IEA Energy in Buildings and Communities TCP

IEA EBC Annex 87

Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)

Bjarne W. Olesen and Ongun Berk Kazanci
Intl. Centre for Indoor Environment and Energy, Technical University of Denmark

December 2022

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AGENDA

- 16:30 | Introduction to IEA-EBC Annex 87, **Bjarne W. Olesen**, ICIEE/DTU, Denmark
  16:40 | Desk mounted Personalized ventilation systems, **Ongun Berk Kazanci**, ICIEE/DTU, Denmark
  16:55 | Footwarmers providing efficient heating, **Hui Zhang**, UC-Berkeley, USA
  17:10 | Questions and answers
  17:20 | Heated and cooled chairs, **Sabine Hoffmann**, Technical University of Kaiserslautern, Germany
  17:35 | Wearable heating and cooling technology, **Joon-Ho Choi**, University of Southern California, USA
  17:50 | Questions and answers

  18:00 | End of webinar

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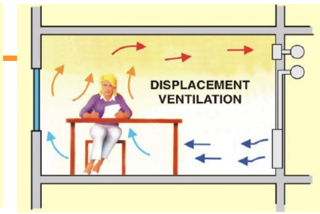
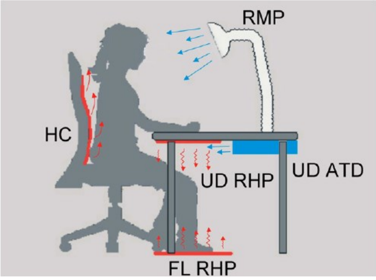
WHAT IS PECS?

- Personal Environmental Control System (PECS) with the functions of heating, cooling, ventilation, lighting and acoustic has advantages of controlling the localized environment at occupant's workstation by their preference instead of conditioning an entire room.
- This improves personal comfort, health and energy efficiency of the entire heating, ventilation and air-conditioning (HVAC) system substantially.
- Personalized ventilation will also protect against cross contaminations, which are critical in open plan offices and work places with close distance.

EBC



Source: Melikov 2010



Source: Watanabe et al. 2010

Source: Zhang et al. 2010

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OBJECTIVES

- Establish design criteria and operation guidelines for PECS
- Quantify the benefits regarding health, comfort and energy performance.
- Control concepts and guidelines for operating PECS in spaces with general ambient systems for heating, cooling, ventilation and lighting.

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SCOPE

- Includes all types of PECS for local heating, cooling, ventilation, air cleaning, lighting and acoustic.
- Includes desktop systems, which are mounted on desks or integrated in a furniture
- Chairs with heating/cooling and ventilation.
- Wearables, where heating/cooling and ventilation are included in garments or devices attached to occupants' body.
- Not including cars

EBC

TARGET AUDIENCE

- Manufacturers (who need design guidelines)
- Building owners and consultants (who need information on performance, advantages, problems, operation, how PECS is operated together with other building systems)
- Users (need same info as building owners and for home workplaces)
- Standardisation Bodies (revision of standards for indoor environmental quality).

EBC

Schedule

- January 2022-December 2022: Preparation phase
- January 2023-December 2025: Working phase
- January 2025-December 2026: Reporting phase

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Subtask A: Fundamentals

- **Leader**
  - **Mariya P. Bivolarova, Technical University of Denmark, Denmark**
- **Co-leader:**
  - **Dolaana Khovalyg, EPFL, Switzerland**
- **Activity A1:** Definition and identification of the requirements of PECS in terms of localized and background Indoor Environmental Quality (IEQ) i.e., thermal, air quality, lighting, and acoustics.
- **Activity A2:** Outline the benefits of PECS regarding comfort, health and productivity based on literature and new research.
- **Activity A3:** Outline the minimum energy cost requirements for PECS.

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Subtask B: Applications and Technologies

- **Leader:**
  - **Kai Rewitz, RWTH Aachen University, Germany**
- **Co-leader**
  - **Joyce Kim, University of Waterloo, Canada**
- **Activity B1:** Summarize the working principles, capabilities and limitations of existing PECS, based on literature.
- **Activity B2:** Identify future development and improvement suggestions for PECS for optimal energy, IEQ and cost performance.

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Subtask C: Control, operation and system integration

- **Leader:**
  - **Joon-Ho Choi, University of Southern California, USA**
- **Co-leader**
  - **Bin Yang, Tianjin Chengjian University, Tianjin, China**

- **Activity C1:** Identify and summarize existing methods for controlling PECS (including sensors used for control).
- **Activity C2:** Develop guidelines on integrating PECS with ambient conditioning systems in buildings.

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Subtask D: IEQ and Energy Performance evaluation

- **Leader:**
  - **Douaa Al-Assad, KU-Leuven, Belgium**
- **Co-leader**
  - **Marco Perino, Politecnico di Torino, Italy**
- **Activity D1:** Collection of existing methods of studying and testing PECS.
- **Activity D2:** Identification of generic power requirements for PECS to achieve energy savings compared to ambient conditioning systems.
- **Activity D3:** Development of universal and standardized ways of evaluating and reporting performance of PECS.

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Subtask E: Policy and advisory actions

- **Leader:**
  - **Rajan Rawal, CRABSE, CEPT University, India????**
- **Co-leader:TBD**
- **Activity E1:** Summary of national and international building codes and standards regarding PECS.
- **Activity E2:** Develop ways of overcoming current barriers for a wide implementation of PECS in buildings.
- **Activity E3:** Provide input to existing national and international standards about requirements, characteristics, and performance of PECS.

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DELIVERABLES

1. Guidebook on requirements for PECS
2. State-of-the-art report on PECS
3. Guidebook on PECS design, operation and implementation in buildings (including integration of PECS with ambient conditioning systems)
4. Report on test methods for performance evaluation of PECS
5. Universal criteria about requirements, characteristics, and performance of PECS to be used in national and international standards

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International Centre for Indoor Environment and Energy

Desk Mounted Personalized Ventilation Systems

Ongun Berk Kazanci, PhD

Associate Professor in IEQ and HVAC Systems at Technical University of Denmark

Senior Engineer Building Physics at Buro Happold

Indoor Environmental Quality and Personalized Environmental Control Systems (PECS)

IEQ – Indoor Environmental Quality

4 Environmental Parameters

Thermal | Indoor Air | Luminous | Acoustic

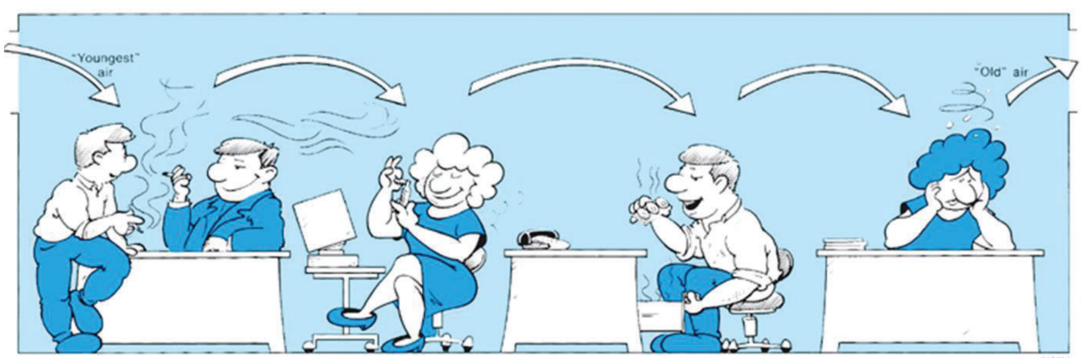
Energy Efficiency,
Carbon Neutrality

Comfort, Satisfaction, Productivity, Health and Well-being
Of people

Personalized Environmental Control Systems (PECS) – Personalized Ventilation (PV)

- PECS condition the immediate surroundings of the occupants, creating a ”personalized” space
- PECS provide individual control of indoor environmental quality (IEQ) factors
  - Heating / cooling, ventilation, lighting, and acoustics
- Why is PECS particularly important and relevant right now?
- COVID-19 pandemic
  - Increased interest in infection control -> personalized ventilation can provide fresh air more efficiently
- Climate change
  - Resiliency to climate-related disruptions, e.g., heatwaves, wildfires and outdoor air pollution, etc.
  - Energy efficiency, carbon neutrality
- Comfort and health of indoor occupants -> interaction of multiple IEQ factors

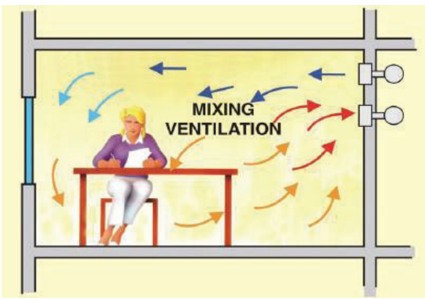
Indoor Air Quality – Personalized Ventilation (PV)

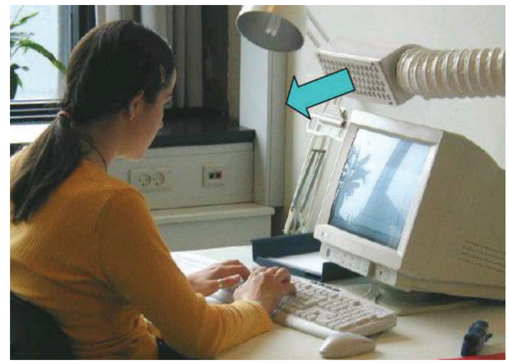


> *We would hesitate to drink water from a swimming pool polluted by human bioeffluents. Still, we accept consuming indoor air that has previously been in the lungs of other persons and is polluted by human bioeffluents and other contaminants generated in the space.*
>
> – P. O. Fanger, 2001

Personalized Ventilation (PV) Systems

- Local volume conditioning: it aims at supplying the clean and cool air close to an occupant before it is mixed with the room air
- The most important advantage of personalized ventilation is its potential to provide clean, cool and dry air at inhalation (breathing zone)



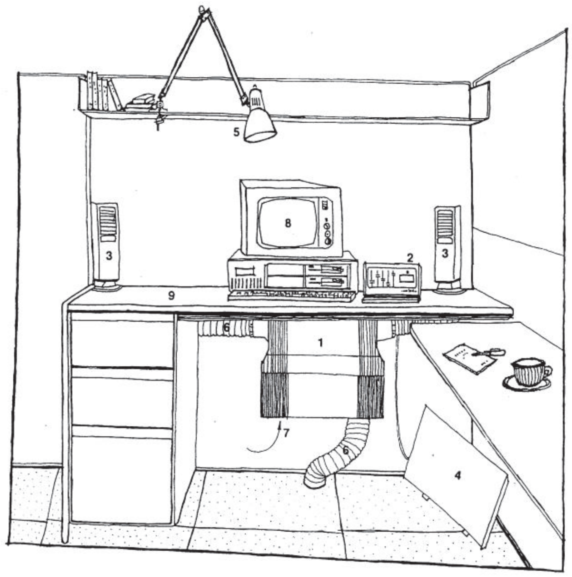


Melikov, 2010

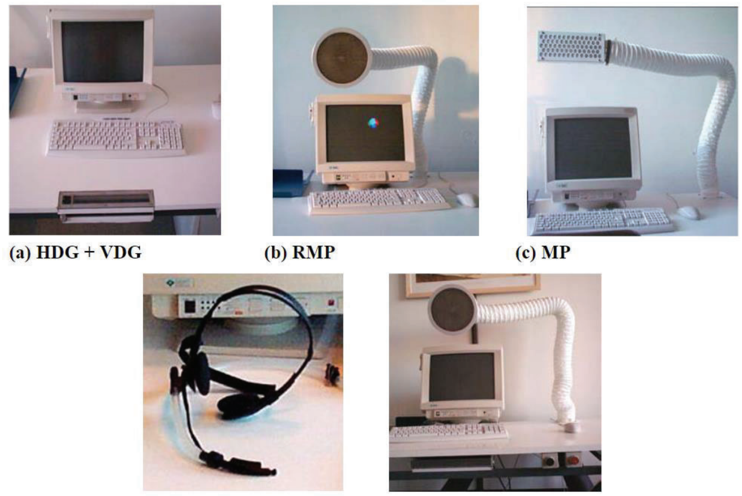
PECS and PV Studies

- Personalized heating, cooling, and ventilation
- Earlier studies had more focus on personalized ventilation, and individual needs and preferences
- Different Air Terminal Devices (ATDs)
- Different systems and combinations
- Approaches:
    - Physical measurements
    - Measurements with (breathing) thermal manikins
    - Human subject experiments
    - Field measurements

PECS and PV Studies



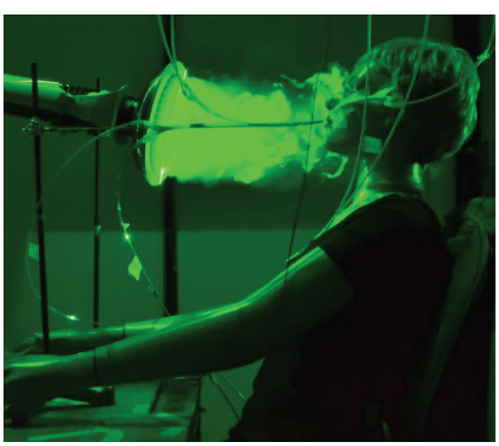
Bauman et al., 1998



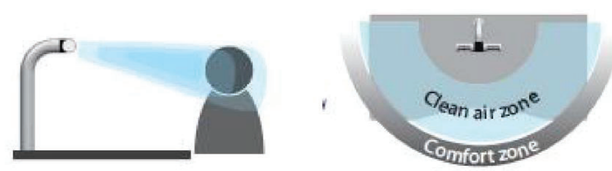
(a) HDG + VDG (b) RMP (c) MP (d) Headset (e) RMP + HDG

