Footwarmers providing efficient heating

Hui Zhang

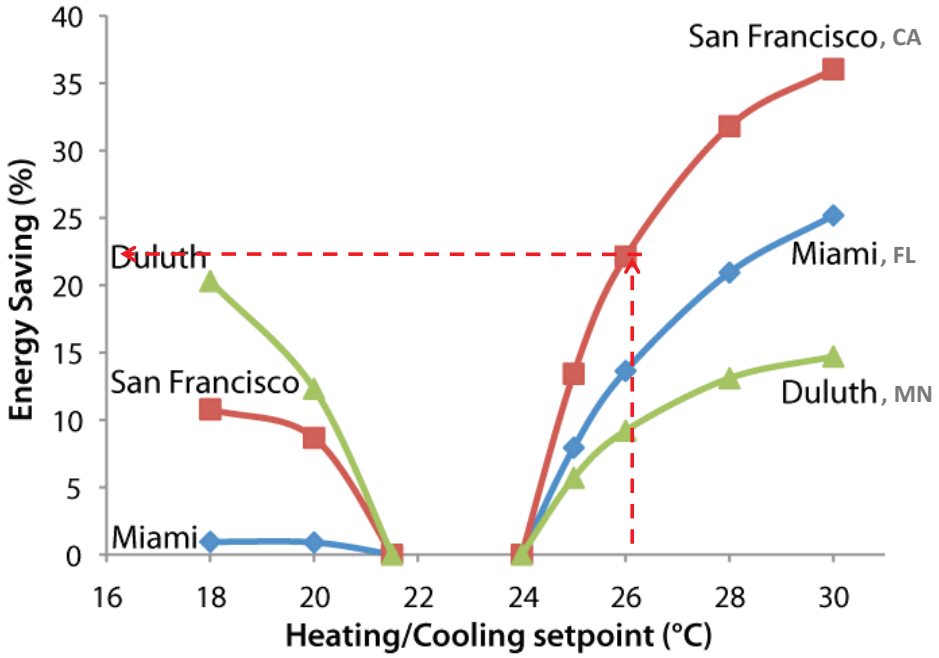
Center for the Built Environment (CBE)

University of California Berkeley

CBE
CENTER FOR THE BUILT ENVIRONMENT

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.

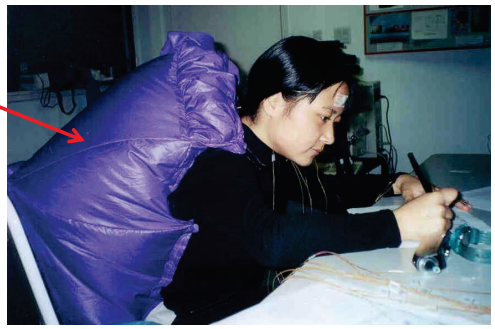


Hoyt, T., E. Arens, and H. Zhang. 2015. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment* 88, 89-96

Perception varies across the body

Human testing of sensations for 16 individual body parts

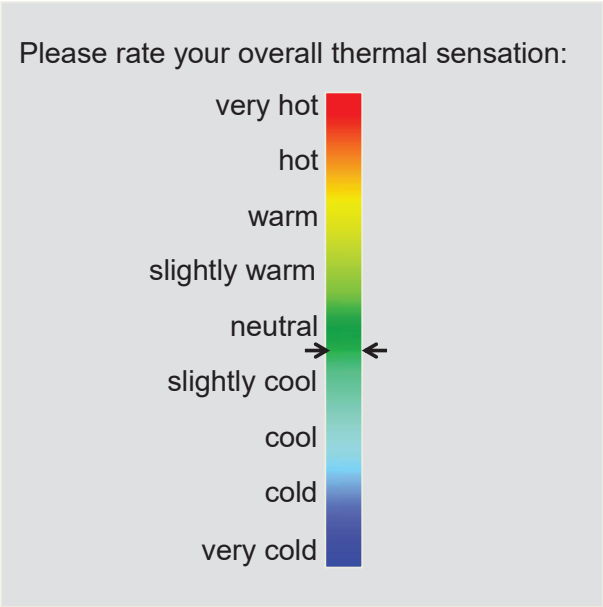
warm/cooled air supplied to individual body parts

