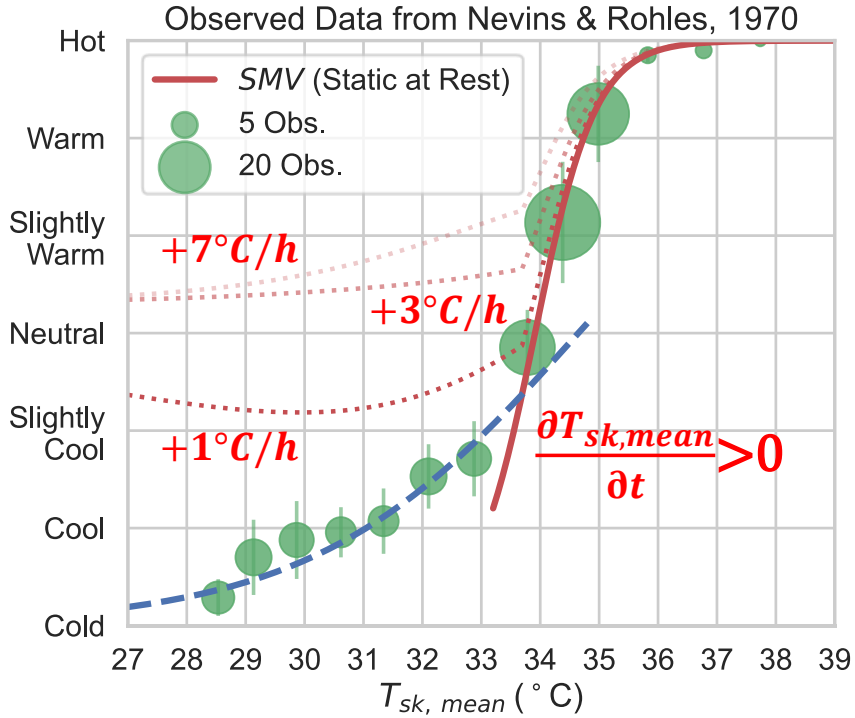
Physiological state

$$T_{core}$$
$$T_{sk,mean}$$
$$\frac{\partial T_{sk,mean}}{\partial t}$$
$$W_{sk}$$

Thermal sensation model

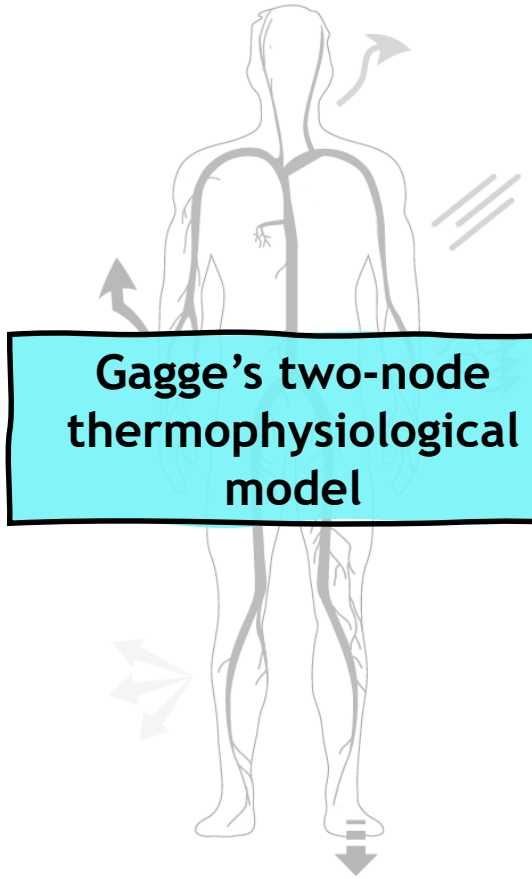


Data from 60 transient thermal conditions at rest



Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Modelling



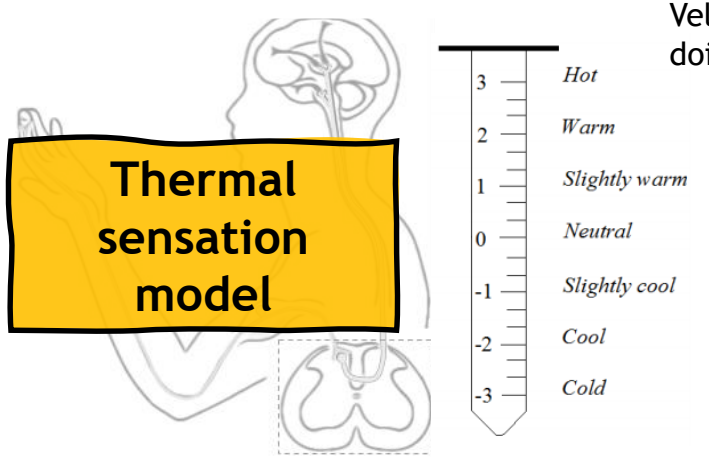
Environment

Gagge's two-node thermophysiological model

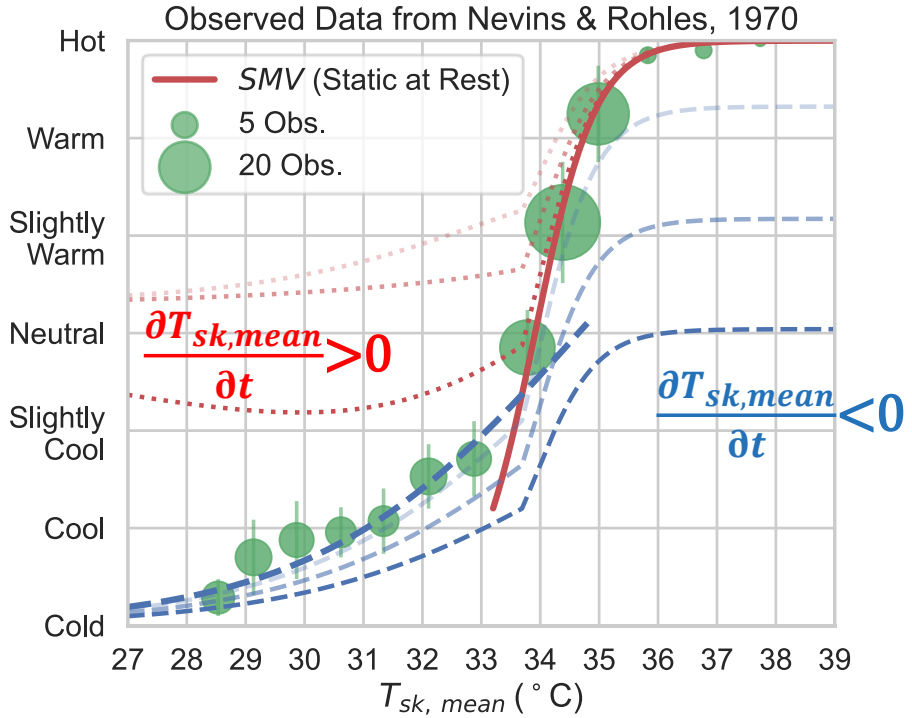
Physiological state

$$T_{core}$$
$$T_{sk,mean}$$
$$\frac{\partial T_{sk,mean}}{\partial t}$$
$$W_{sk}$$