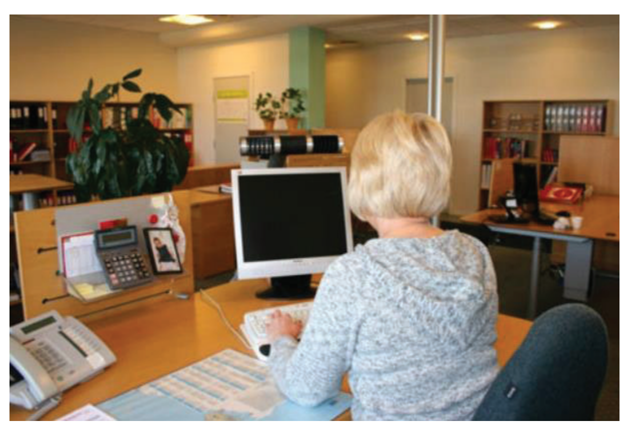
Kaczmarczyk et al., 2006

PECS and PV Studies



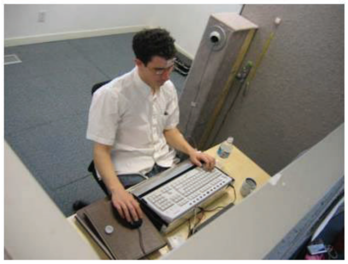
Bivolarova et al., 2017



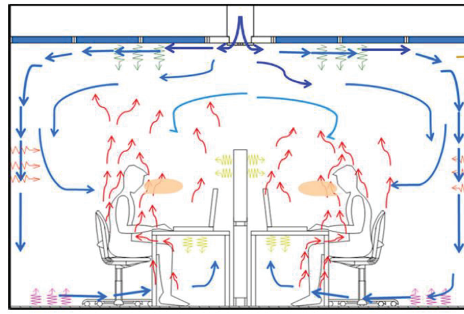


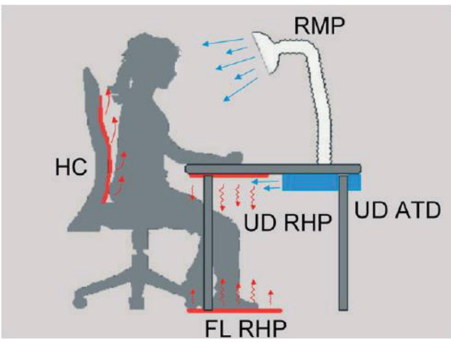
Melikov, 2016

PECS and PV Studies

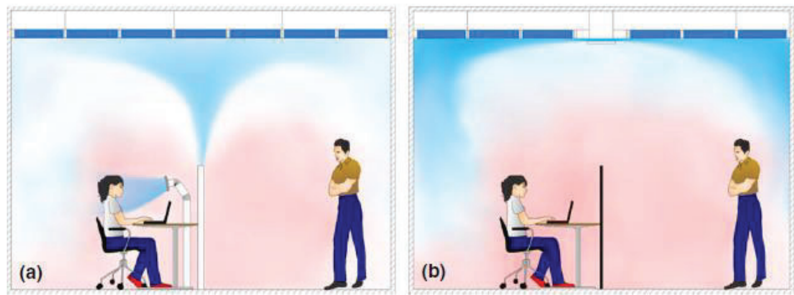


Zhang et al., 2009





Watanabe et al., 2010



Melikov, 2016

Development of PECS Prototypes at DTU

v1
- Air Terminal Device (ATD)
  - Recirculation + Filter
- 3 Independent Heating Panels (for thighs, shin, and feet)

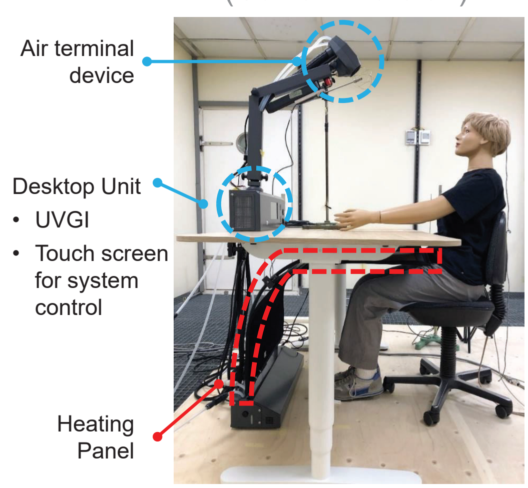
v2
- Improved ATD
  - Recirculation + Filter
  - **Cooling mode** (Peltier element, waste heat dissipation by **air**)
- Same heating panel as v1

Mockup: Flexible Heating Panel (FHP)

v3
- Improved ATD
  - Recirculation + Filter + **UVGI**
  - Cooling mode (Peltier element, waste heat removal by **water**)
- **Single Flexible Heating Panel**

Settings (Discrete)	
Ventilation	1 – 10
Cooling	1 – 5
Heating	1 – 10

PECS v3
(Current Version)



Kazanci et al., 2022 and Shinoda et al. 2022

Summary and next steps

- Development and improvement of PECS with functions that could address multiple IEQ factors
- Guidance (unified method) in performance evaluation, installation, and operation
- Research gaps that need to be addressed:
  - Integration with the ambient (main HVAC) system
  - Building codes/regulations, standards
  - Commissioning and maintenance
  - User interfaces and interaction with occupants
  - Sizing
  - Cost-benefit and productivity
- To be addressed in IEA EBC Annex 87 - Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (https://annex87.iea-ebc.org)

Bivolarova, M. (2022) Knowledge gaps regarding Personalised Environmental Control Systems (PECS). CLIMA 2022 Congress. Seminar | New IEA EBC Annex on Personalized Environmental Control Systems (PECS)

Thank you for your attention

Ongun Berk Kazanci, PhD
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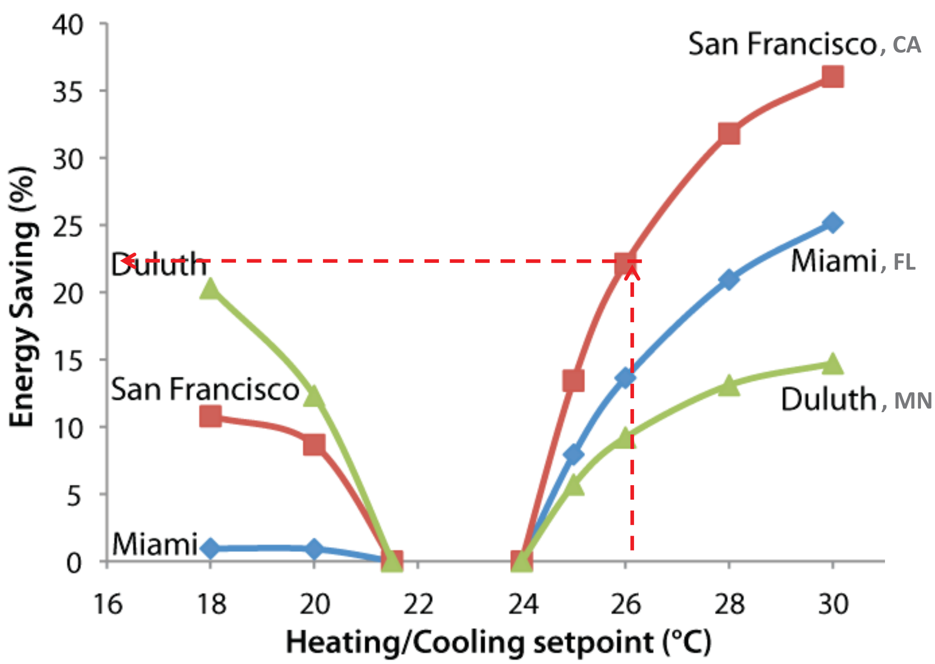
Footwarmers providing efficient heating

Hui Zhang
Center for the Built Environment (CBE)
University of California Berkeley

IEA-EBC Annex 87 workshop, Dec. 2022

Why Personalized Environmental Control Systems?

- PEC meets personal comfort requirement
- Looser control reduces HVAC energy 7-15% per °C by extending set point range
- Tight control is very energy intensive.



Hoyt, T., E. Arens, and H. Zhang. 2015. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment* 88, 89-96

Perception varies across the body

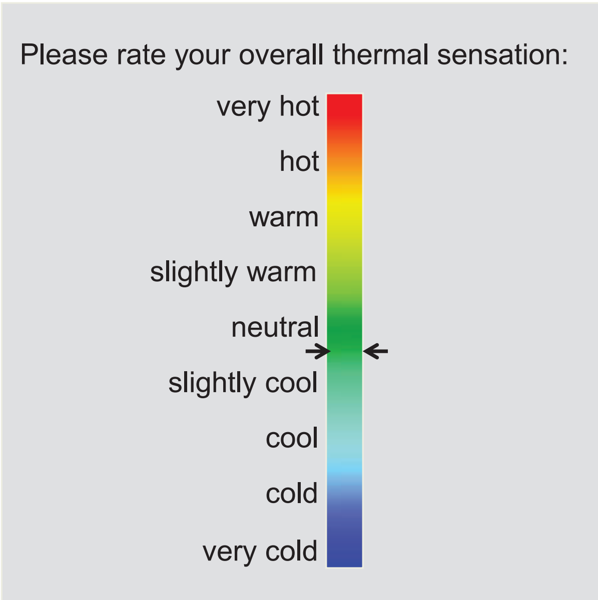
Human testing of sensations for 16 individual body parts

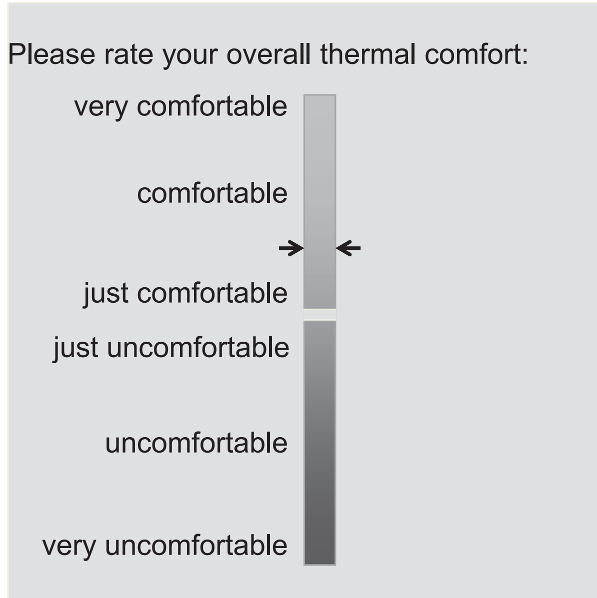
warm/cooled air supplied to individual body parts

Zhang, H. 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments, Ph. D. Thesis

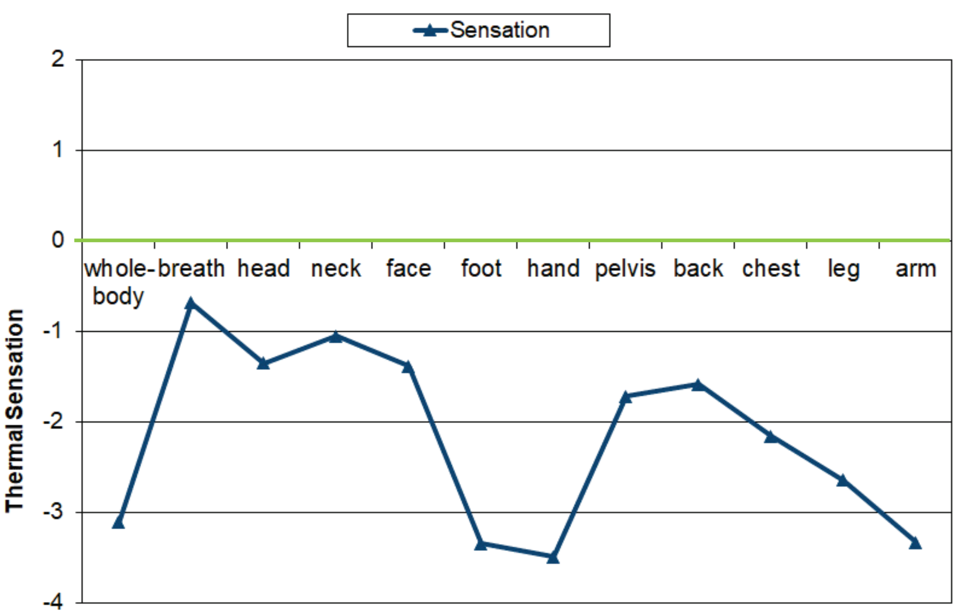
Thermal sensation and comfort scales

Collected for each body segment as well as for the whole-body ('overall').

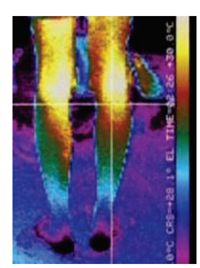




Cool environments: Extremity dictates whole-body discomfort



- Extremities are most important in cool environments
- vasoconstriction is uncomfortable



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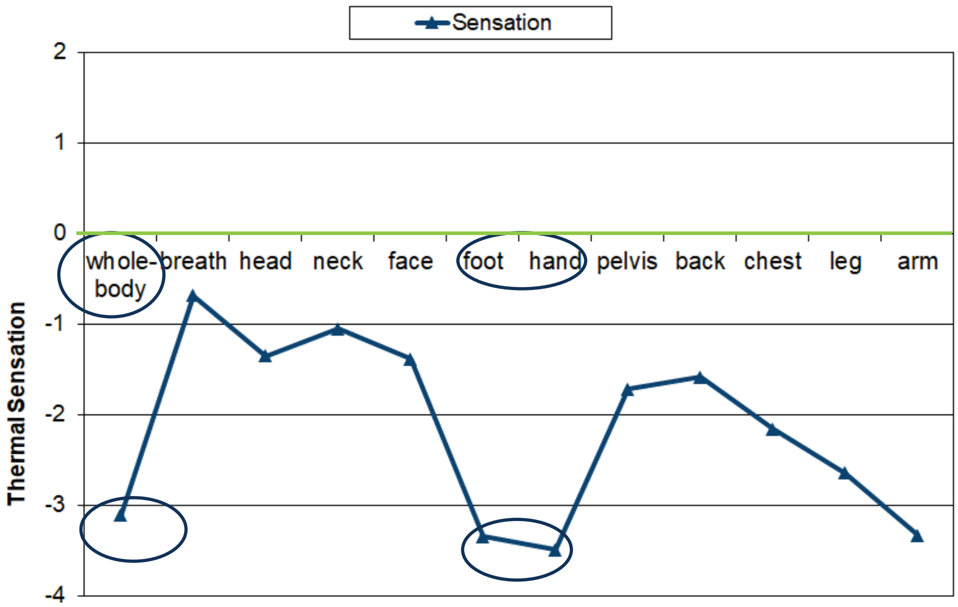

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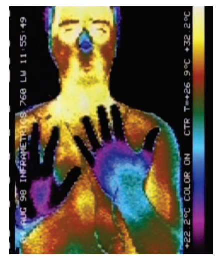

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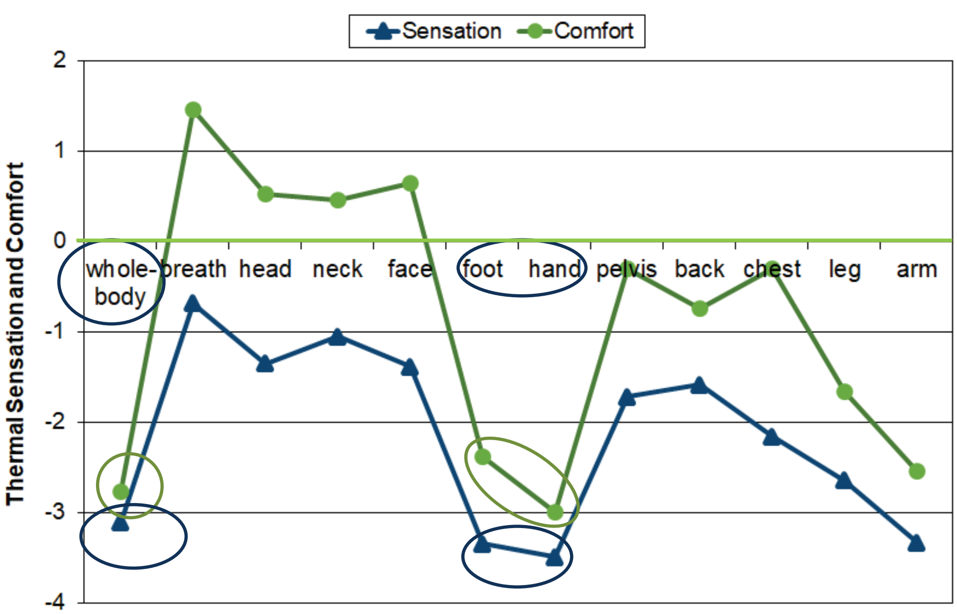