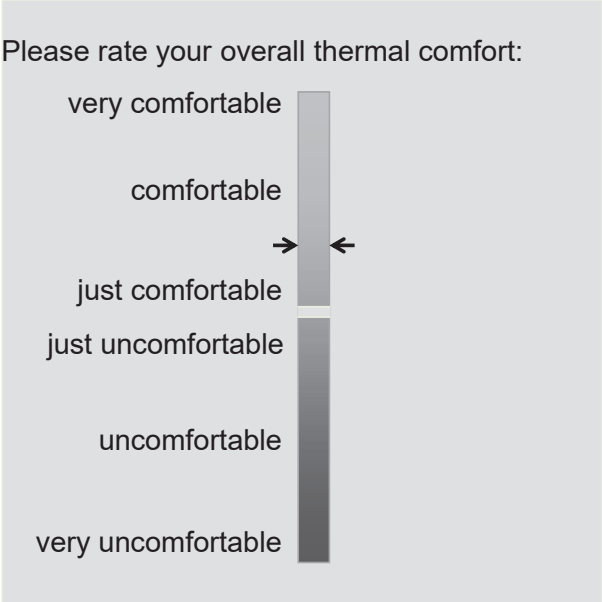


Zhang, H. 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments, Ph. D. Thesis

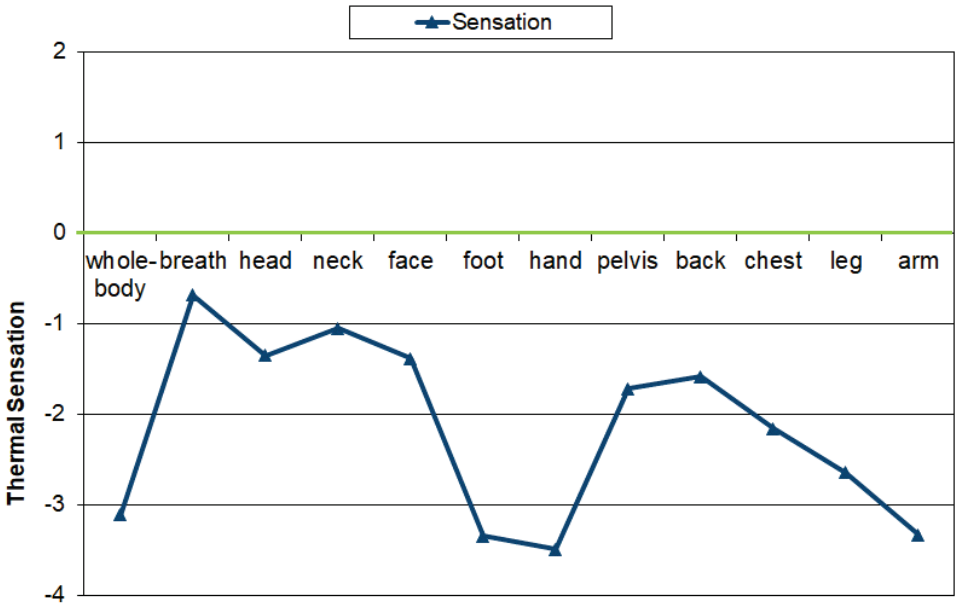
Thermal sensation and comfort scales

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

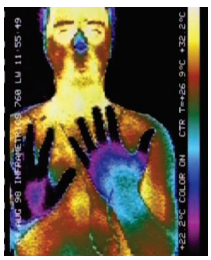


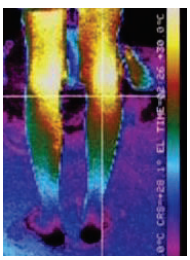