Thermal sensation model

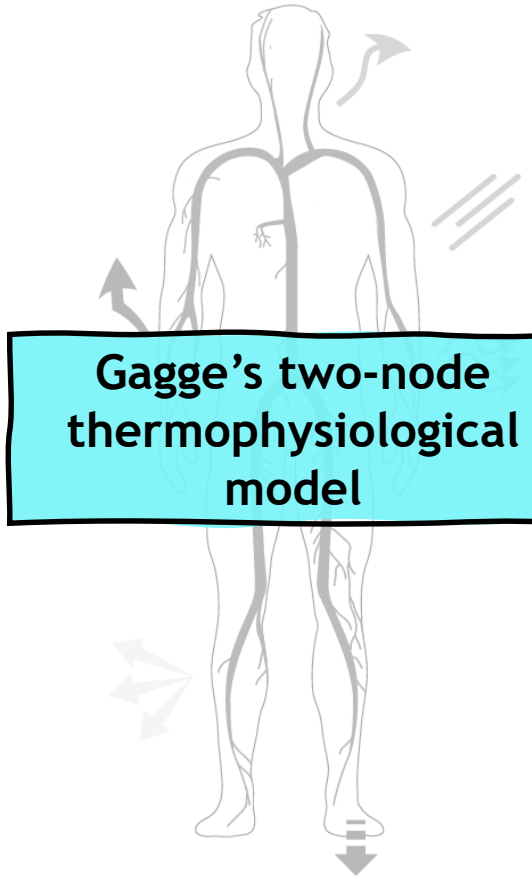


Data from 60 transient thermal conditions at rest



Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Modelling



Environment

Gagge's two-node thermophysiological model

Physiological state

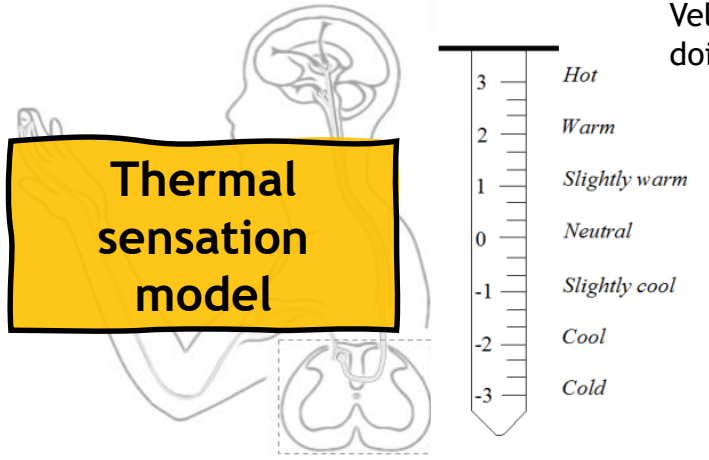
T_{core}

$T_{sk,mean}$

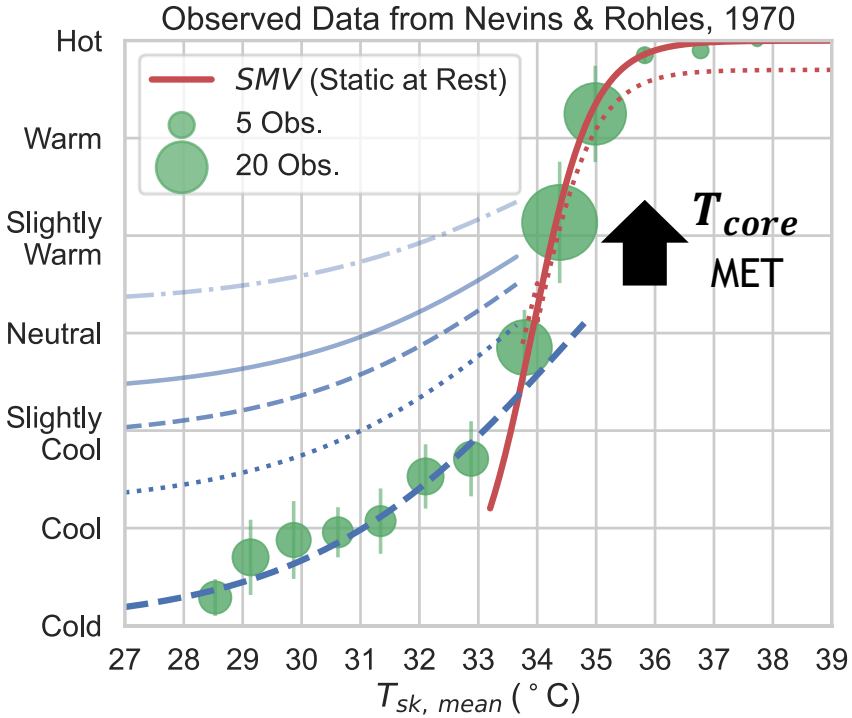
$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Thermal sensation model

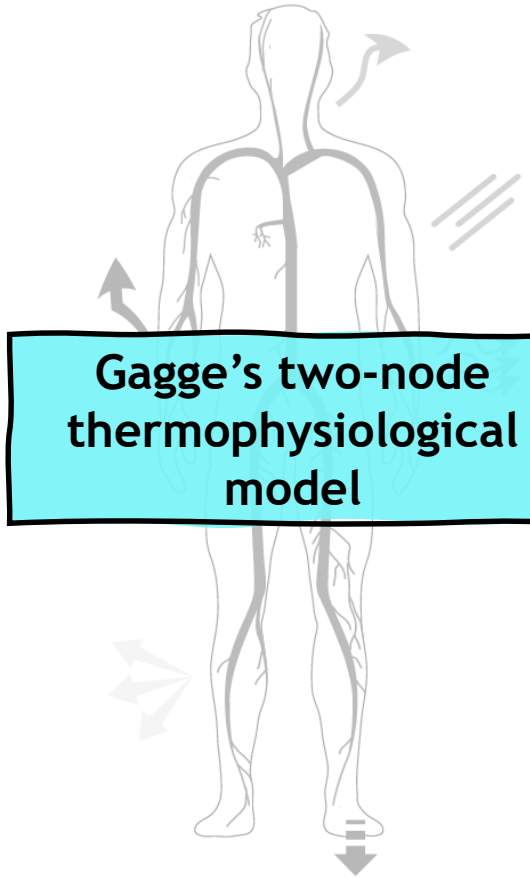


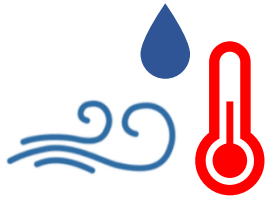
Data from 24 static thermal conditions during exercise



Vellei, 2024
doi: 10.1016/j.buildenv.2024.111469

Modelling





Environment

Gagge's two-node thermophysiological model

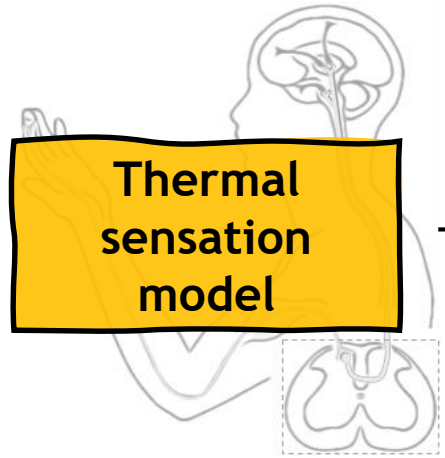
Physiological state

T_{core}

$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

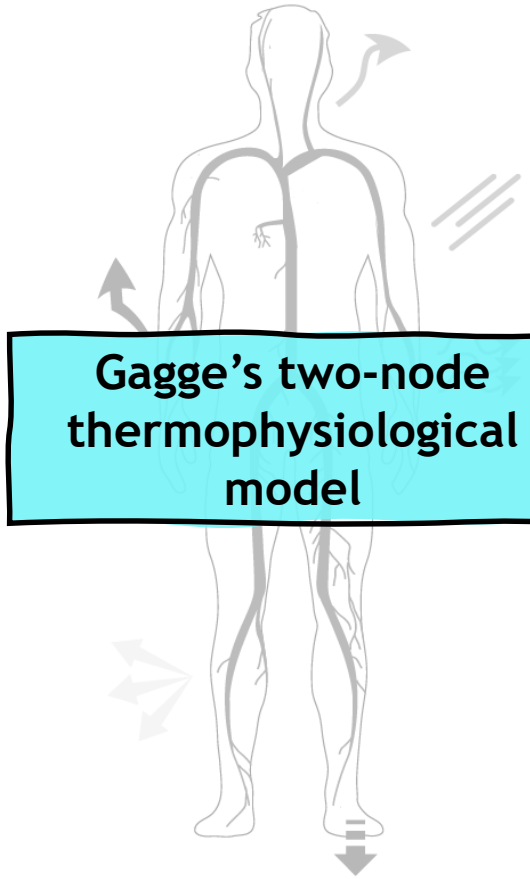
W_{sk}

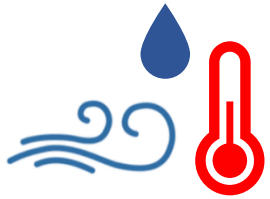


Thermal sensation model

Thermal comfort/pleasure model

Modelling





Environment

Gagge's two-node thermophysiological model

Physiological state

T_{core}

$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Thermal perception

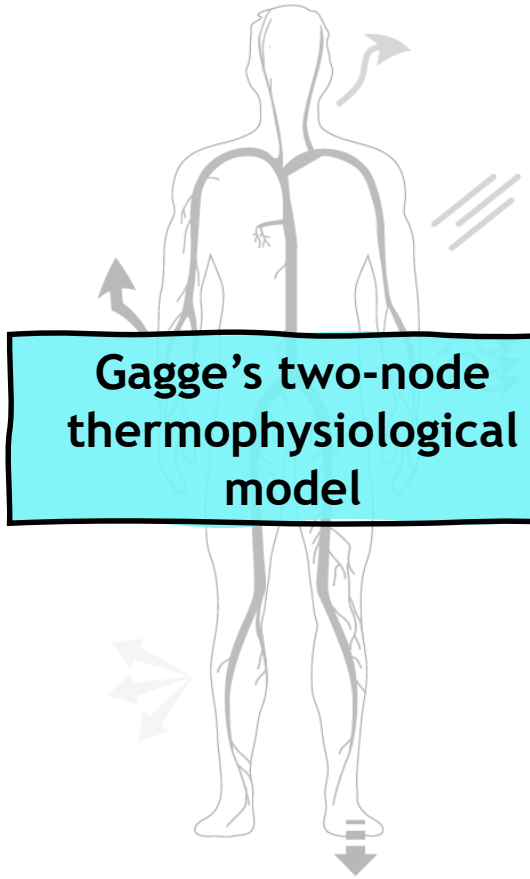
Am I cool … or warm?

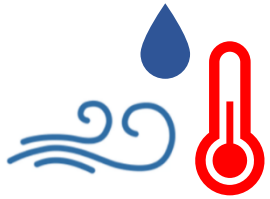
Thermal Alliesthesia

Thermal sensation model

Thermal comfort/pleasure model

Modelling





Environment

Gagge's two-node thermophysiological model

Physiological state

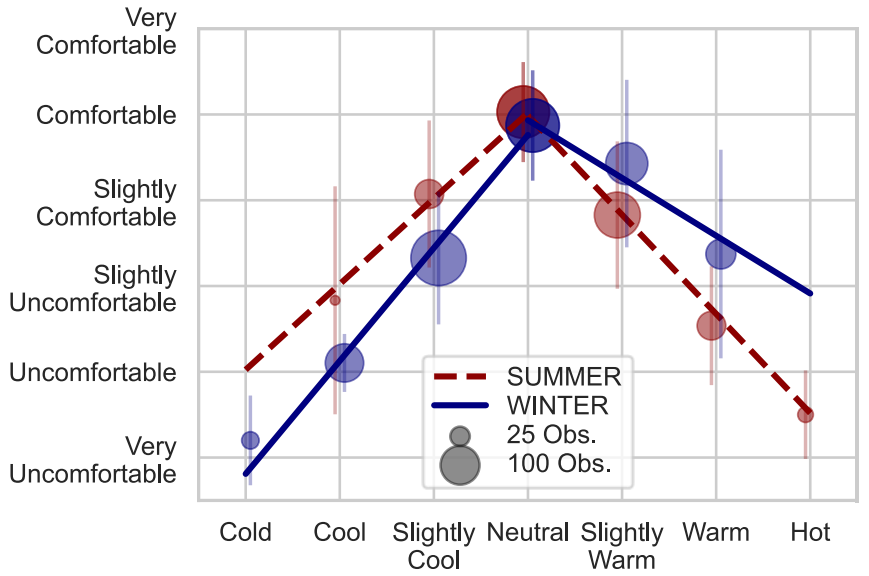
T_{core}

$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Vellei et al., 2023
doi: 10.1051/e3sconf/202339601003