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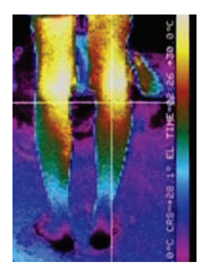
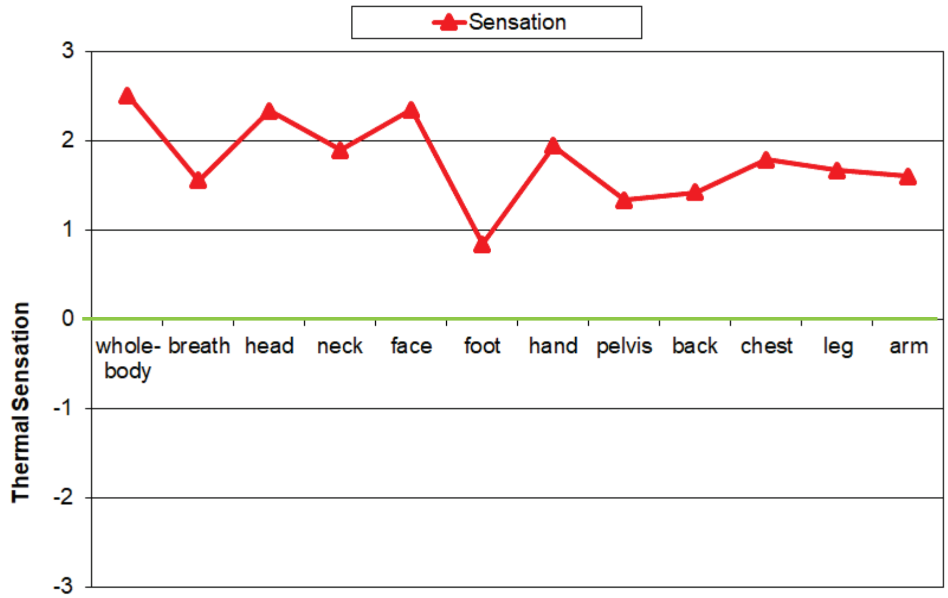


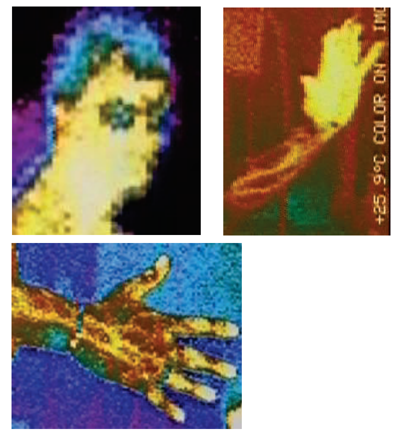
Arens, E., H. Zhang, C. Huizenga. 2006. Partial- and whole body thermal sensation and comfort, Part I: uniform environmental conditions. Journal of Thermal Biology, 31, 53 - 59.

Zhang, H. 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments, Ph. D. Thesis

Warm environments: Head dictates whole-body discomfort



- The head is most important in warm environments
- Both head and hands dilated



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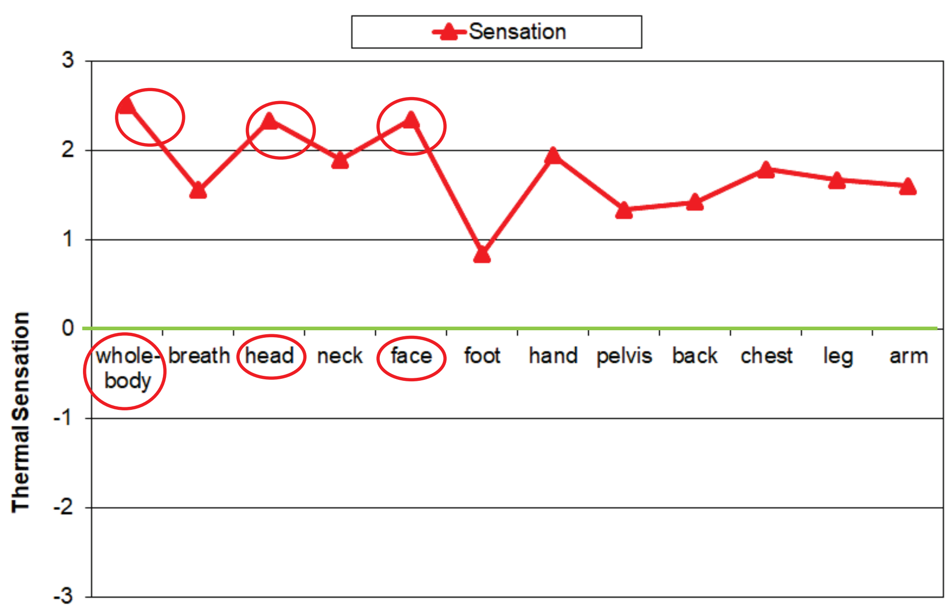

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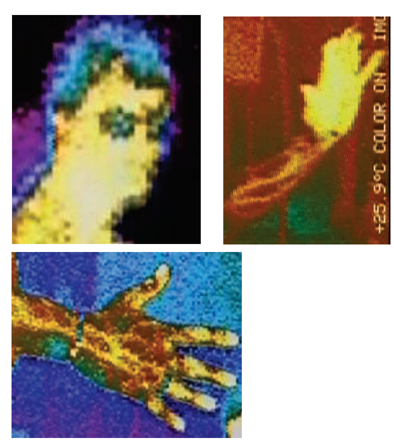

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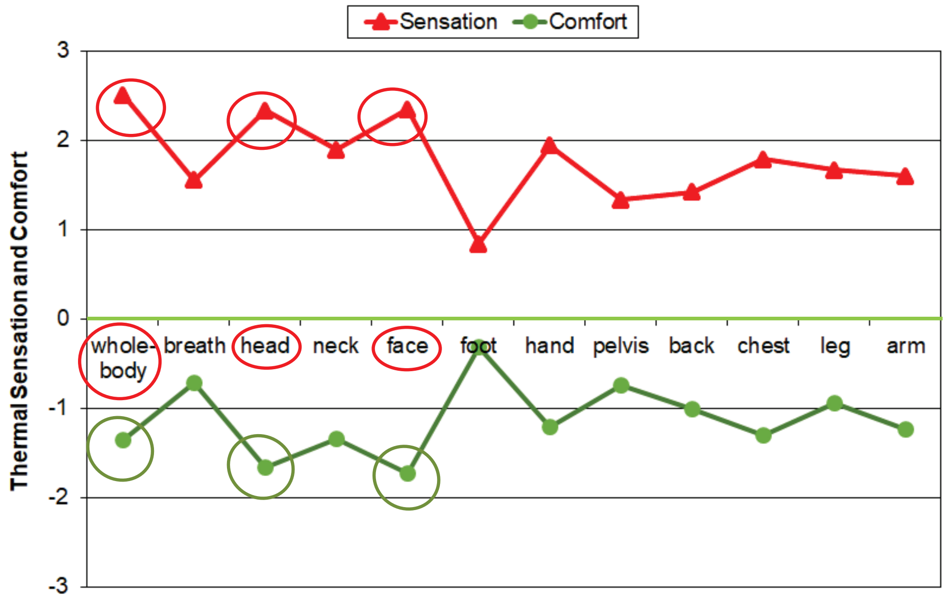

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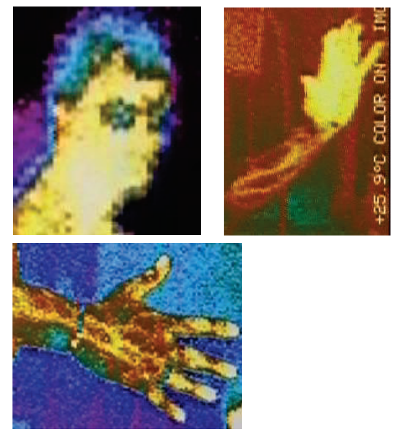

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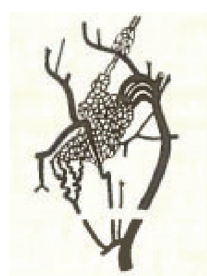
Selective brain cooling in animals

Panting cools blood vessels near brain



Rete: countercurrent blood vessels between arteries and veins near animals' brains

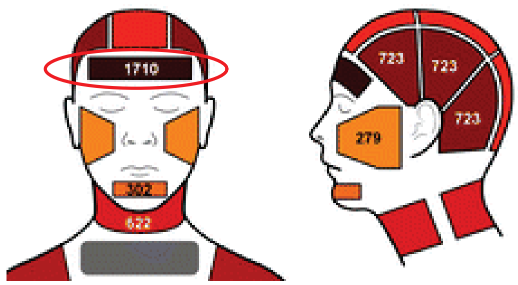
- Evaporation from tongue and nasal mucosa cools blood vessels near brain
- Conserve water
- Happens in many animals (fast running, desert: antelope, gazelle, sheep, oryx…)

Schmidt-Nielsen (1971) "How animals work"
Cabanac (1988): Selective brain cooling in humans

In humans, forehead has the highest sweat production

	Body parts
Greatest	Forehead, neck, back of hand and forearm, back and front of trunk
Middle	Cheeks, arms and legs, lateral surface if trunk
Least	Inside of thighs, soles, palms, armpits

Kuno (1956)



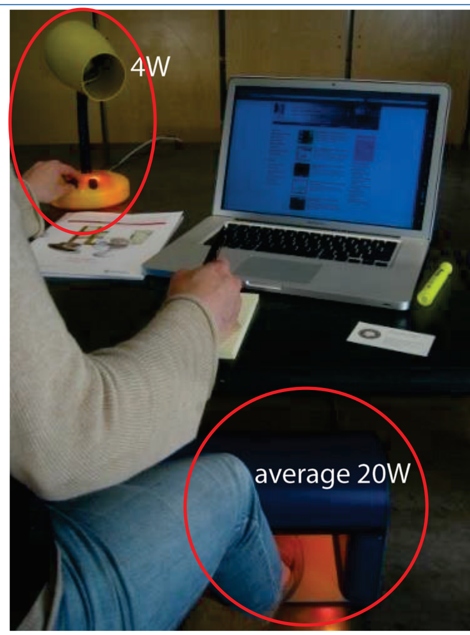
Smith and Havenith (2011)

Kuno Y (1956), Human Perspiration

Smith, CJ and G. Havenith. 2011, Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia, Eur J Appl Physiol (2011) 111:1391–1404

Personal comfort systems (PCS)

- PCS devices allow occupants to control their comfort locally
- We designed a connected system:
  - Head cooling by fan
  - Foot heating by radiation

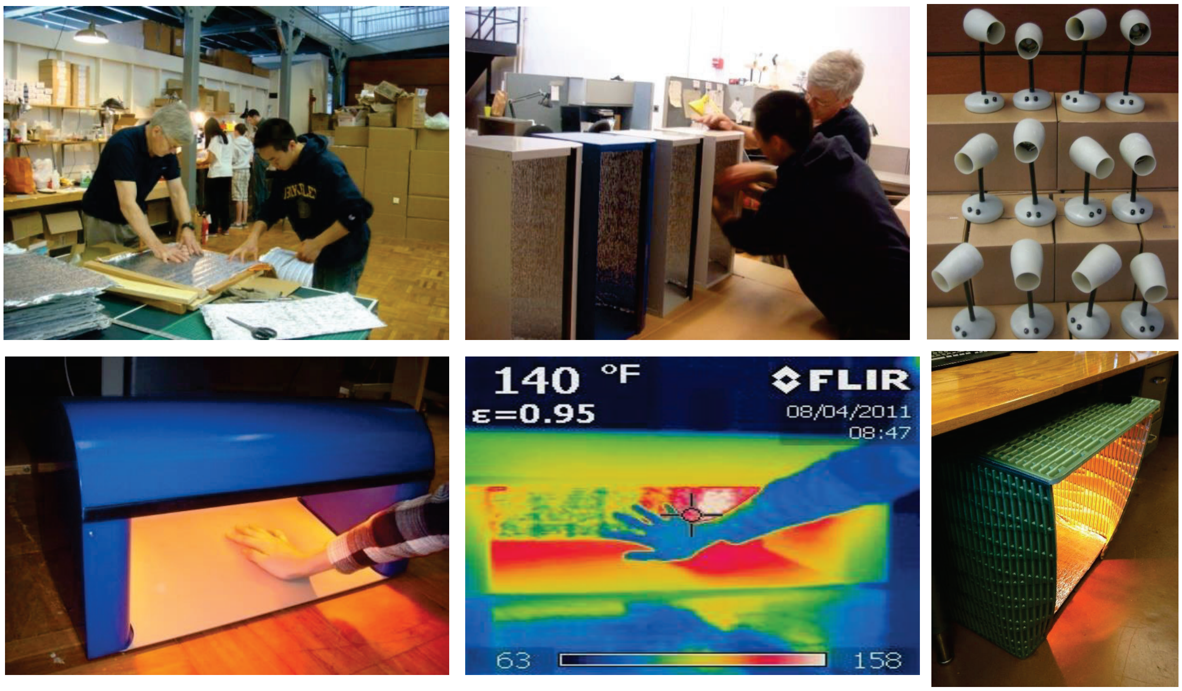


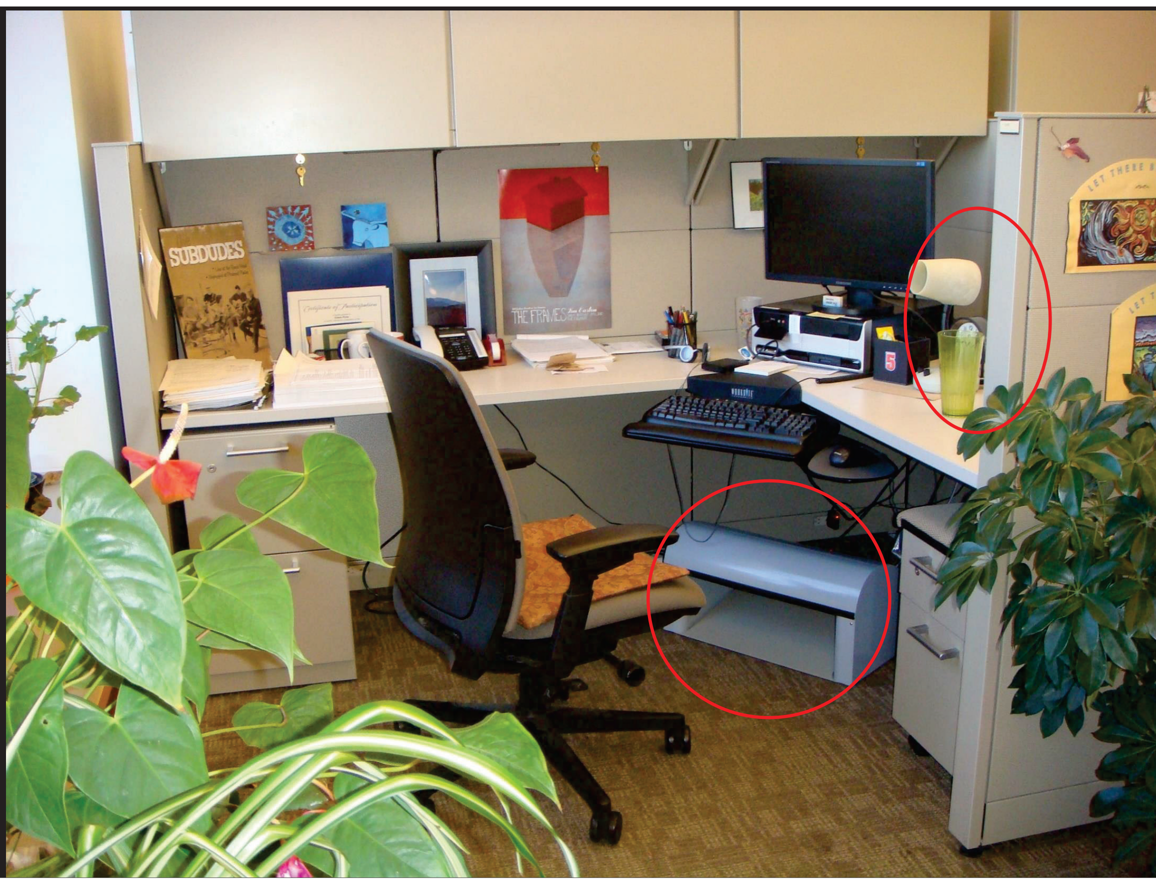
Head cooling and foot warming PCS

Fannon, D. 2015. Developing low-energy personal thermal comfort systems: design, performance, testing, and research methods.