Cool environments: Extremity dictates whole-body discomfort



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





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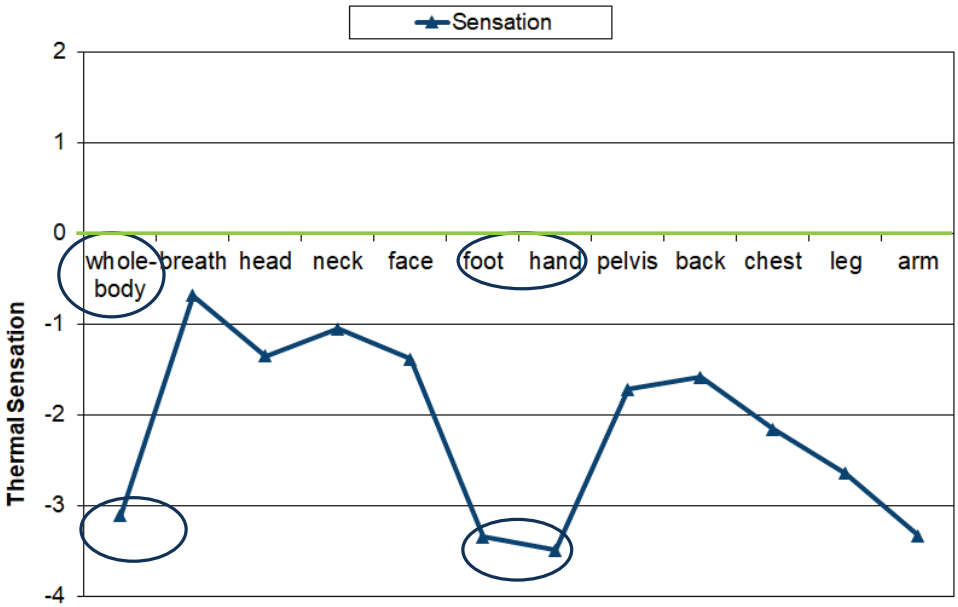

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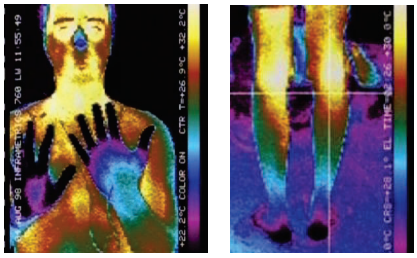

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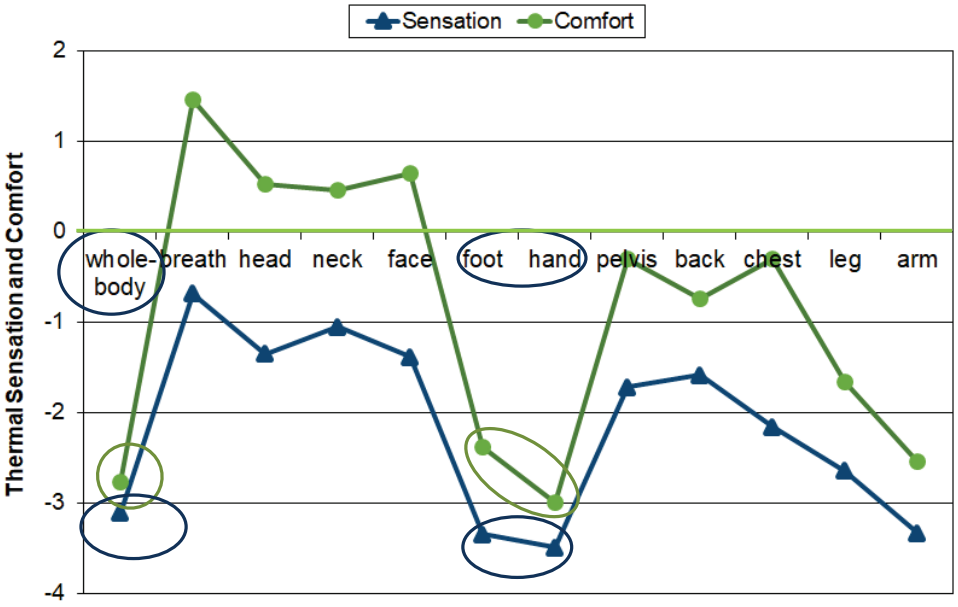