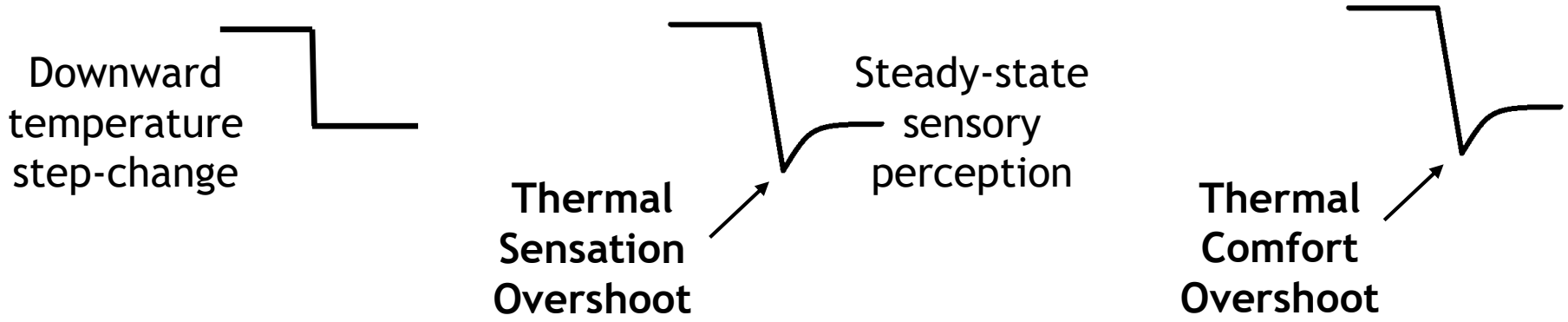


Thermal Alliesthesia

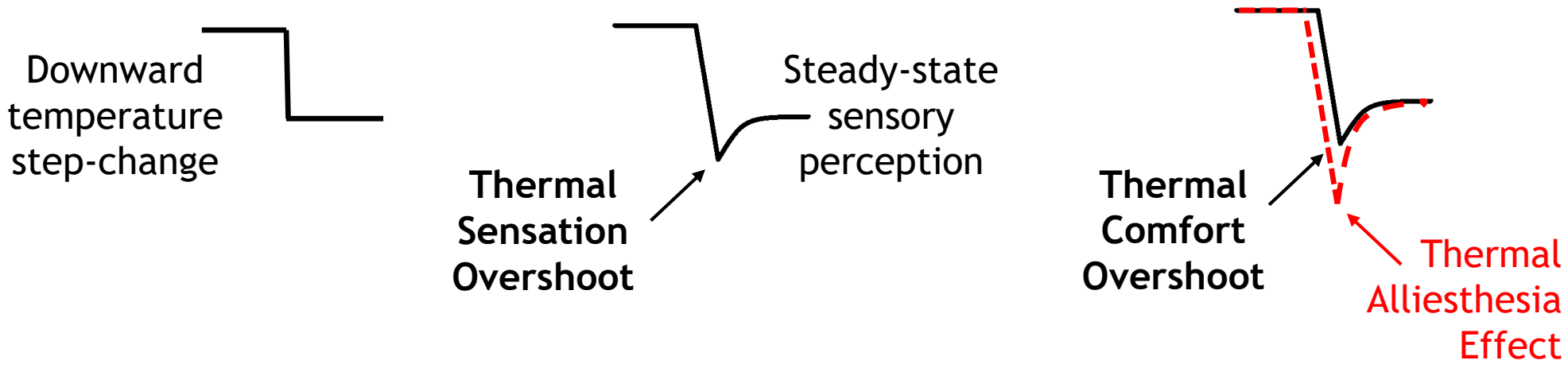
Thermal sensation model

Thermal comfort/pleasure model

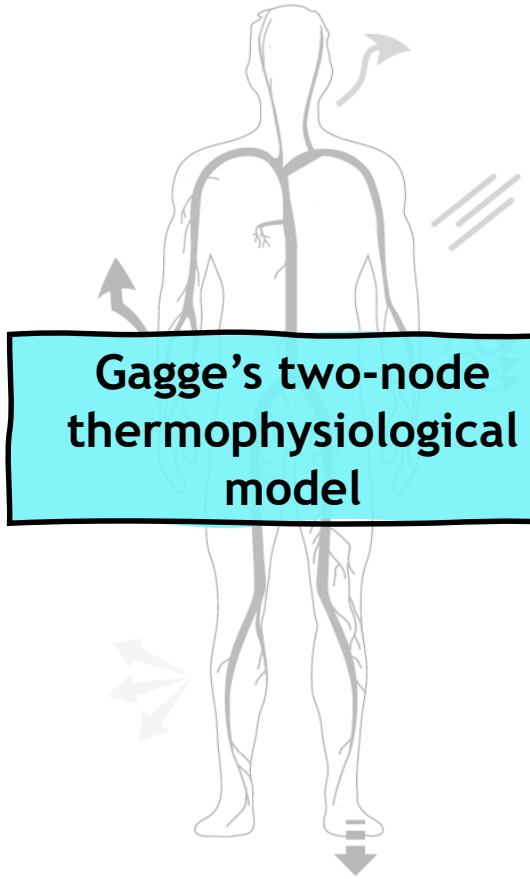
Thermal Alliesthesia

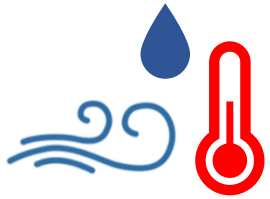


Thermal Alliesthesia



Modelling





Environment

Gagge's two-node thermophysiological model

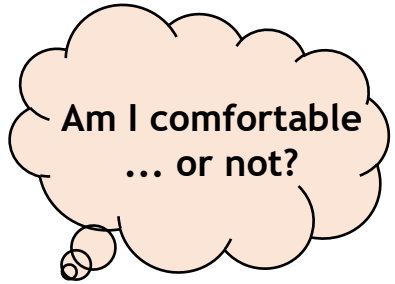
Physiological state

T_{core}

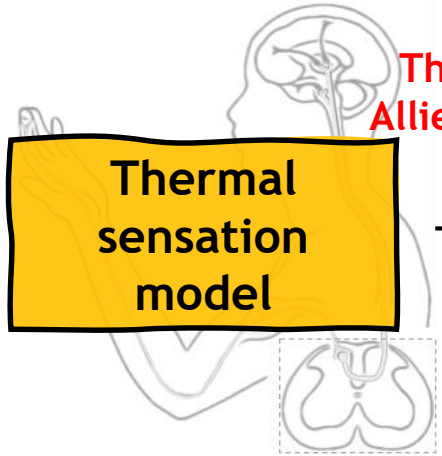
$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}



Thermal Perception

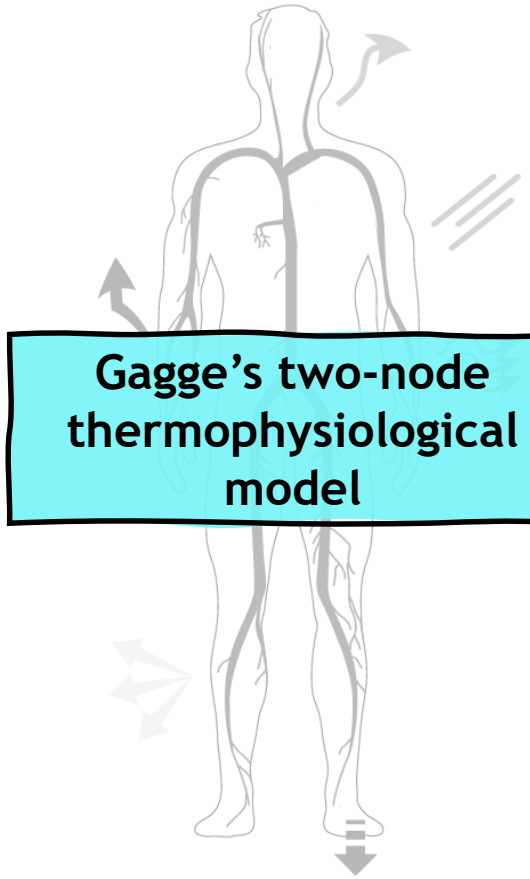


Thermal Alliesthesia

Thermal sensation model

Thermal comfort/pleasure model

Modelling



Environment

Occupant behaviour model

Gagge's two-node thermophysiological model

Physiological state

T_{core}

$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Thermal sensation model

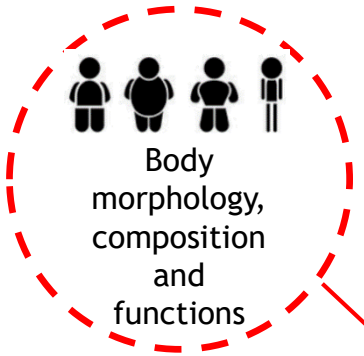
Thermal Alliesthesia

Thermal comfort/pleasure model

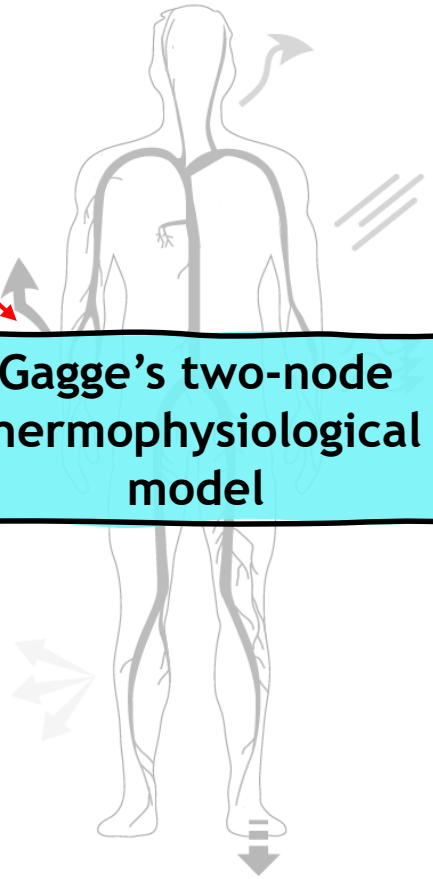
Am I comfortable ... or not?