Zhang, H., E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y.C. Zhai, and M. Pigman. 2015. Using footwarmers in offices for thermal comfort and energy savings. Energy and Buildings, 104 (3), 233 – 243.

Footwarmer+fan assembly (!)





A field study in a campus building: 6 months in winter

Objectives

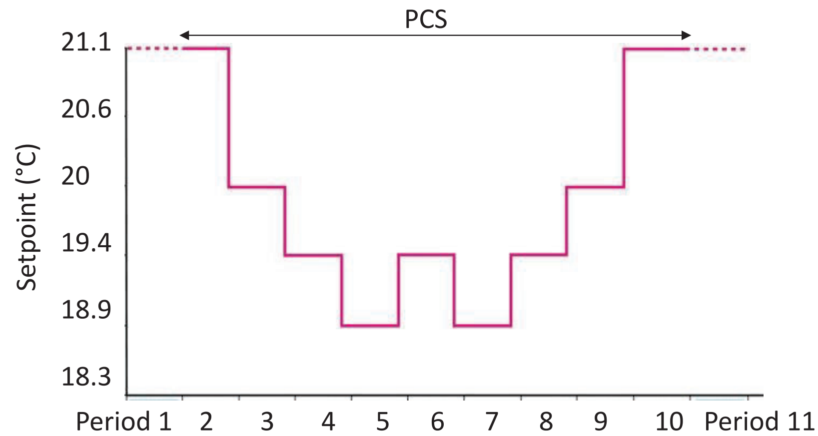
Demonstrate the use of fan/footwarmer over a whole winter

Method

- Provided PCSs to 25 occupants
- Lowered heating setpoint from 21.5℃ to 19℃
- Surveyed occupants' satisfaction
- Monitored HVAC energy consumption

Results

- Equivalent comfort was maintained
- Over 30% savings in heating energy over winter



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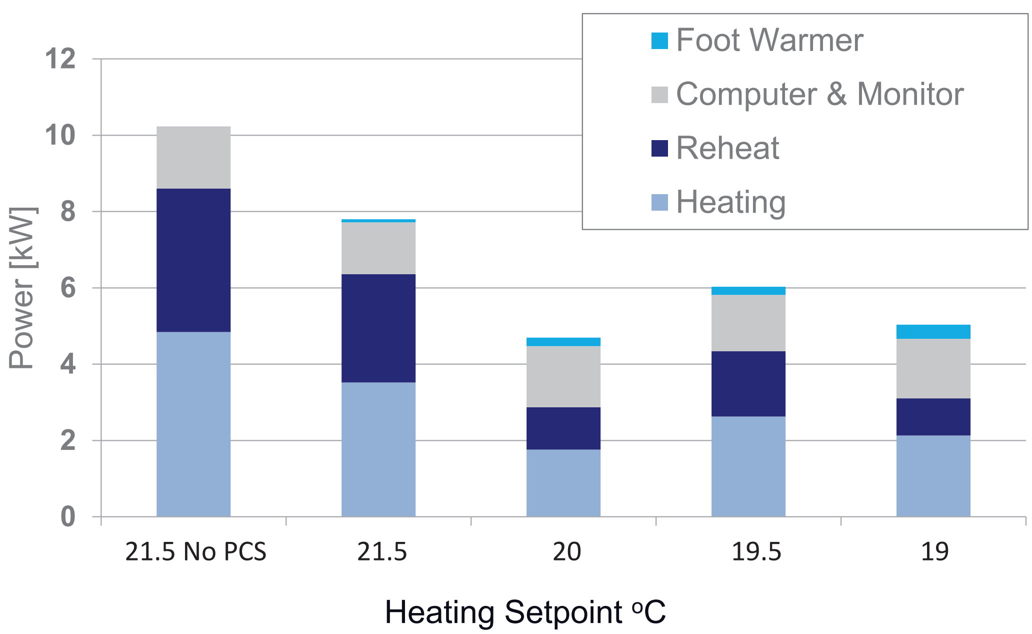
Measured power usage by footwarmer is negligible



Thermal perception at a more detailed scale

Thermal sensitivity: test method

Neutral ambient temperature

- 25ºC, 40%RH

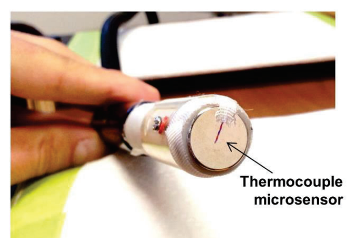
Thermal probe

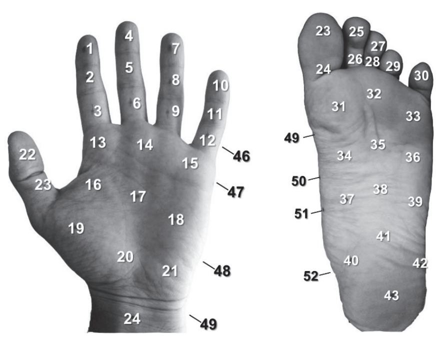
- PhysiTemp, 14mm probe
- 50 test points on hand, 50 on foot

Test procedure

- 31 ± 5 ºC stimulus
- Thermocouple records T_{skin} change
- Voting thermal sensation on 10 points scale

$$\boldsymbol{Sensitivity} = \frac{\boldsymbol{Thermal\ sensation}}{\boldsymbol{\Delta Tskin}}$$

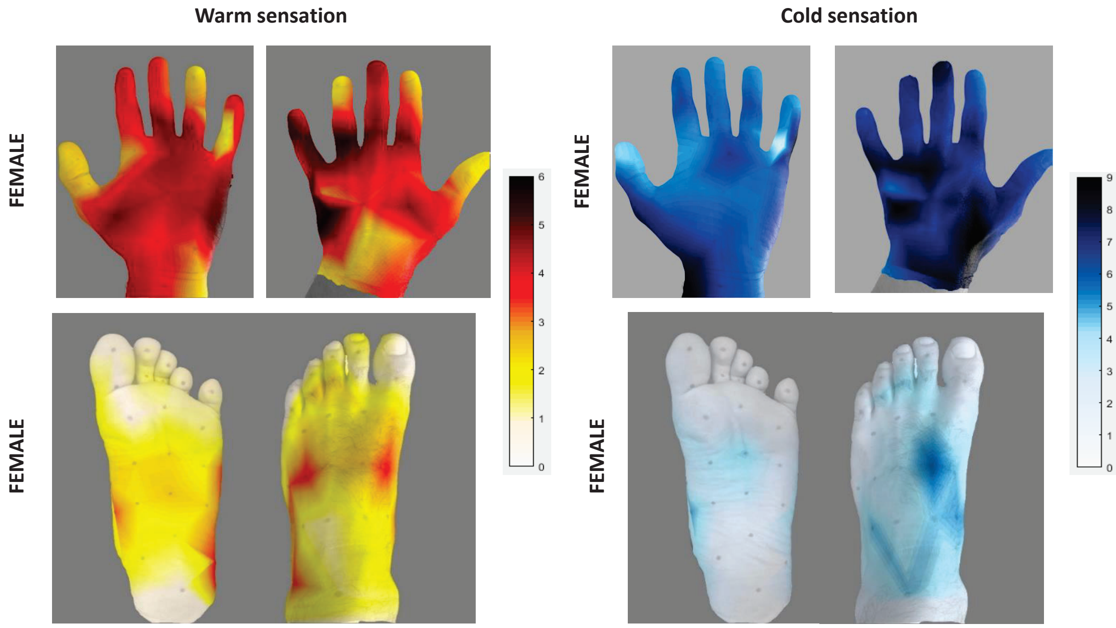




Very Hot	10	Very Cold
	9	
	8	
	7	
	6	
	5	
	4	
	3	
	2	
	1	
Not hot at all	0	Not cold at all

Filingeri, D., H. Zhang, E. Arens. 2018. Thermosensory micromapping of warm and cold sensitivity across glabrous and hairy skin of male and female hands and feet, Journal of Applied Physiology, 125: 723–736

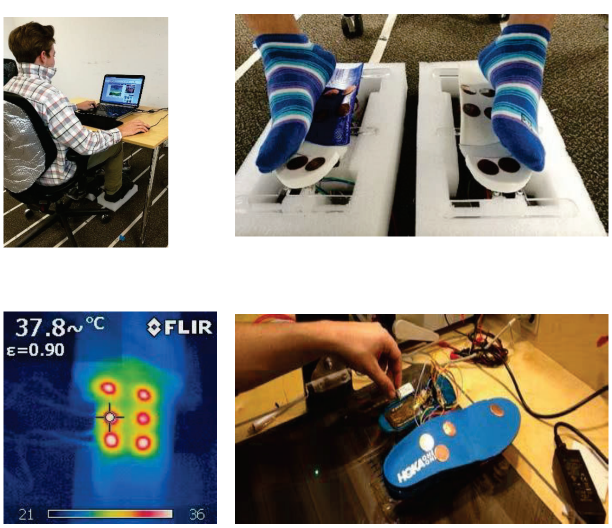
Warm/cool sensitivity maps of hands and feet



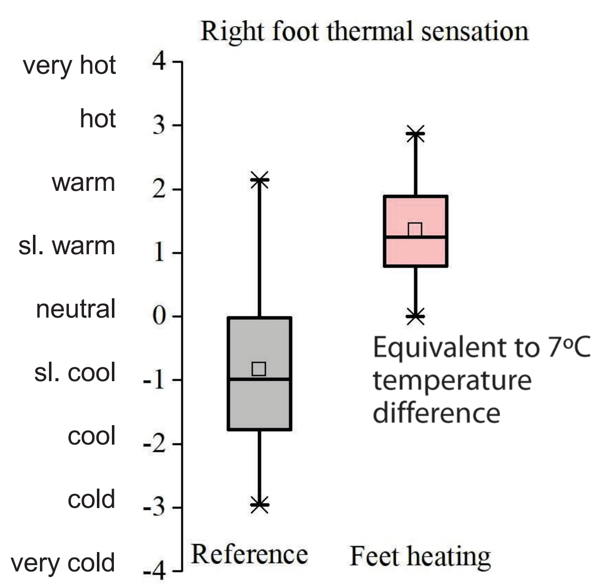
Filingeri, D., H. Zhang, E. Arens. 2018. Thermosensory micromapping of warm and cold sensitivity across glabrous and hairy skin of male and female hands and feet, Journal of Applied Physiology, 125: 723–736

Tests of spot-heated insoles on foot sensation

10 female, 10 male, 18°C, 40%RH



1.2 Watts



Luo, M., E. Arens, H. Zhang, A. Ghahramani, Z. Wang. Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices. Building and Environment. 2018, 143: 206-216

Going further with comfort: alliesthesia

What is alliesthesia? (Cabanac 1969)

- Sensory *pleasure* with variation. In transient or non-uniform environments, an environmental stimulus that has the prospect of restoring body to thermal comfort, is perceived as 'very pleasant' (alliesthesia)
- Traditional stable and uniform environments are not perceived as 'very pleasant'

Cabanac M. 1969. Plaisir ou deplaisir de la sensation thermique et homeothermie. Physiology and Behavior 4:359–64.

Zhang H, E. Arens, C. Huizenga, T. Han. 2010. Thermal sensation and comfort models for non-uniform and transient environments: Part II: local comfort of individual body parts. Building and Environment, 45(2), 389 - 398.

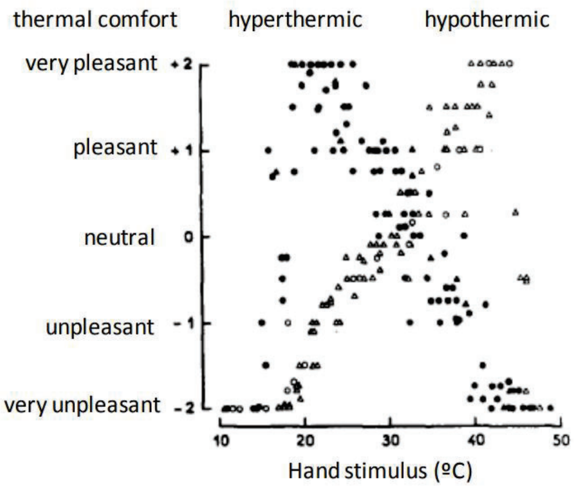
de Dear RJ. Revisiting an old hypothesis of human thermal perception: Alliesthesia. Building Research & Information, 2011, 39(2):108-117.

Parkinson T, de Dear R, 2014, Thermal pleasure in built environments: physiology of alliesthesia, Building Research Information. In press.

Zhang, H., E. Arens, and Y. Zhai. 2015. A review of the corrective power of personal comfort systems in non-neutral ambient environments. Building and Environment, 91, 15-41.