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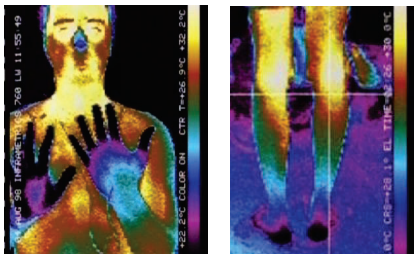
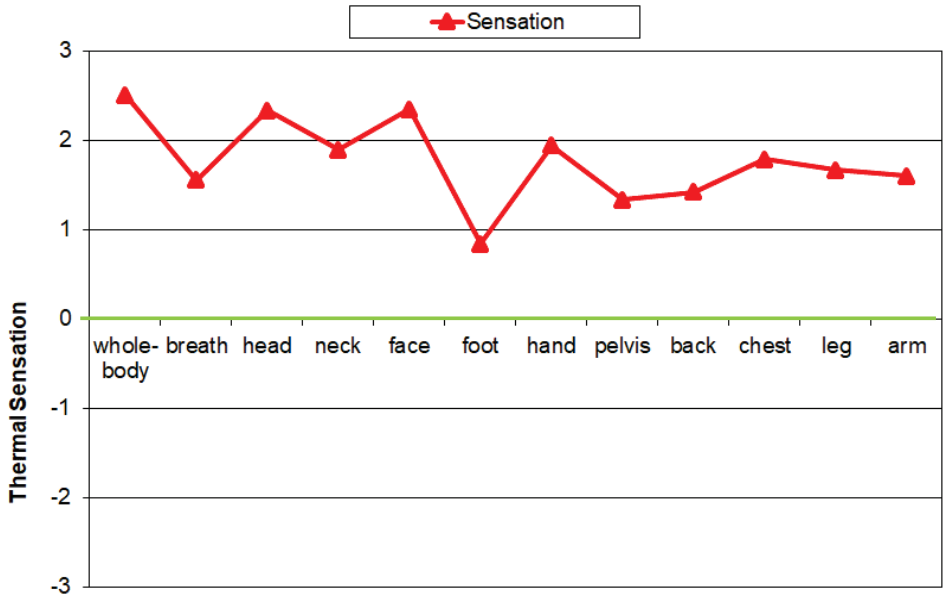


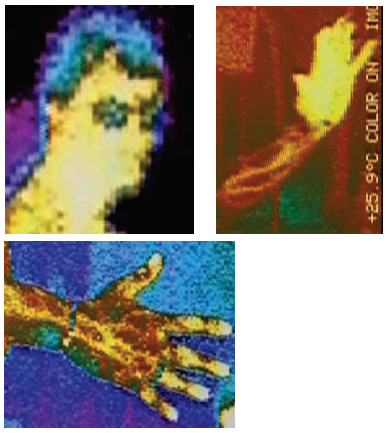
Arens, E., H. Zhang, C. Huizenga. 2006. Partial- and whole body thermal sensation and comfort, Part I: uniform environmental conditions. Journal of Thermal Biology, 31, 53 - 59.

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

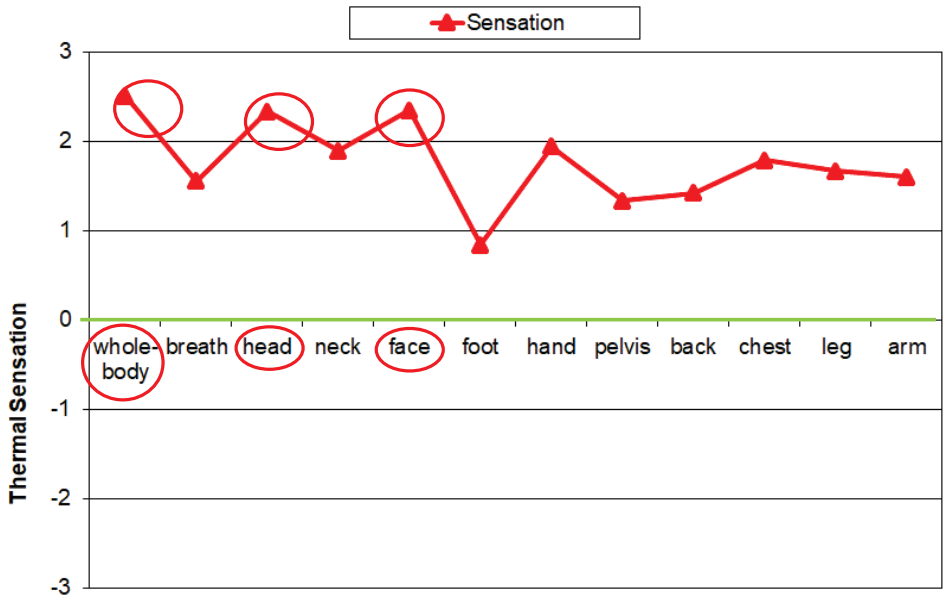
Warm environments: Head dictates whole-body discomfort