Thermal Perception

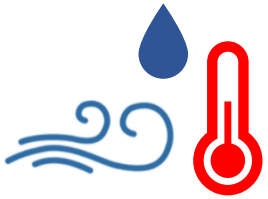
Variability



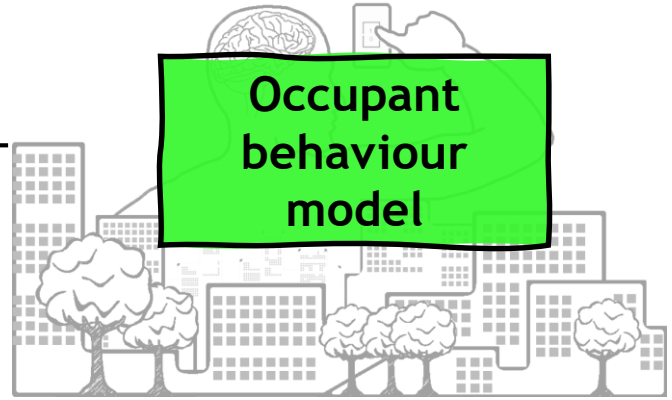
Body morphology, composition and functions



Gagge's two-node thermophysiological model



Environment



Occupant behaviour model

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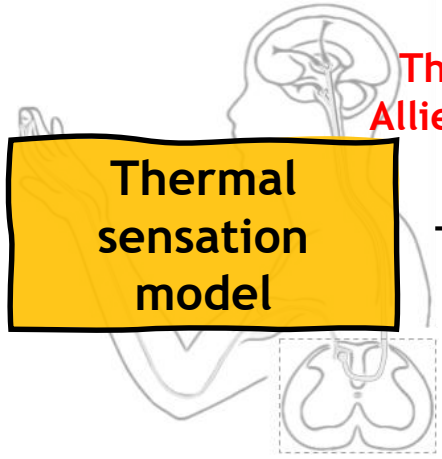
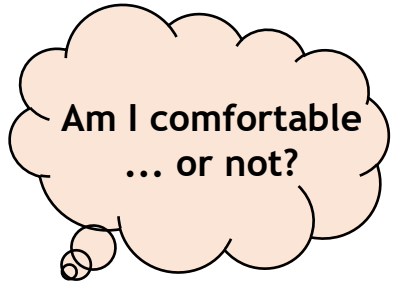
W_{sk}



Thermal sensation model

Thermal Alliesthesia

Thermal comfort/pleasure model



Thermal Perception

Variability

Body morphology, composition and functions

Environment

Occupant behaviour model

Gagge's two-node thermophysiological model

Physiological state

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$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}

Body morphology, composition and functions

Thermal Alliesthesia

Thermal sensation model

Thermal comfort/pleasure model

Am I comfortable ... or not?

Thermal Perception

Variability

Body morphology, composition and functions

Gagge's two-node thermophysiological model

Environment

Occupant behaviour model

Factors

Psychological
Socio-economic
Demographic
Cultural

Am I comfortable ... or not?

Thermal Perception

Physiological state

T_{core}

$T_{sk,mean}$

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Body morphology, composition and functions

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Body morphology, composition and functions

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Factors

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Thermal Perception

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Body morphology, composition and functions

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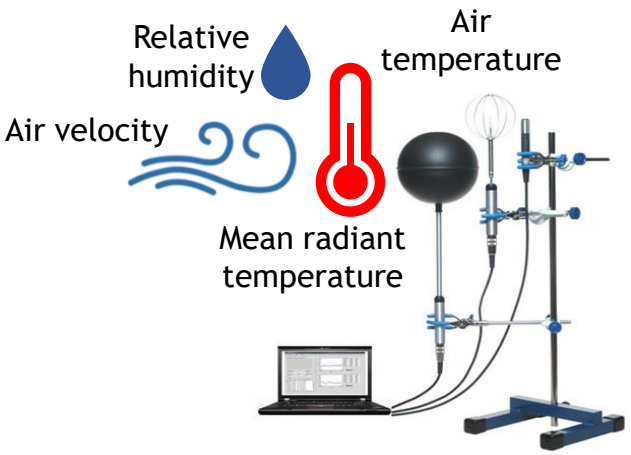
Thermal comfort/pleasure model

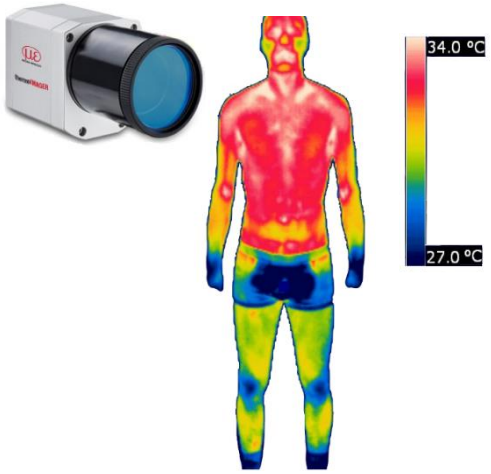
Experiments

under controlled dynamic thermal conditions

Physical Measurements 1 min



Skin Temperature Recording 30 sec



How do you feel right here, right now?

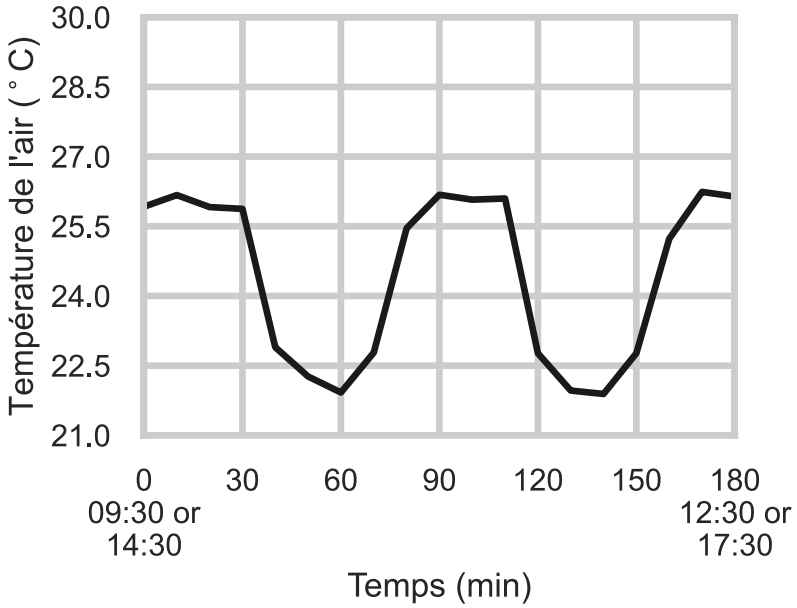
Subjective Measurements 10 min

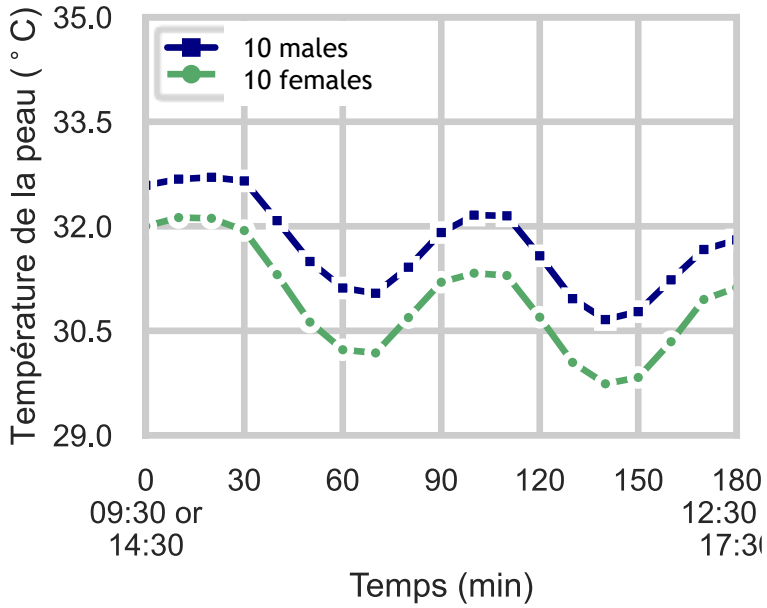
- ☐ Cold
- ☐ Cool
- ☐ Slightly Cool
- ☐ Neutral
- ☐ Slightly Warm
- ☐ Warm
- ☐ Hot

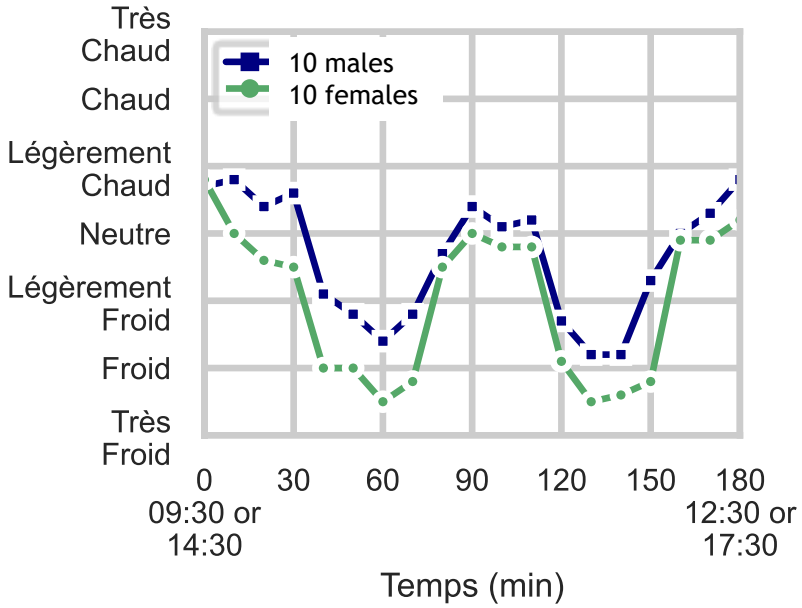
Vellei et al., 2023
doi: 10.1016/j.buildenv.2022.109677