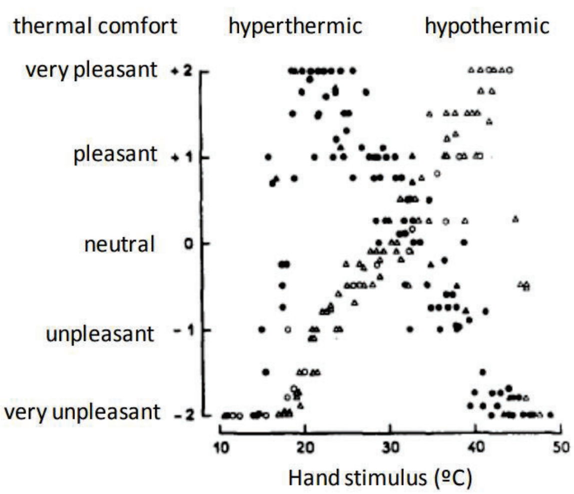
Brager, G., H. Zhang, and E. Arens. 2015. Evolving opportunities for providing thermal comfort. Building Research and Information, Vol. 43, No. 3, 1–14

Early studies of transient alliesthesia

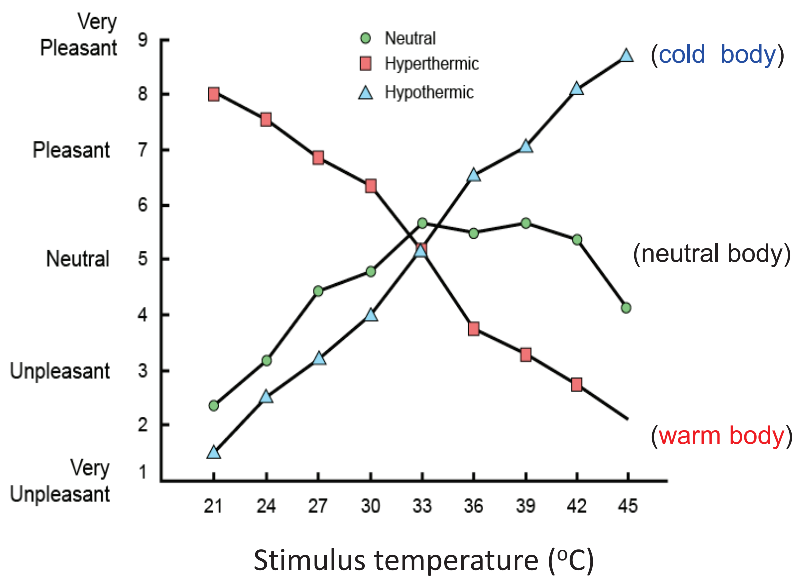


Cabanac M. Plaisir ou deplaisir de la sensation thermique et homeothermie. Physiology and Behavior 1969;4: 359-364.

Early studies of transient alliesthesia



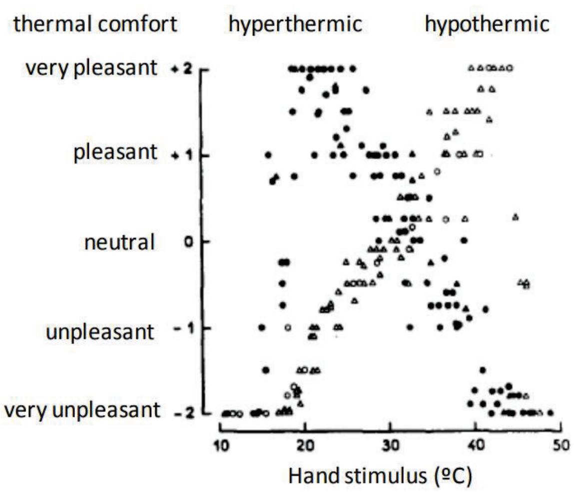
A hand into a bucket of water



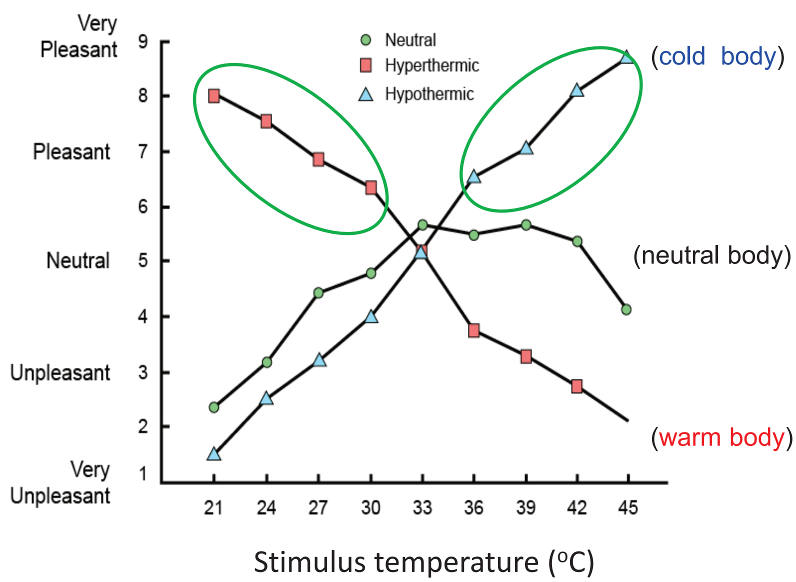
Cabanac M. Plaisir ou deplaisir de la sensation thermique et homeothermie. Physiology and Behavior 1969;4: 359-364.

Adapted from Mower DM. Perceived intensity of peripheral thermal stimuli is independent of internal body temperature. Journal of Comparative and Physiological Psychology 1976;90(12):1152–5

Early studies of transient alliesthesia



A hand into a bucket of water

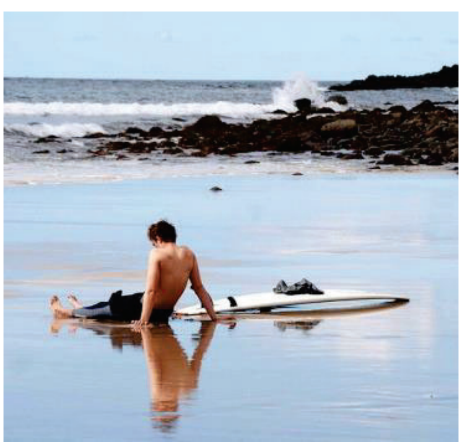


Cabanac M. Plaisir ou deplaisir de la sensation thermique et homeothermie. Physiology and Behavior 1969;4: 359-364.

Adapted from Mower DM. Perceived intensity of peripheral thermal stimuli is independent of internal body temperature. Journal of Comparative and Physiological Psychology 1976;90(12):1152–5

Transient extends to spatial alliesthesia

Transient and non-uniform environments can be more pleasant



Variation and pleasantness

Similar to taste, color…

A watercolor by me: Double bridge, Shanghai, China

Closing comments

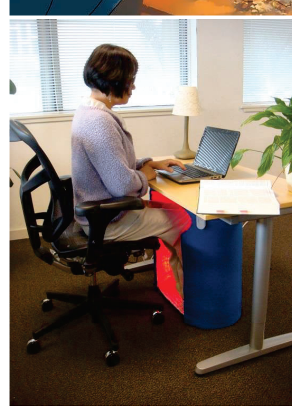
We can provide better comfort with PEC or PCS (Personal comfort systems)

- Take better advantage of human physiology
- Actively develop alliesthesia approaches
- Address people's everyday thermal transients

PCS also allows us to reduce AC energy use

(10% HVAC energy drop for each 1 °C setpoint extension)

A win-win situation for the world!




Thank you!
MAUI

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Heated and cooled chairs

Sabine Hoffmann

Technische Universität Kaiserslautern

living lab smart office space

Webinar – IEA EBC Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)

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Motivation

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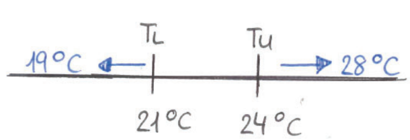
- Individual perception of thermal sensation and thermal comfort differs

-> Integrated heating and cooling function to fulfill individual needs and preferences

- Increase of the HVAC dead band

-> Reduction of energy consumption



living lab smart office space

The office chair

Heating: Heating wires

- → heat transfer by conduction
- → reduction of heat loss of the body

Cooling: Fans

- → heat transfer by convection
- → increase of sensible heat loss of the body
- → latent heat loss

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The office chair

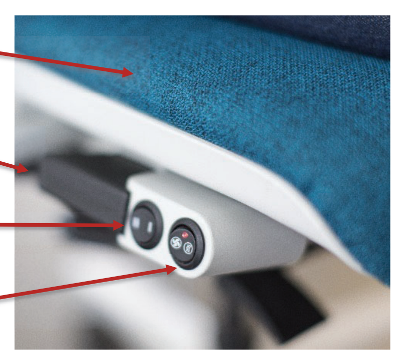
Heating: Heating wires

- → heat transfer by conduction
- → reduction of heat loss of the body

heating 1:	8 W
heating 2:	12 W
cooling 1:	2 W
cooling 2:	4 W

Cooling: Fans

- → heat transfer by convection
- → increase of sensible heat loss of the body
- → latent heat loss



The field study

- office building, 50 % window-to-wall ratio
- exterior shades, manually operated
- operable windows
- no air conditioning
- S-E-E and N-W-W oriented
- mid-July through mid Oct 2015

The field study

10 female 16 males

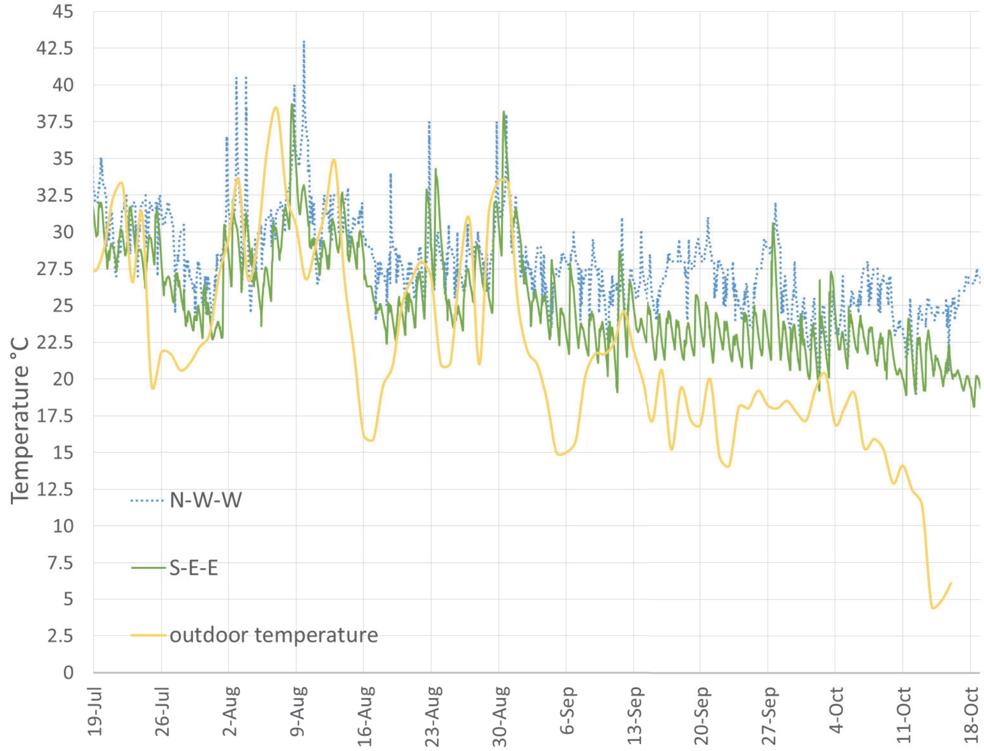
average age:	38.7 years (26-56)
average duration:	21.4 days (min 5 d)

online survey at 11:00 am and 3:30 pm

Thermal sensation	Thermal comfort
Very Hot	Very comfortable
Hot	Comfortable
Warm	Slightly comfortable
Slightly warm	Just comfortable
Neutral	
Slightly cool	Just uncomfortable
Cool	Slightly uncomfortable
Cold	Uncomfortable
Very cold	Very uncomfortable

Hoffmann, Sabine and Katharina Boudier. 2016. "A new approach to provide thermal comfort in office buildings: A field study with heated and cooled chairs." In Proceedings of Indoor Air Quality Ventilation & Energy Conservation in Buildings (IAQVEC), Incheon Songdo, Republic of Korea, October 2016.

Outdoor and room temperatures of two example office rooms



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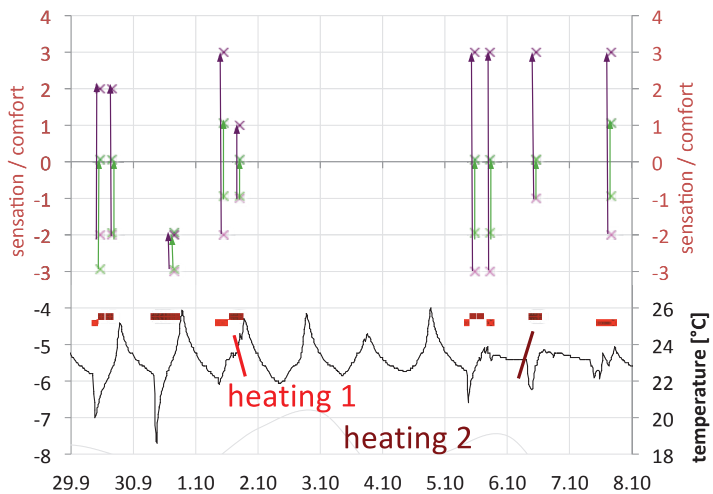
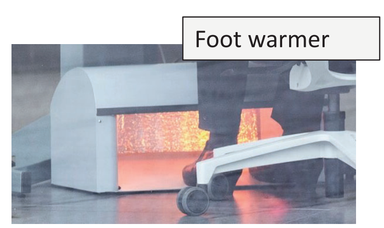
Operation of chairs



Sensation heating 🡅 :	85 %	(n = 67)
Comfort heating 🡅 :	83 %	(n = 64)
Acceptable room temp.:	$\theta_{acc.} \approx$ 19-20 °C	



Operation of chairs

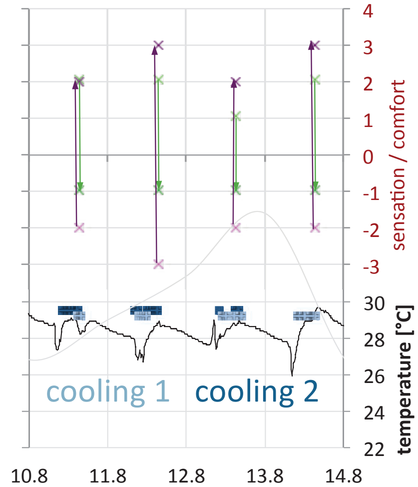
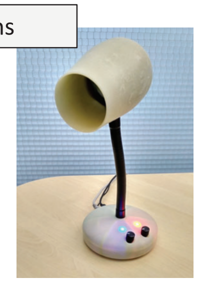


Table top fans



sensation cooling	↓:	35 %	(n = 228)
comfort cooling	↑:	31 %	(n = 219)
Acceptable room temp.:	$\theta_{acc.} \approx$ 29-30 °C		