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



Warm environments: Head dictates whole-body discomfort



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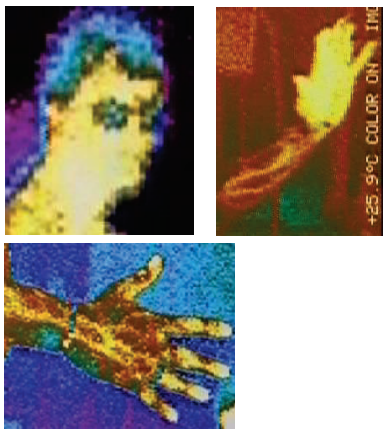

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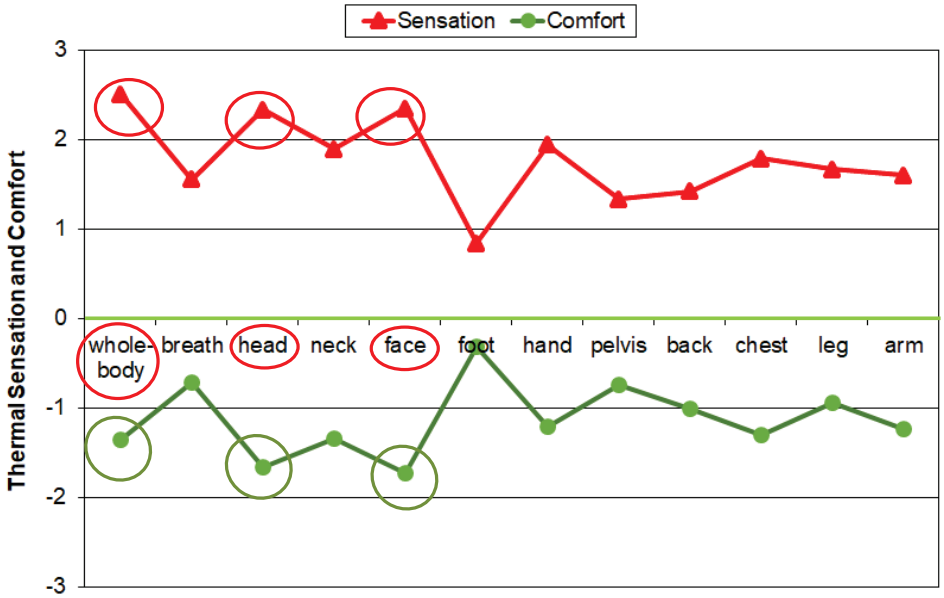

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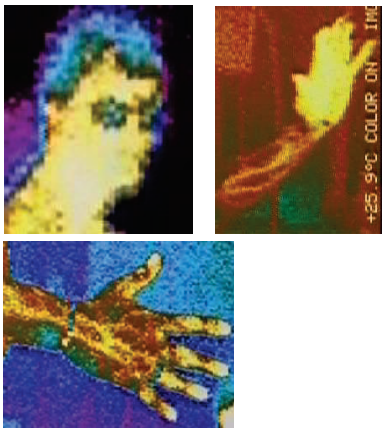

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Zhang, H. 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments, Ph. D. Thesis

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…)