Experiments

10 males and 10 females







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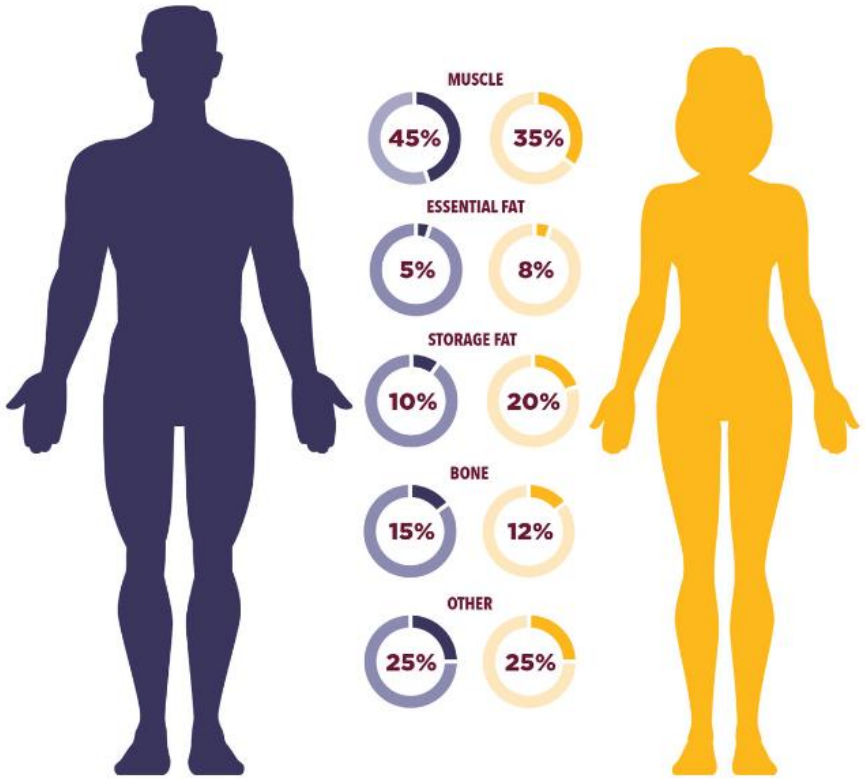
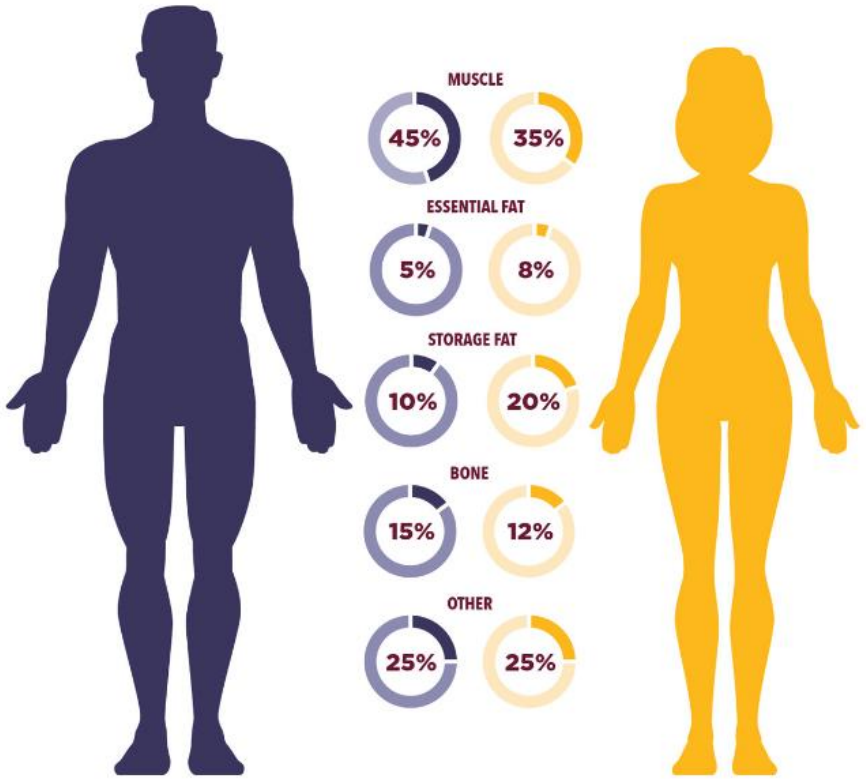
Variability

BIOLOGICAL SEX



Variability

BIOLOGICAL SEX



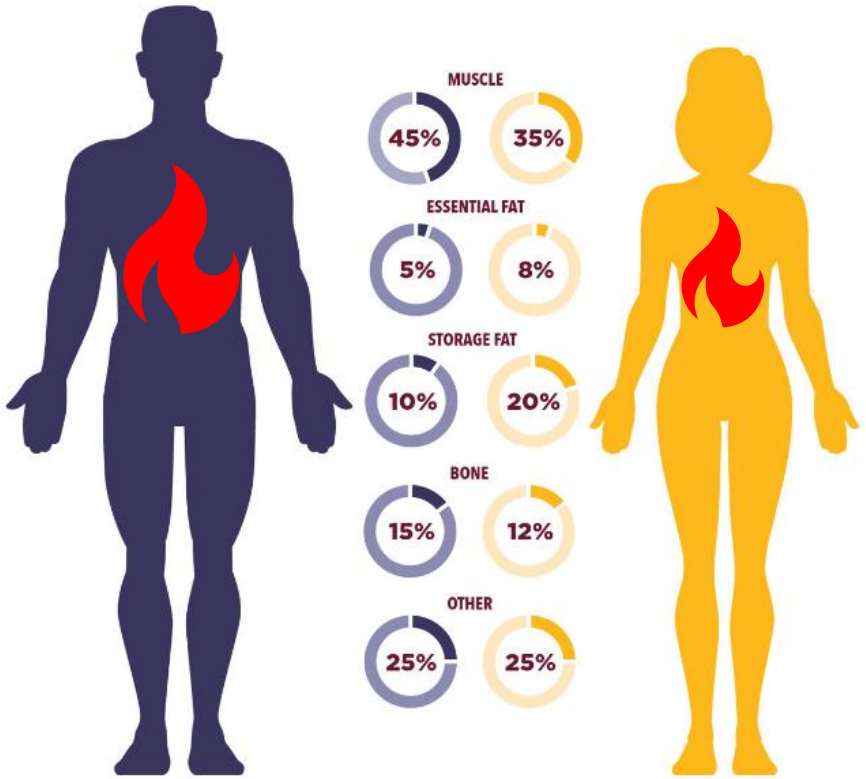
On average, females have:

COLD

- a lower metabolic rate
- a higher fat mass
- a smaller body mass

Variability

BIOLOGICAL SEX



On average, females have:

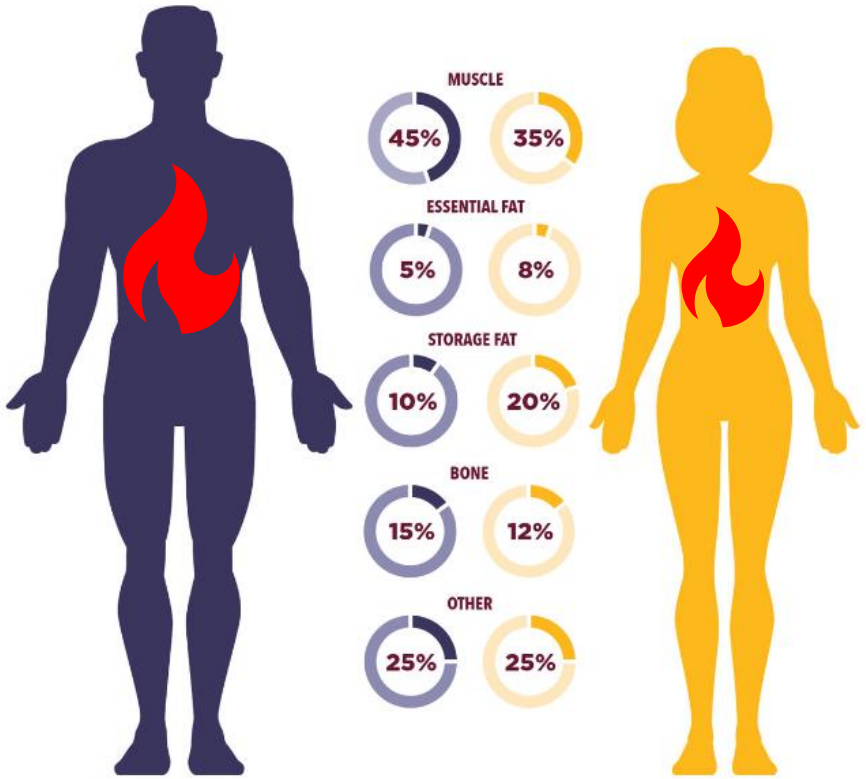
COLD

- a lower metabolic rate
- a higher fat mass
- a smaller body mass

lower maximal heat production capability

Variability

BIOLOGICAL SEX



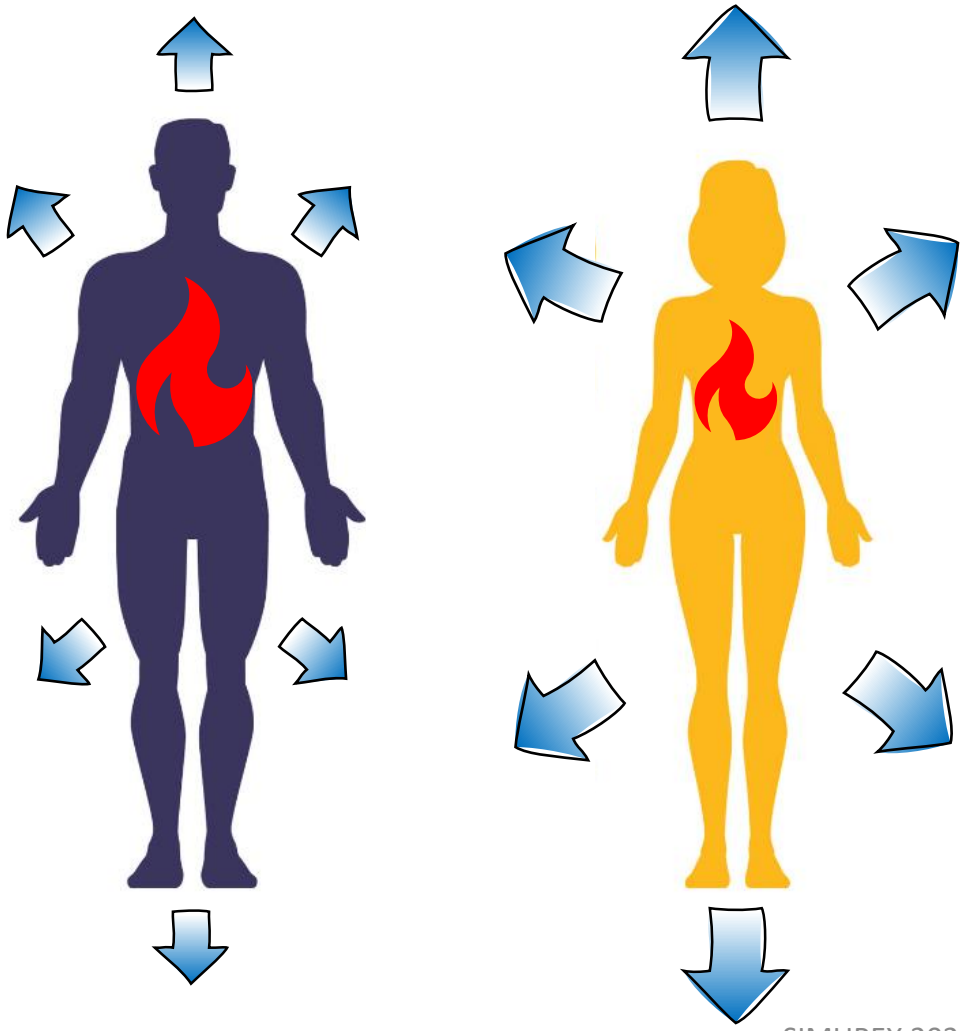
On average, females have:

COLD

- a lower metabolic rate
- a higher fat mass
- a smaller body mass
- a higher surface-to-mass ratio

Variability

BIOLOGICAL SEX



On average, females have:

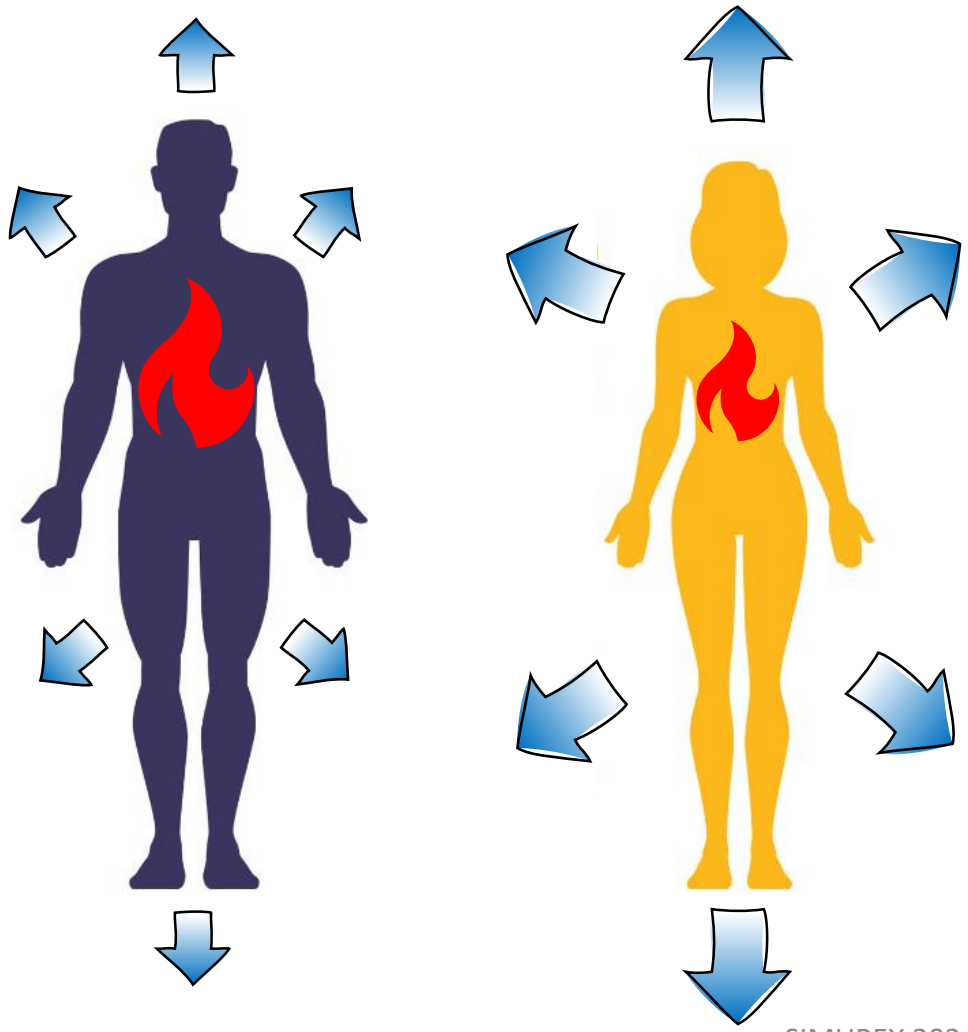
- a lower metabolic rate
- a higher fat mass
- a smaller body mass
- a higher surface-to-mass ratio

COLD

lower thermal inertia and greater convective heat loss per unit of mass

Variability

BIOLOGICAL SEX



On average, females have:

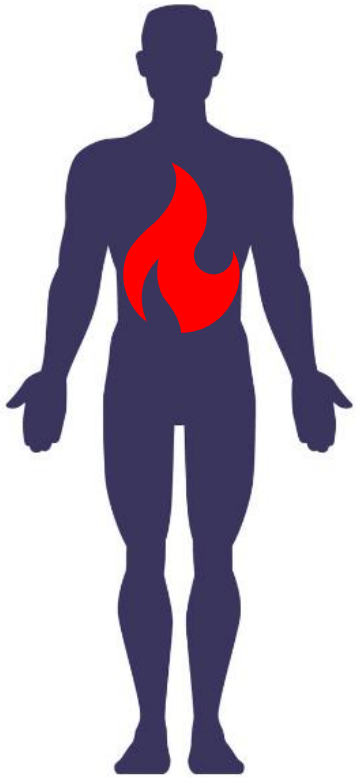
- a lower metabolic rate
- a higher fat mass
- a smaller body mass
- a higher surface-to-mass ratio
- a greater vasomotor response
- an earlier onset of shivering

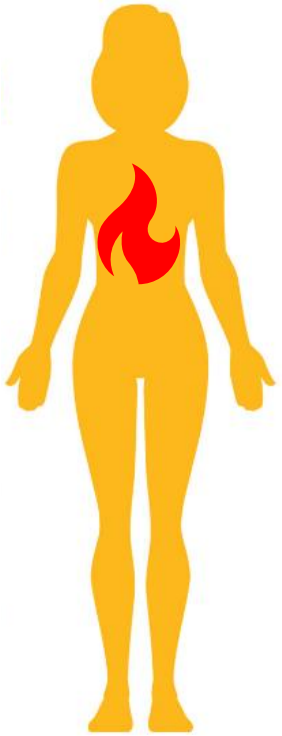
COLD

FAVORABLE FUNCTIONAL DIFFERENCES

Variability

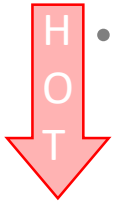
BIOLOGICAL SEX





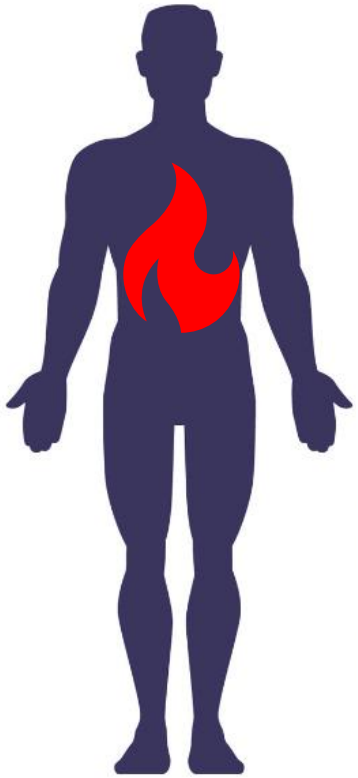
On average, females have:

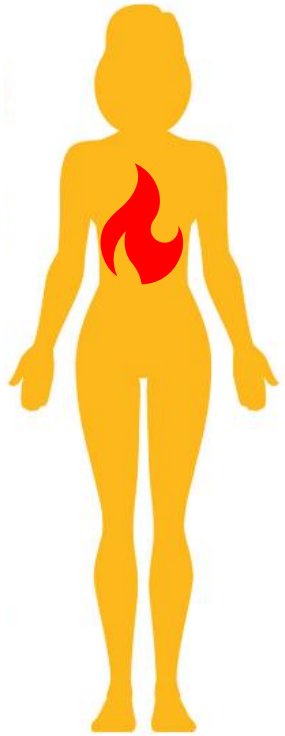
- a lower metabolic rate
- a higher fat mass
- a smaller body mass
- a higher surface-to-mass ratio
- a greater vasomotor response
- an earlier onset of shivering
- a smaller blood volume



Variability

BIOLOGICAL SEX





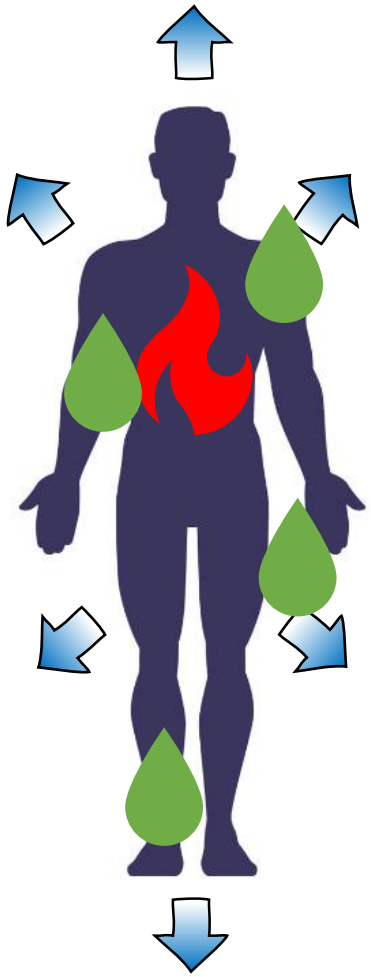
On average, females have:

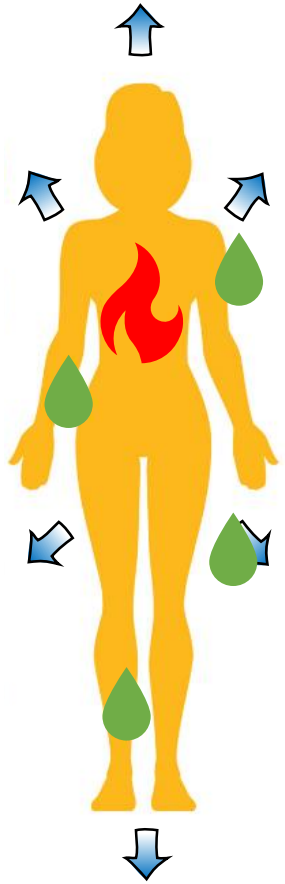
- a lower metabolic rate
- a higher fat mass
- a smaller body mass
- a higher surface-to-mass ratio
- a greater vasomotor response
- an earlier onset of shivering
- a smaller blood volume
- a lower sweat secretion rate

HOT

Variability

BIOLOGICAL SEX





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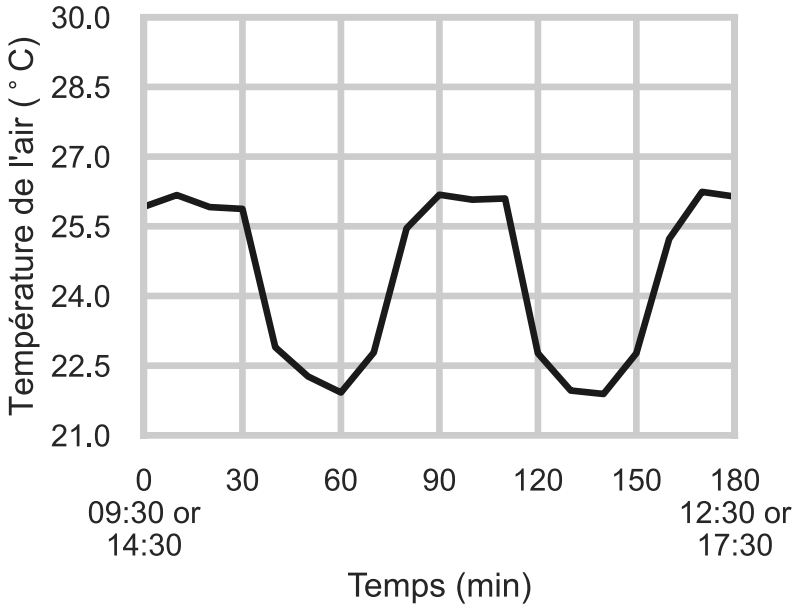
- an earlier onset of shivering
- a smaller blood volume
- a lower sweat secretion rate

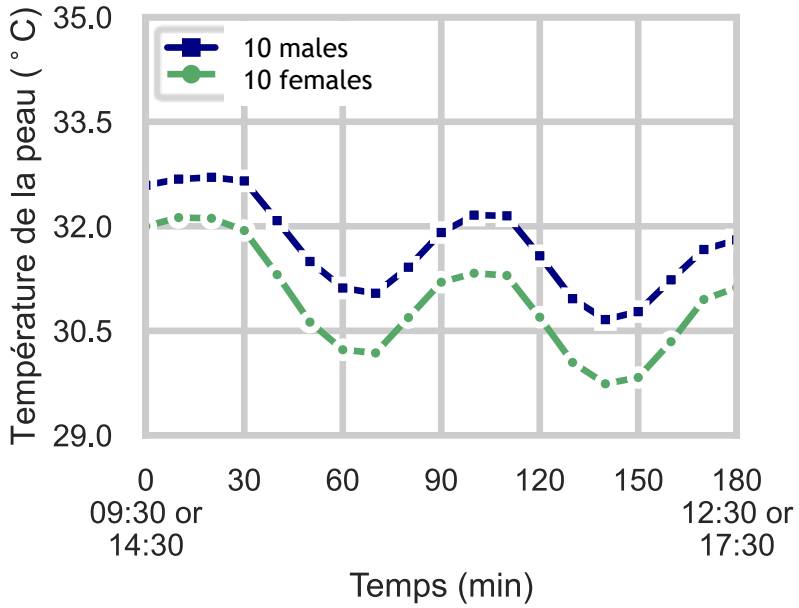
HOT

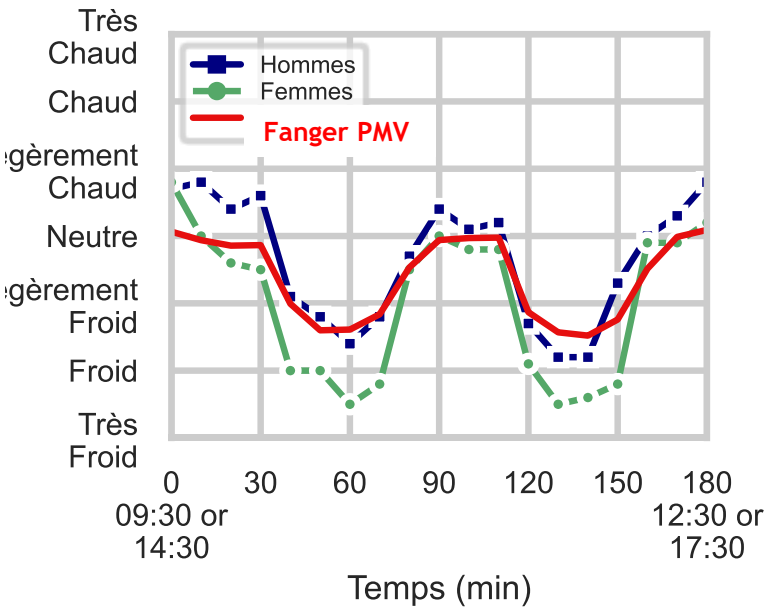
lower convective and evaporative heat dissipation

Experiments

10 males and 10 females







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doi: 10.1016/j.buildenv.2022.109677

Experiments

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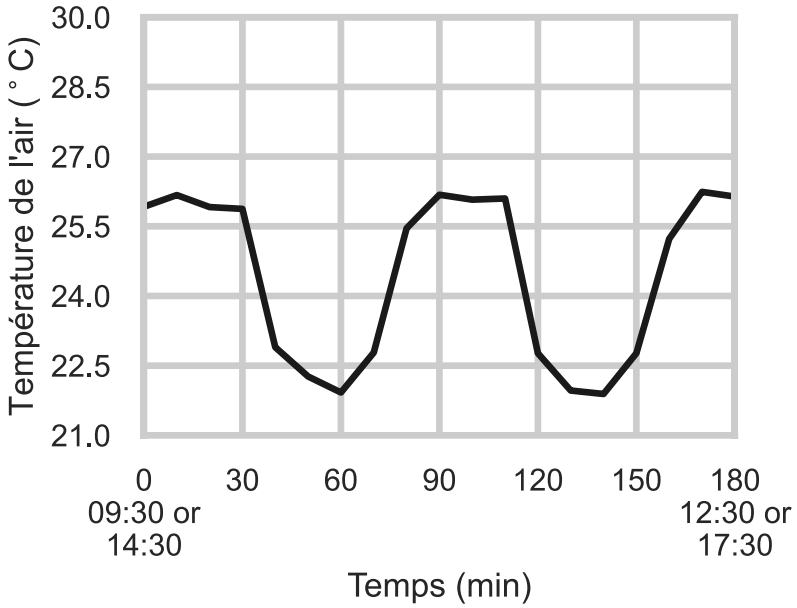
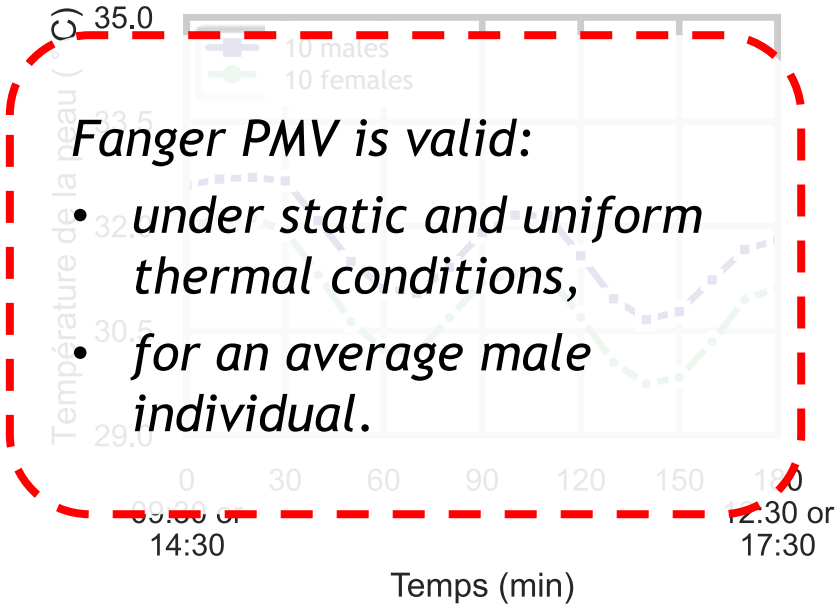
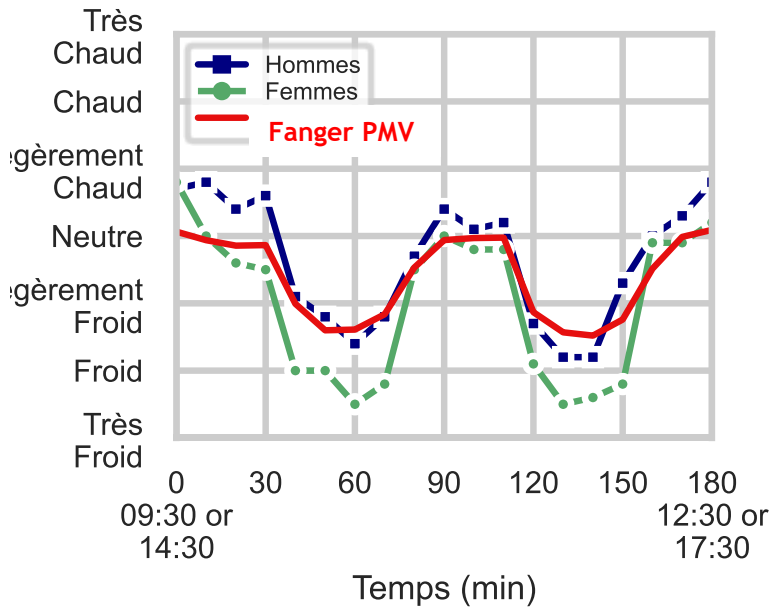