Results

	Total number of votes	+	0	-
COOLING				
Impact on sensation	228	3.1 %	62.3 %	**34.6 %**
Impact on comfort	219	**31.1 %**	61.6 %	7.3 %
HEATING				
Impact on sensation	67	**85.1 %**	14.9 %	0 %
Impact on comfort	64	**82.8 %**	14.1 %	3.1 %

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Comfort modeling

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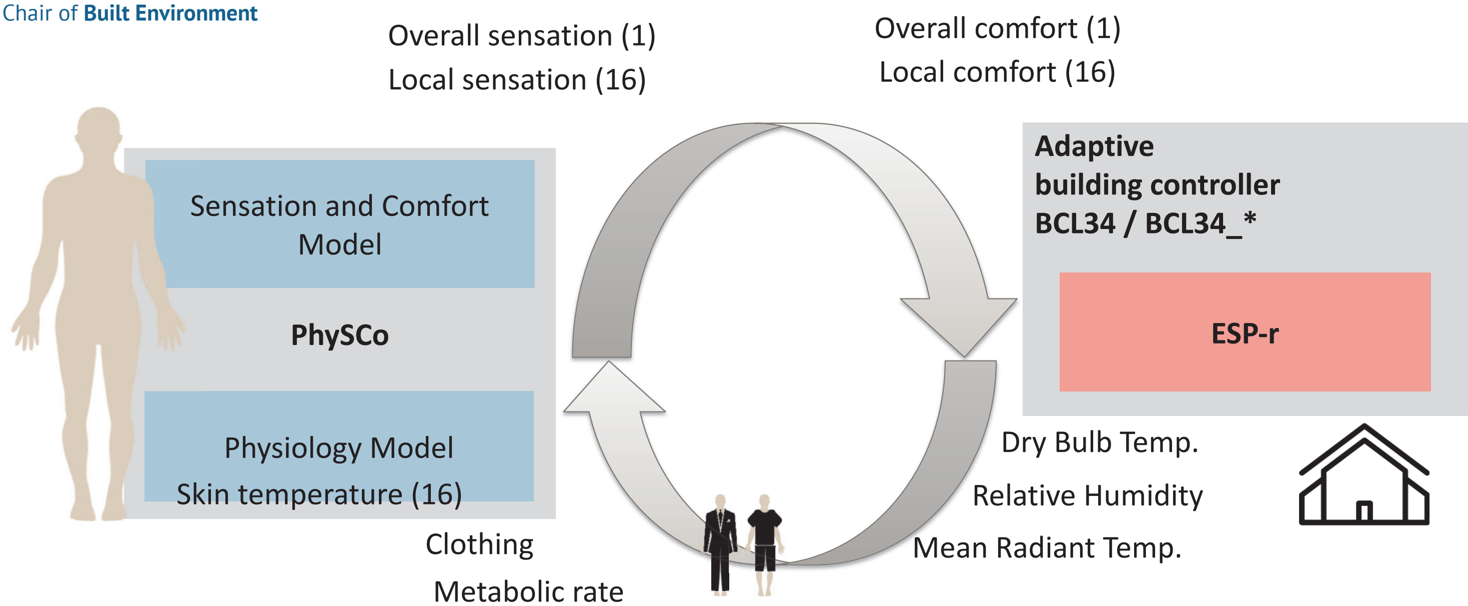

Boudier, Katharina, Massimo Fiorentini, Sabine Hoffmann, Raghuram Kalyanam, and Gergios Kokogiannakis. 2016. "Coupling a thermal comfort model with building simulation for user comfort and energy efficiency." In Proceedings of the Central European Symposium on Building Physics (CESBP) and BauSIM, Dresden, Germany, September 2016, 481–487

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Comfort modeling

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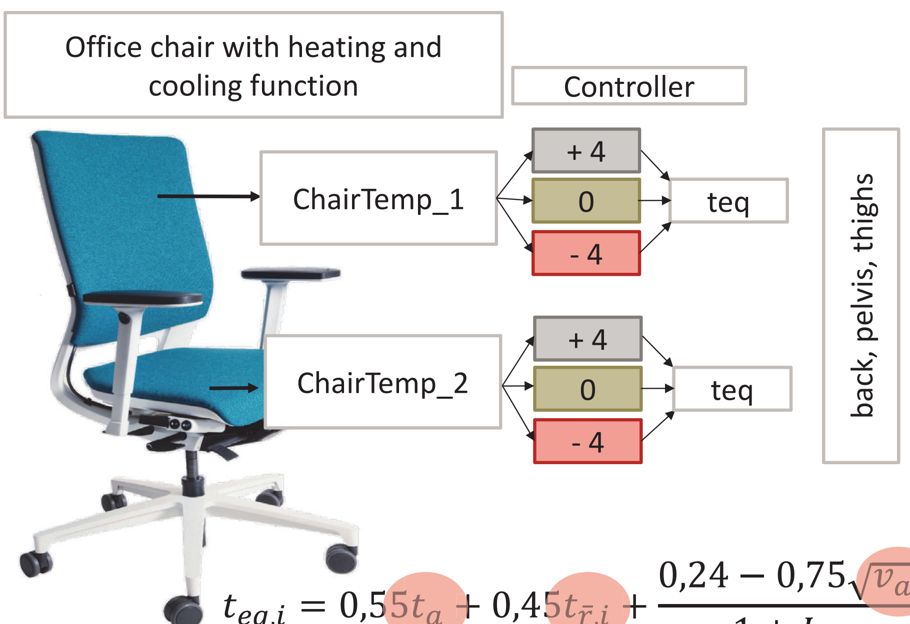

0,41 m/s

$$t_{eq,i} = 0{,}55\,t_a + 0{,}45\,t_{\bar{r},i} + \frac{0{,}24 - 0{,}75\sqrt{v_{a,i}}}{1 + I_{cl,i}}(36{,}5 - t_a)$$

+ 4
0
- 4

*„Modellierung der Interaktion von Gebäudenutzer*innen und Gebäudetechnik - Potenzialanalyse dezentraler Heiz- und Kühlsysteme hinsichtlich der thermischen Behaglichkeit und des Energieverbrauchs auf Basis eines adaptiven Gebäudereglers –" Dissertation Katharina Boudier, 2021, TU Kaiserslautern https://kluedo.ub.uni-kl.de/frontdoor/deliver/index/docId/6390/file/_Dissertation_BoudierKatharina.pdf*

Results

		BCL00	BCL34	BCL34 _ ThW	BCL34 _ Chair	BCL34 _ ThW _ Chair	BCL34 _ Chair_ Vent26	BCL34 _ Chair_ Vent30	BCL34 _ ThW _ Chair_ Vent26	BCL34 _ ThW _ Chair_ Vent30
Winter	Endenergy [kWh_{el}]	278	243	342	273	357	274	--	358	--
	Reduction [%]	0,0%	12,5%	-23,1%	1,8%	-28,3%	1,5%	--	-28,9%	--
Spring	Endenergy [kWh_{el}]	76	76	94	79	100	79	69	100	92
	Reduction [%]	0,0%	-0,6%	-24,6%	-3,8%	-32,3%	-3,7%	9,3%	-32,5%	-
Summer	Endenergy [kWh_{el}]	326	320	344	321	347	300	276	333	327
	Reduction [%]	0,0%	1,9%	-5,5%	1,5%	-6,4%	7,8%	15,3%	-2,0%	-0,2%

Boudier, Katharina, and Sabine Hoffmann. 2022. "Analysis of the Potential of Decentralized Heating and Cooling Systems to Improve Thermal Comfort and Reduce Energy Consumption through an Adaptive Building Controller" Energies 15, no. 3: 1100. https://doi.org/10.3390/en15031100

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Conclusion

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- The field study showed promising results: Increase in thermal comfort particularly in heating mode (> 80 %), less in cooling mode (> 30 %)
- The modeling approach showed potential to reduce energy consumption while maintaining thermal comfort
- Development of a commercial product
- Significant barriers for greater market penetration
- New potential with energy crisis and lower indoor temperatures

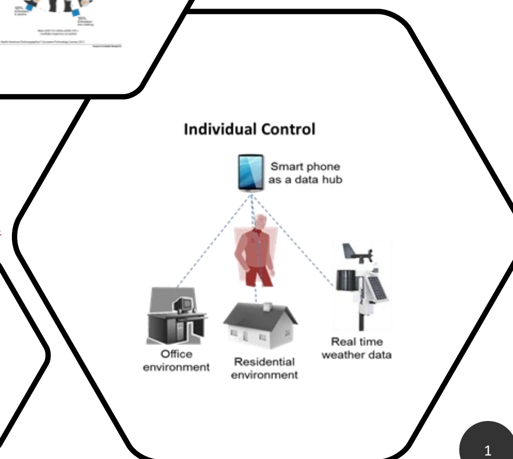
living lab smart office space

Sabine Hoffmann: „Personal Comfort Systems: Lessons from the creation of the 'Klimastuhl'" Commentary https://www.buildingsandcities.org/insights/commentaries/personal-comfort-systems-lessons.html

Dec. 12, 2022

EBC
Energy in Buildings and Communities Programme

Wearable Heating and Cooling Technology



USC
Center for Wellness in the Built Environment

Joon-Ho Choi, PhD, LEED AP, Assoc. AIA
Associate Professor of Building Science
Associate Dean of Research and Creative Work
Director, Center for Wellness in the Built Environment
School of Architecture
University of Southern California
Annex 87 Subtask C - Leader

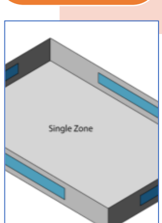
1

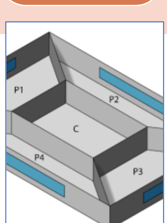
1

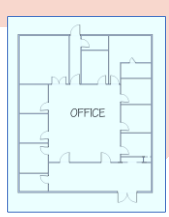
IEA – EBC Annex 87: Personalized Environmental Control Systems AIVC Webinar on Annex 87

HVAC Controls

- Single zone control
- Zonal control
- Multi-zone control
- Individual ambient control
- Micro control (via contact)







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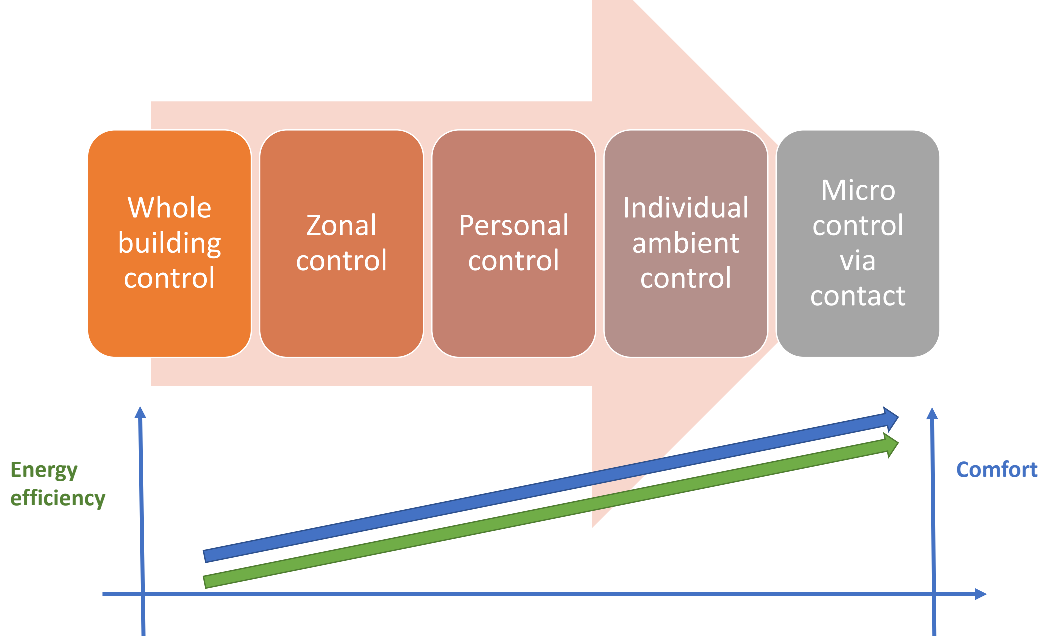
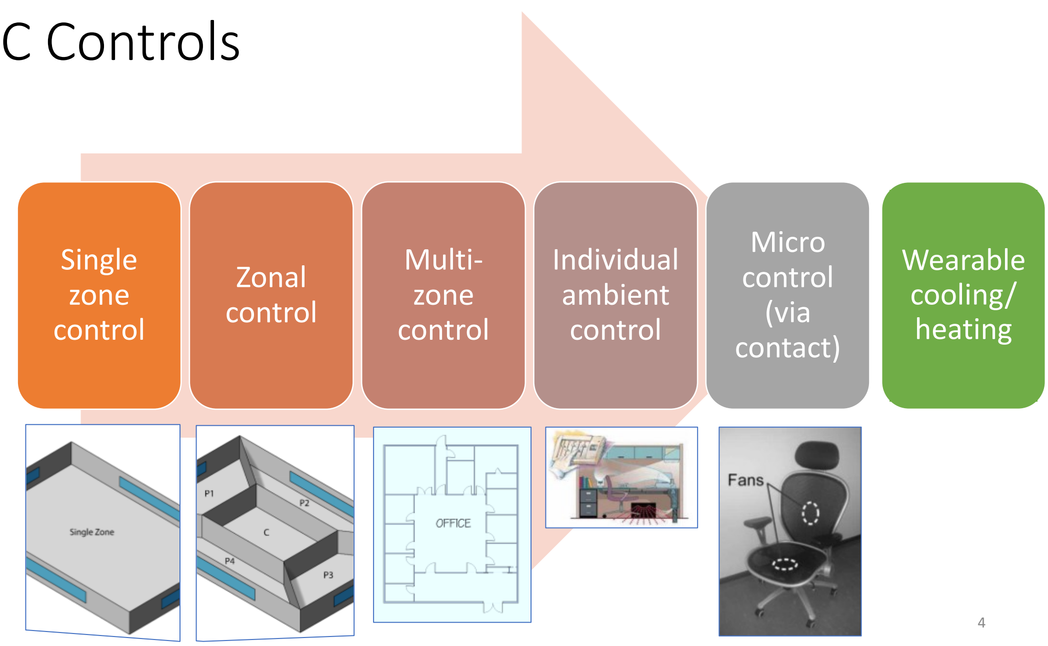
2



3

3

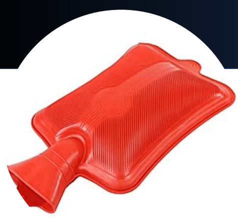
HVAC Controls



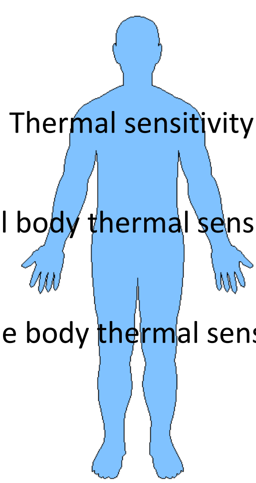
4

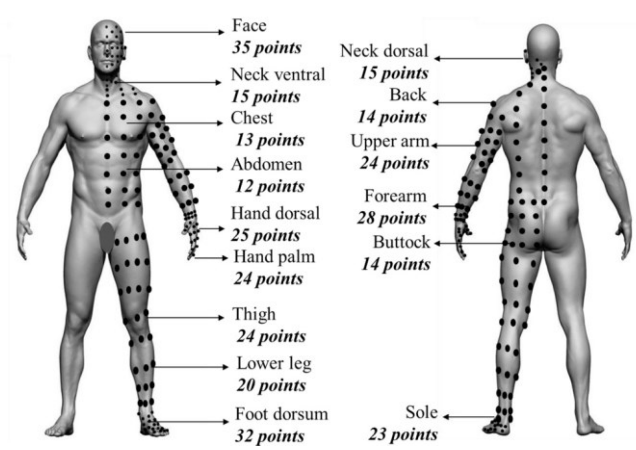
4

We already have a wearable conditioning strategy?