Fanger PMV is valid:

- *under static and uniform thermal conditions,*
- *for an average male individual.*



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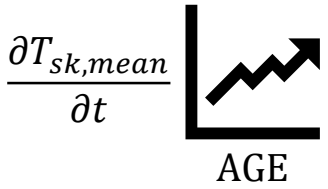
Experiments

under controlled dynamic thermal conditions
with 29 males and 35 females
MLM with possible two-way interactions

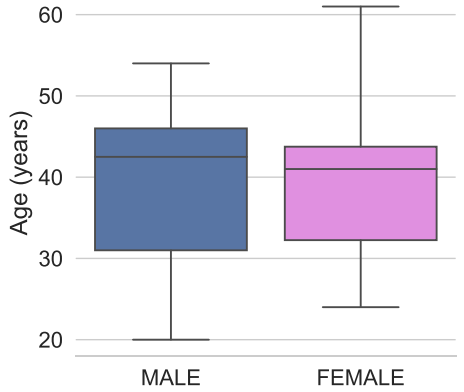
AGE and BMI

$$TSV = f\left(T_{sk,mean},\ \frac{\partial T_{sk,mean}}{\partial t},\ \underbrace{\frac{\partial T_{sk,mean}}{\partial t} * \mathrm{AGE}},\ \frac{\partial T_{sk,mean}}{\partial t} * \mathrm{BMI}\right)$$

Positive Coef.



thermal sensitivity increases with age up to 50-60 years and then decreases for elderly



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MLM with possible two-way interactions

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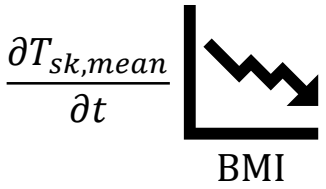
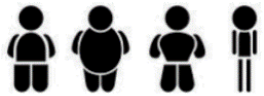
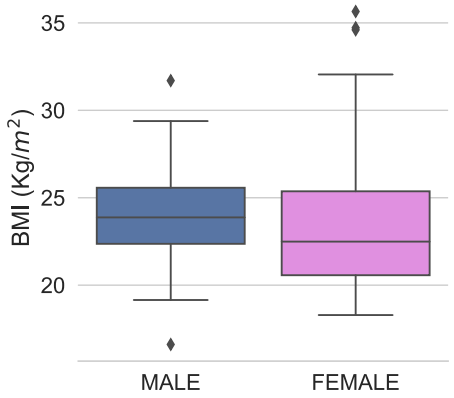
Negative Coef.



a higher BMI is associated with a higher thickness of subcutaneous fat





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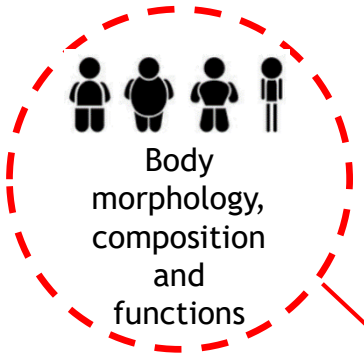
Variability



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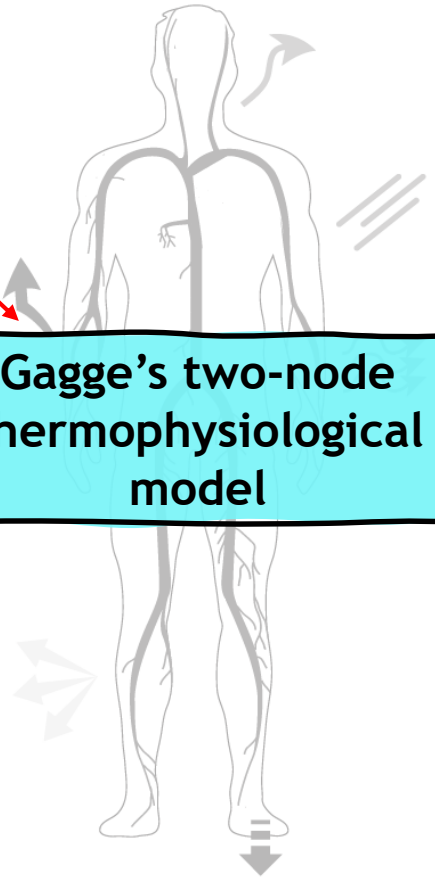
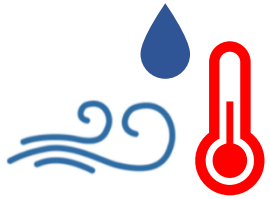
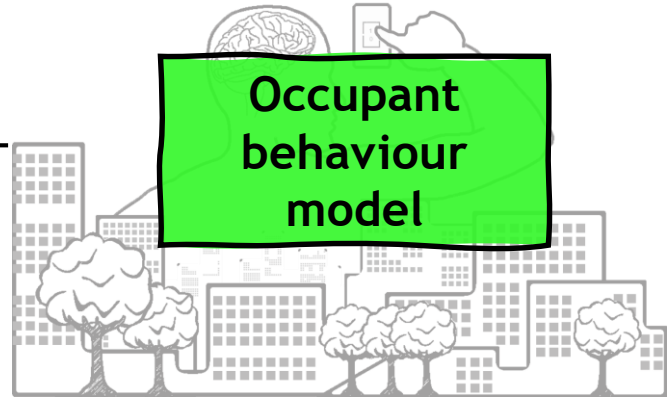


Gagge's two-node thermophysiological model



Environment



Occupant behaviour model

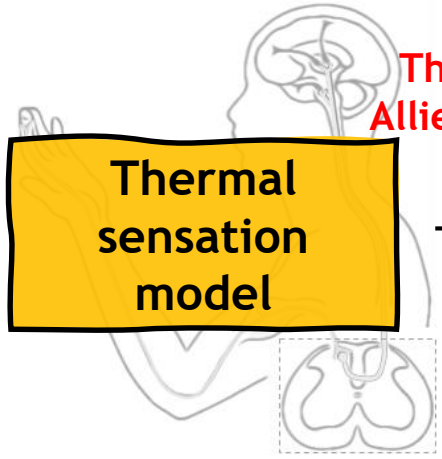
Physiological state

T_{core}

$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

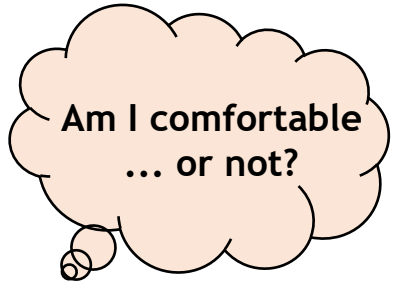
W_{sk}



Thermal Alliesthesia

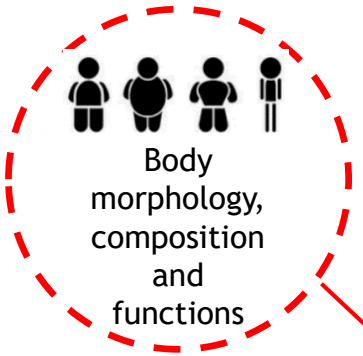
Thermal sensation model

Thermal comfort/pleasure model

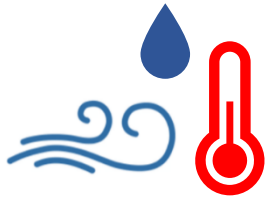


Thermal Perception

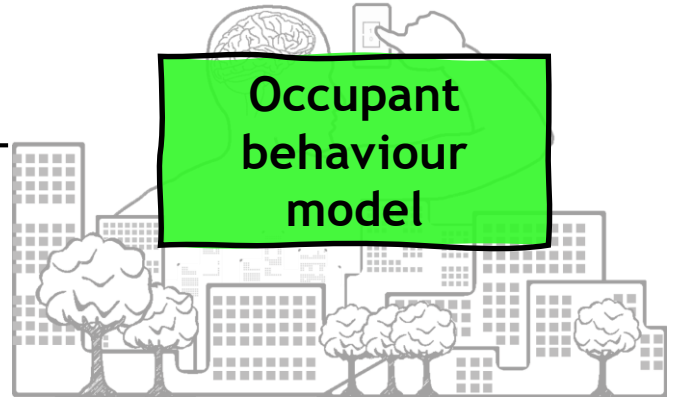
Variability



Body morphology, composition and functions



Environment



Occupant behaviour model

Gagge's two-node thermophysiological model

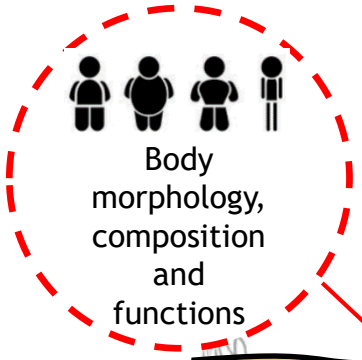
Physiological state

T_{core}

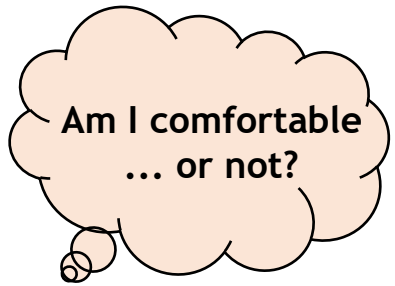
$T_{sk,mean}$

$\frac{\partial T_{sk,mean}}{\partial t}$

W_{sk}



Body morphology, composition and functions



Am I comfortable ... or not?

Thermal Perception

Thermal Alliesthesia

Thermal sensation model

Thermal comfort/pleasure model

Thank you ! Merci ! Grazie !

Contact: marika.vellei@u-bordeaux.fr

Data & Models: https://figshare.com/authors/Marika_Vellei/14106006