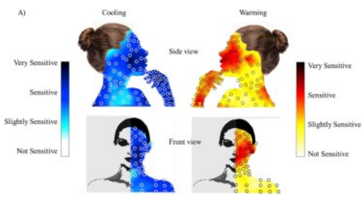
Earlier generation of wearable cooling/ heating ?

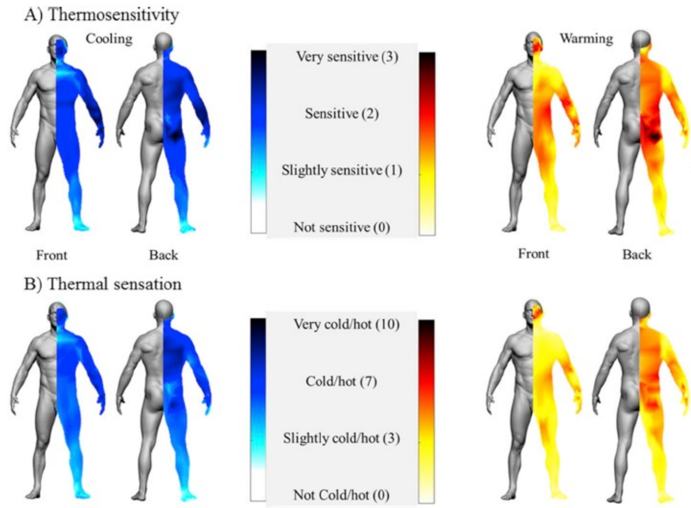




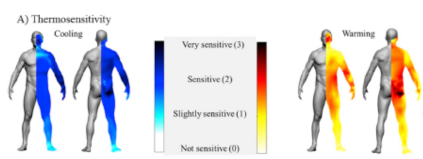
(Meh, D., Denislic, M., 1994)

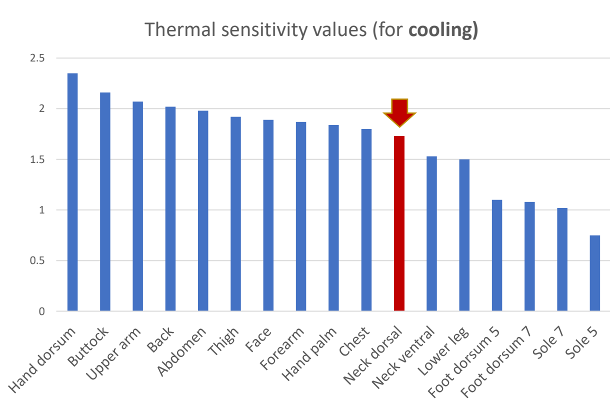
Thermosensitivity and thermal sensation map of the human body

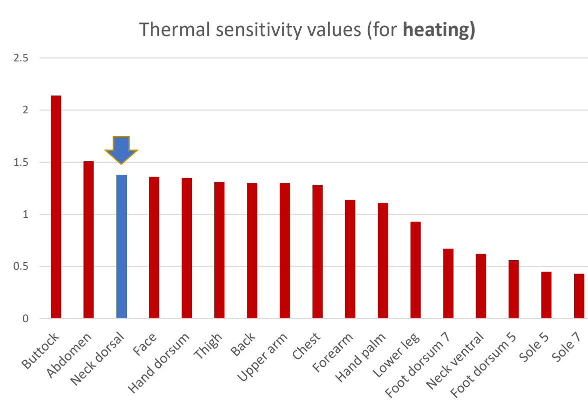




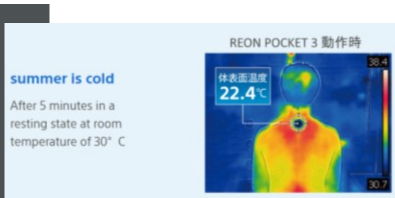
(Luo, M., et al., 2020)

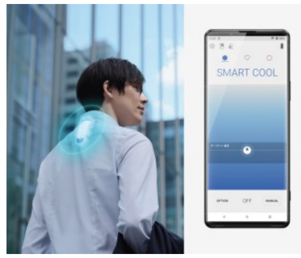






(Luo, M., et al., 2020)





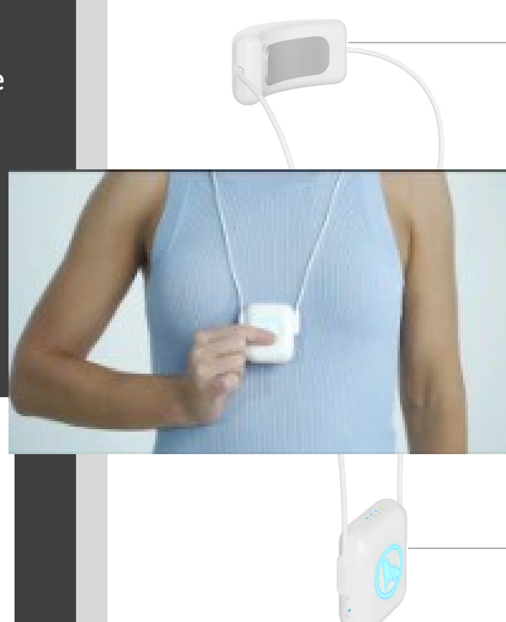
Wearable thermo device (SONY REON POCKET , 2019)

- COOL/WARM automatically starts when the main unit is attached to the neck, and automatically stops when the main unit is removed and placed on a desk
- Battery—power based
- Cooling mode: 8 hours
- Heating mode: 27 hours

9

GEMM, 2021: A pocket-sized, wearable cooling and heating device

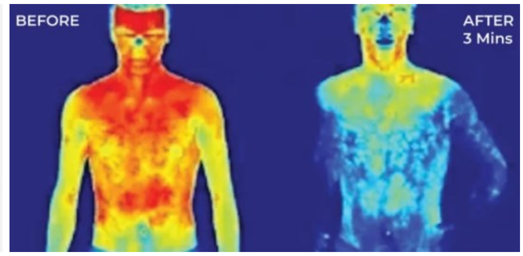
- **Thermo-electric technologies to bring an instant cooling or heating at the touch of a button.**
- **Manual control**
- **Plug & Play**
- **Battery-based**
- **It can be worn on the outside or inside of clothing.**

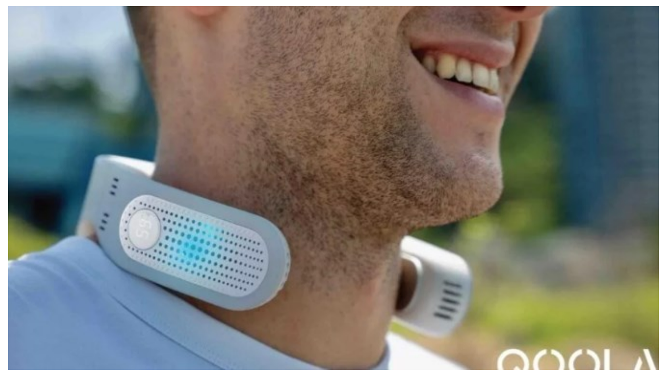


10

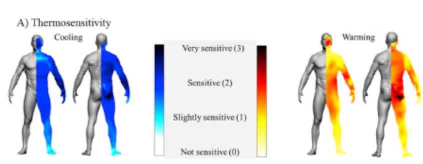
QOOLA WEARABLE AIR-CONDITIONER

It can dissipate cooling for users in hot weather and generate heating in cold weather. It is suitable in both Winter and Summer.

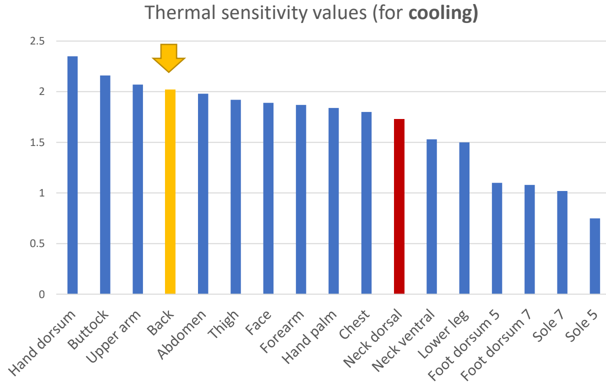




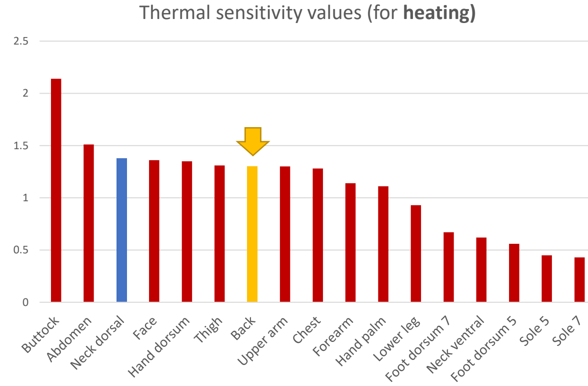
(Geeky Gadgets, 2022)



Thermal sensitivity values (for **cooling**)



Thermal sensitivity values (for **heating**)



‘UCOOLITY’ WEARABLE AIR CONDITIONER

1. A solution for sports enthusiasts and workers alike to help them maintain their routine when dealing with high temperatures
2. Delivers up to 10-hours of use per charge to easily accommodate all-day use
3. Keeps the user up to 33-degrees Fahrenheit cooler compared to the surrounding environment

(Trendhunter, 2022)

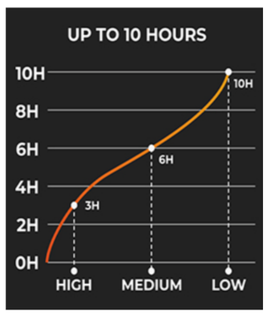
13

USB Cooling Jacket with Fans

- The upgraded 90mm fans are more powerful to provide stronger wind to the body and distribute air more evenly.
- Thanks to the ergonomic design, this cooling fan jacket can promote sweat evaporation, improve ventilation and increase air blow to the whole body, finally effectively reduce body temperature.

Heated Jacket with Battery Pack

- Battery heated coats. Up to 10 hours of heat with best insulation. Powered by ORORO UL-certified rechargeable batteries.



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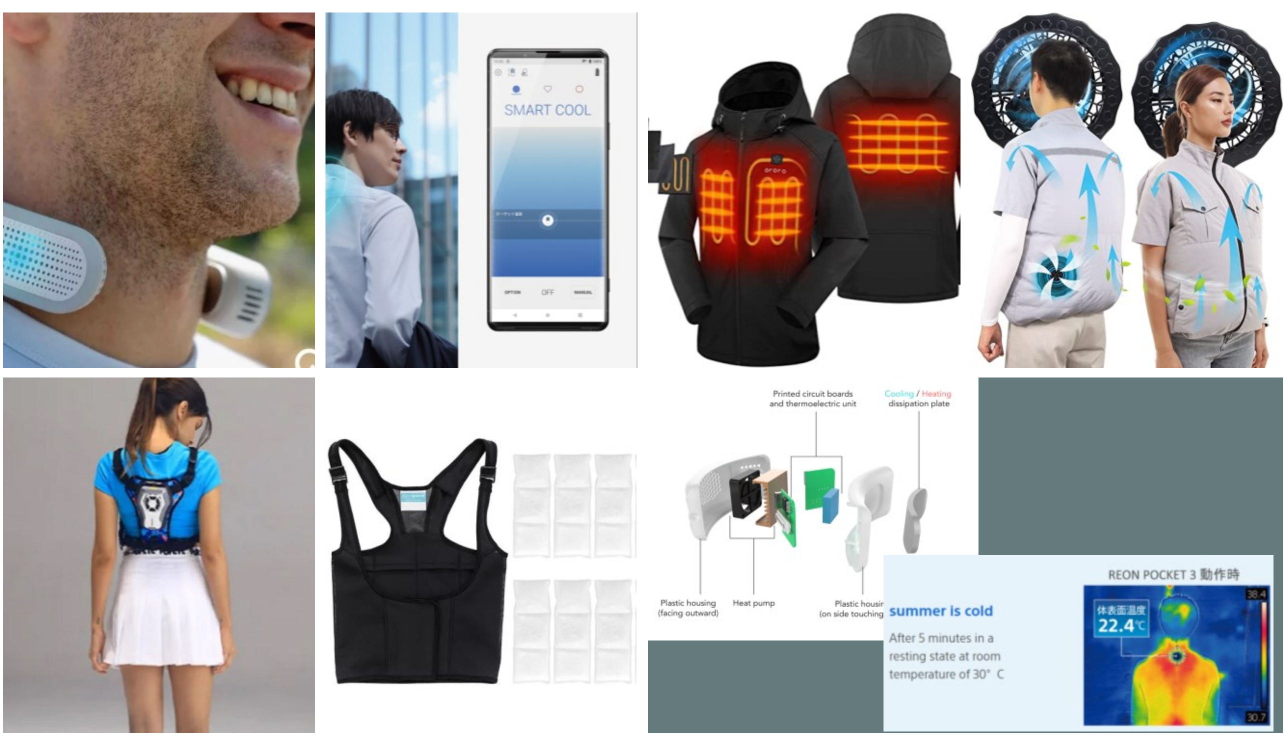

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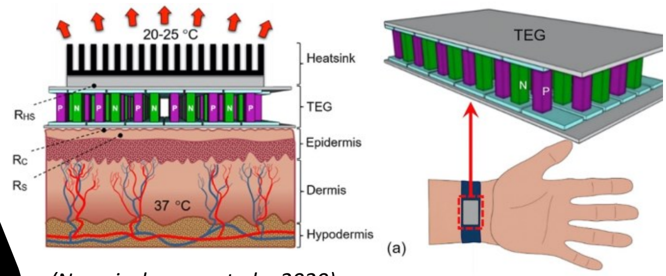
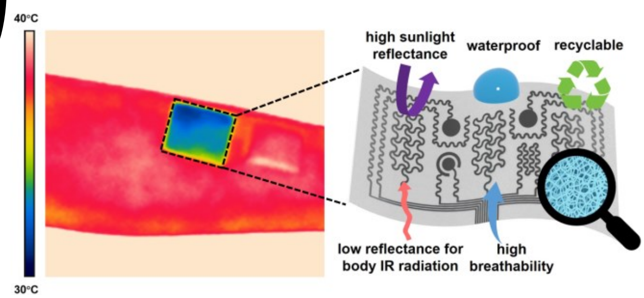
Power Generation using a Wearable

THERMOELECTRIC GENERATORS FOR WEARABLE BODY HEAT HARVESTING (TEGS)

- A significant advance in the design of thermoelectric generators (TEGs) for body heat harvesting applications is reported.
- A comprehensive quasi-3D analytical model was developed to optimize the thermoelectric materials and device parameters.
- The fabricated TEGs exhibited 4-7X higher power density than commercial TEGs on human body.



(Nozariasbmarz, et al. , 2020)



(University of Missouri., 2020)

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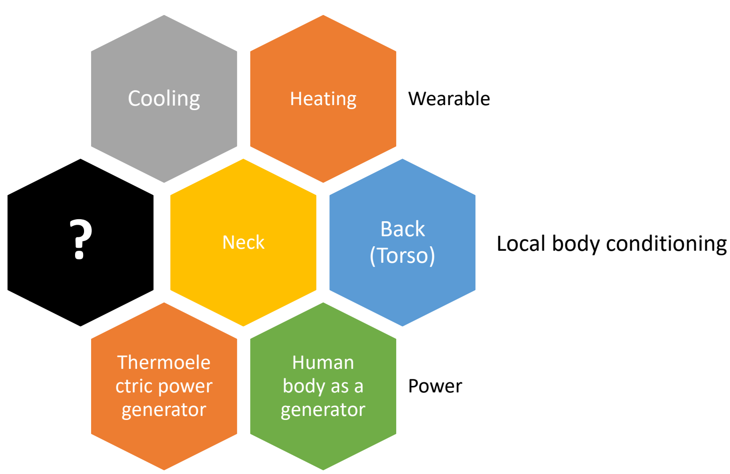
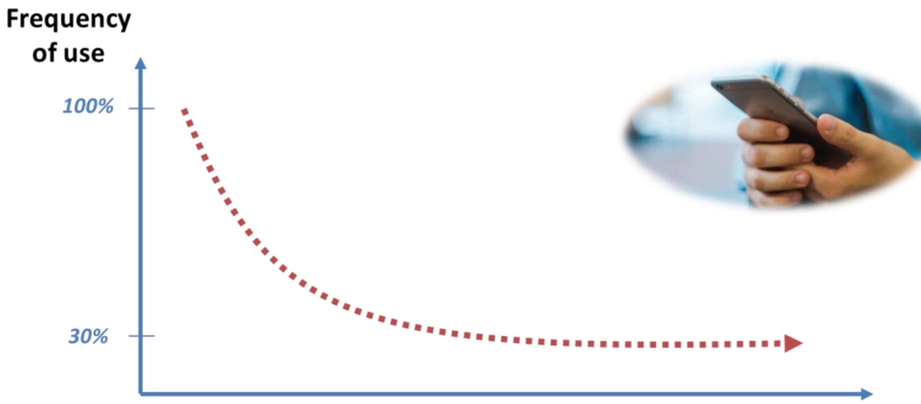
What is missing in the current products / state of the arts?

Automatic control
- Model-based control
- AI-driven control
- Feed-back control
- Feed-forward control
- others



Technical needs to accommodate each user's input in *an unobtrusive and natural way*





(Berkel et al., 2015)

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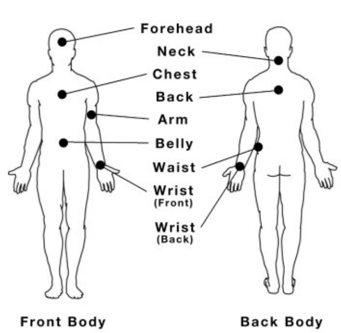
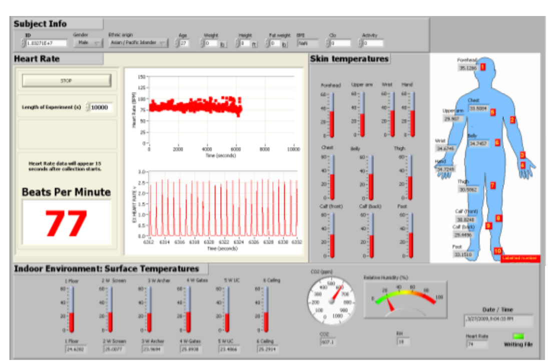
Bio-sensing thermal comfort modeling

Where to measure on the body to develop a thermal comfort model as a function of skin temperature.

- 10 local body segments have been mostly selected in the existing studies.





(Choi's Human-Building Integration, 2018-2021)

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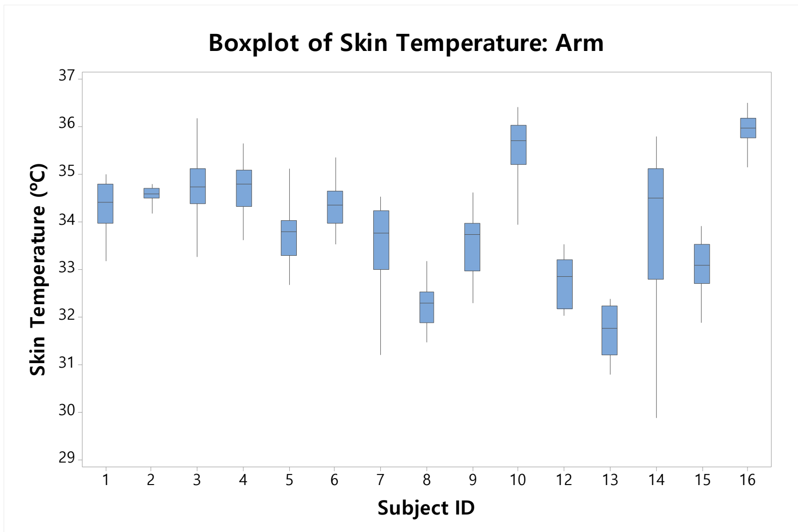
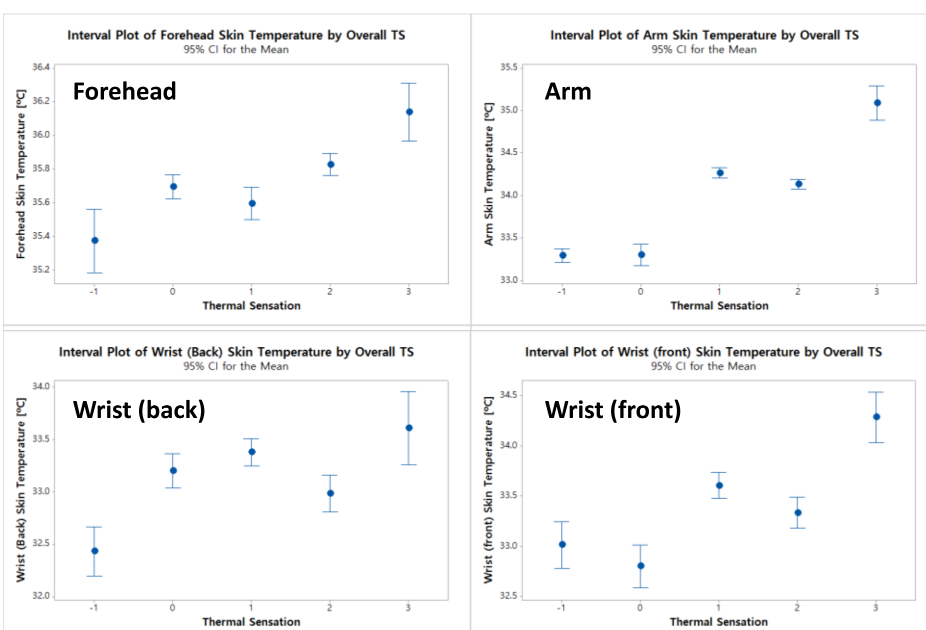
Large variations of skin temperatures per subject



(Choi et al., 2018)

Skin temp. Variations per Thermal Sensation



(Choi et al., 2019)

Thermal sensation prediction model as a function of Machine Learning algorithms (ANN)

- Combinations of Significant Attributes of Estimation Accuracy (using absolute level of skin temperatures)

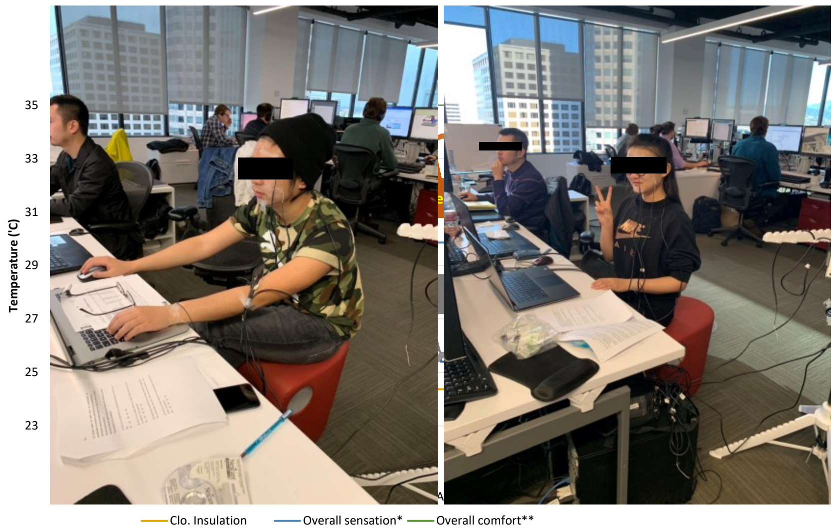
#	Baseline	Combination of Attributes			Accuracy
1	Gender & BMI	*Human factors only*			35.99%
2		Waist			76.03%
3		Arm			70.19%
4		Wrist (front)			68.45%
5		Forehead			68.04%
6		Wrist (back)			65.36%
7		Neck			64.01%
8		Wrist (front)	Wrist (back)		87.17%
9		Waist	Arm		93.02%
10		Waist	Wrist (front)		92.51%
11		Waist	Wrist (back)		92.41%
12		Waist	Arm	Wrist (front)	95.87%
13		Waist, Arm, Wrist (front), Forehead, Wrist (back), Neck			95.27%

Thermal sensation prediction model as a function of Machine Learning algorithms

- Results of Estimation Accuracy based on Single Body Areas/Segments (Skin temp. + Gradient)

#	Baseline	Combination of Attributes		Accuracy
1	Gender & BMI	Chest		89.56 %
2		Waist		91.91 %
3		Arm		91.24 %
4		Wrist (front)		91.27 %
5		Forehead		88.21 %
6		Wrist (back)		93.45 %
7		Neck		89.39 %
8		Belly	Arm	81.56 %
9		Wrist (front and back)		94.39 %

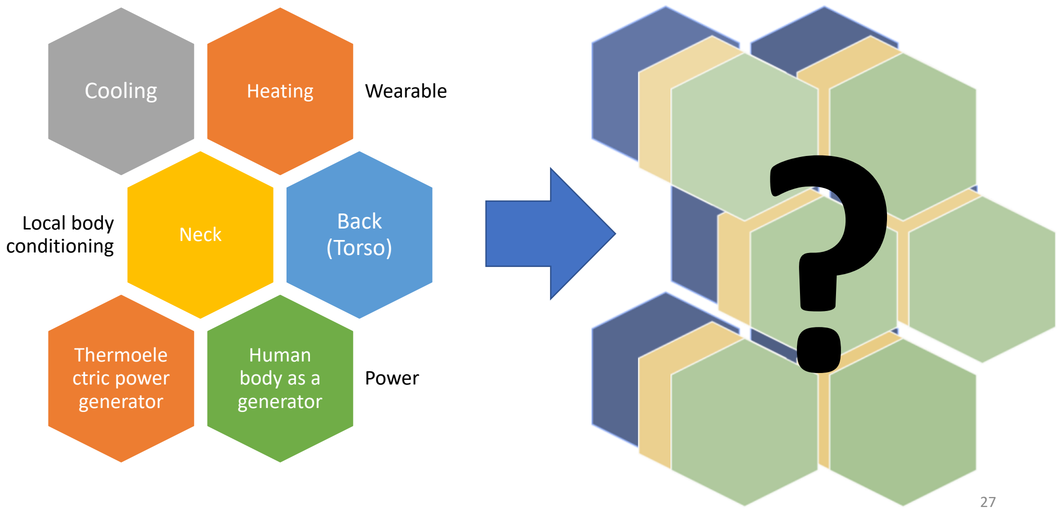
Skin temperature as a thermal sensation estimation index results in 104 correct predictions out of 110 (95+% accuracy).



Lessons from the project

1. A human data-driven thermal sensation model can be established by using **advanced computational algorithms.**
2. Human bio-signals tell us **a lot of significant information**.
3. Environmental comfort is significantly affected by **Individual physiological characteristics**, such as gender, age, and/or ethnic origin.
4. **A conventional/general comfort model** is still effective but limited in prediction accuracy for an individual level.
5. A thermal sensation / comfort model can be established per individual user with the help of **advanced sensing and computational technologies but require a lot f technical procedures to be defined (: Big Data and AI are a must).**

What should be done in future research?



Future Work

- Develop a robust sensing-based thermal sensation/comfort model of for an individual user with considering **individual physiological characteristics.**
- Establish a thermal sensation/comfort modeling design guideline as a function of **critical sensing points on the human body per environmental condition.**
- **Integrate the modeling results with the existing wearable system** for sensing and controls.
- Consider multiple parameters in terms of **indoor, outdoor, building typologies, climate and seasonal conditions, activity level, multiple ambient environmental condition, etc.**
- **Net-zero energy feature**: A thermo-electric generation as a cooling or heating resources while contributing to the power source (for wearables) is a novel technical platform.

Acknowledgement

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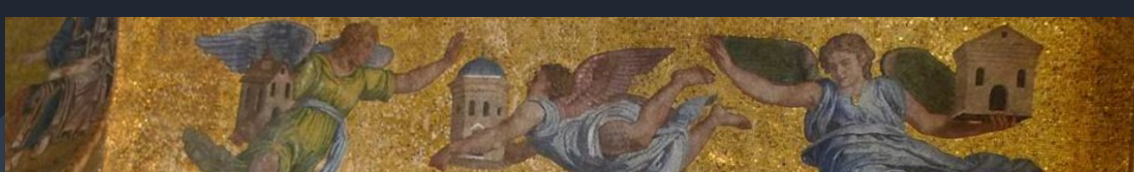
- Part of this presentation is based upon work supported by the *U.S. National Science Foundation (NSF)* under Grant No. 1707068.



Annex 87 - Subtask C: *Control, operation and system integration*

- **Activity C1:** Identify and summarize existing methods for controlling PECS (including sensors used for control).
- **Activity C2:** Develop guidelines on integrating PECS with ambient conditioning systems in buildings.


Thank you.
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Always looking for great collaborators
and partners!