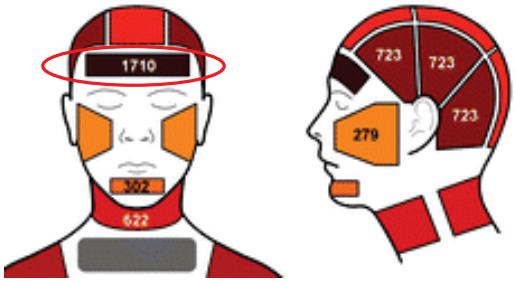
Schmidt-Nielsen (1971) "How animals work"

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)



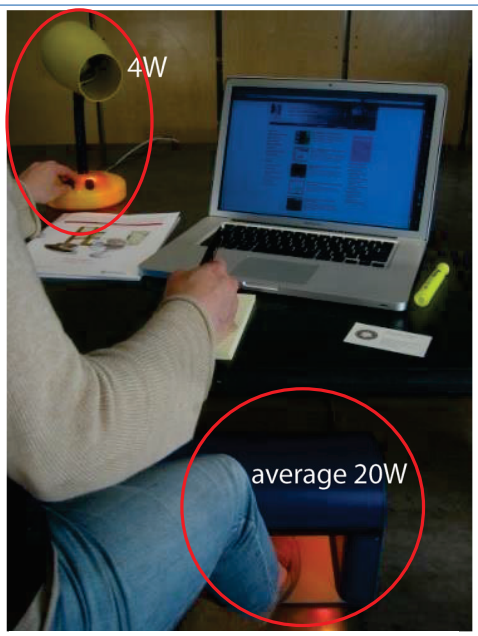
Smith and Havenith (2011)

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

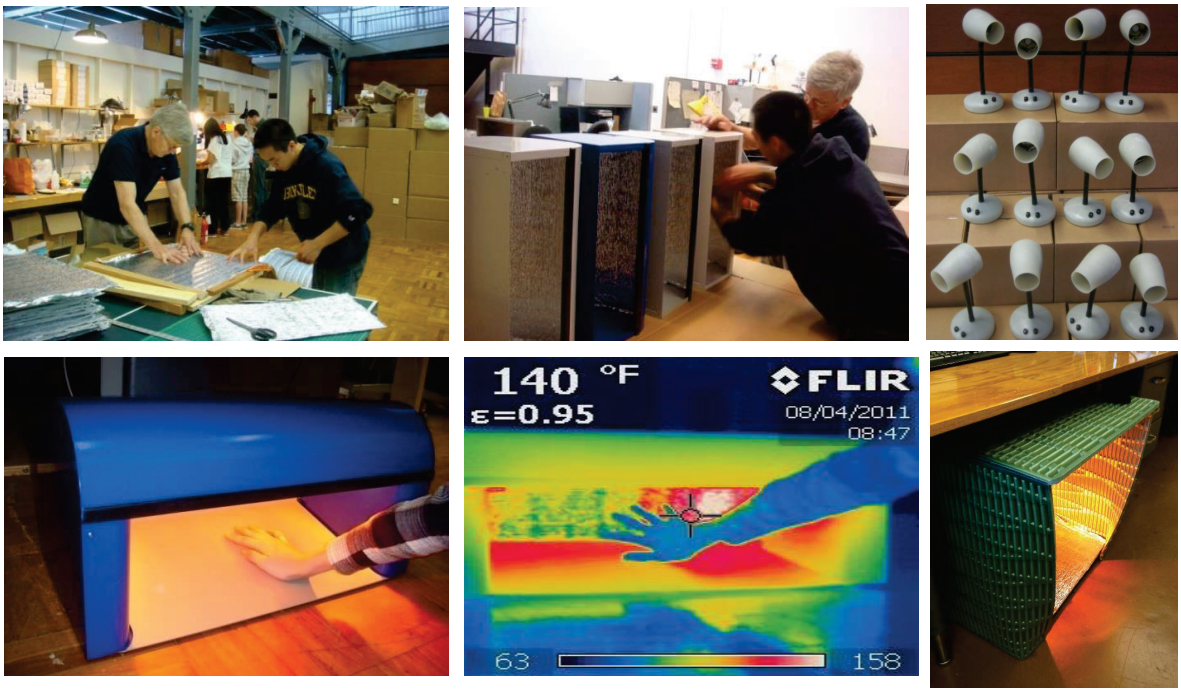


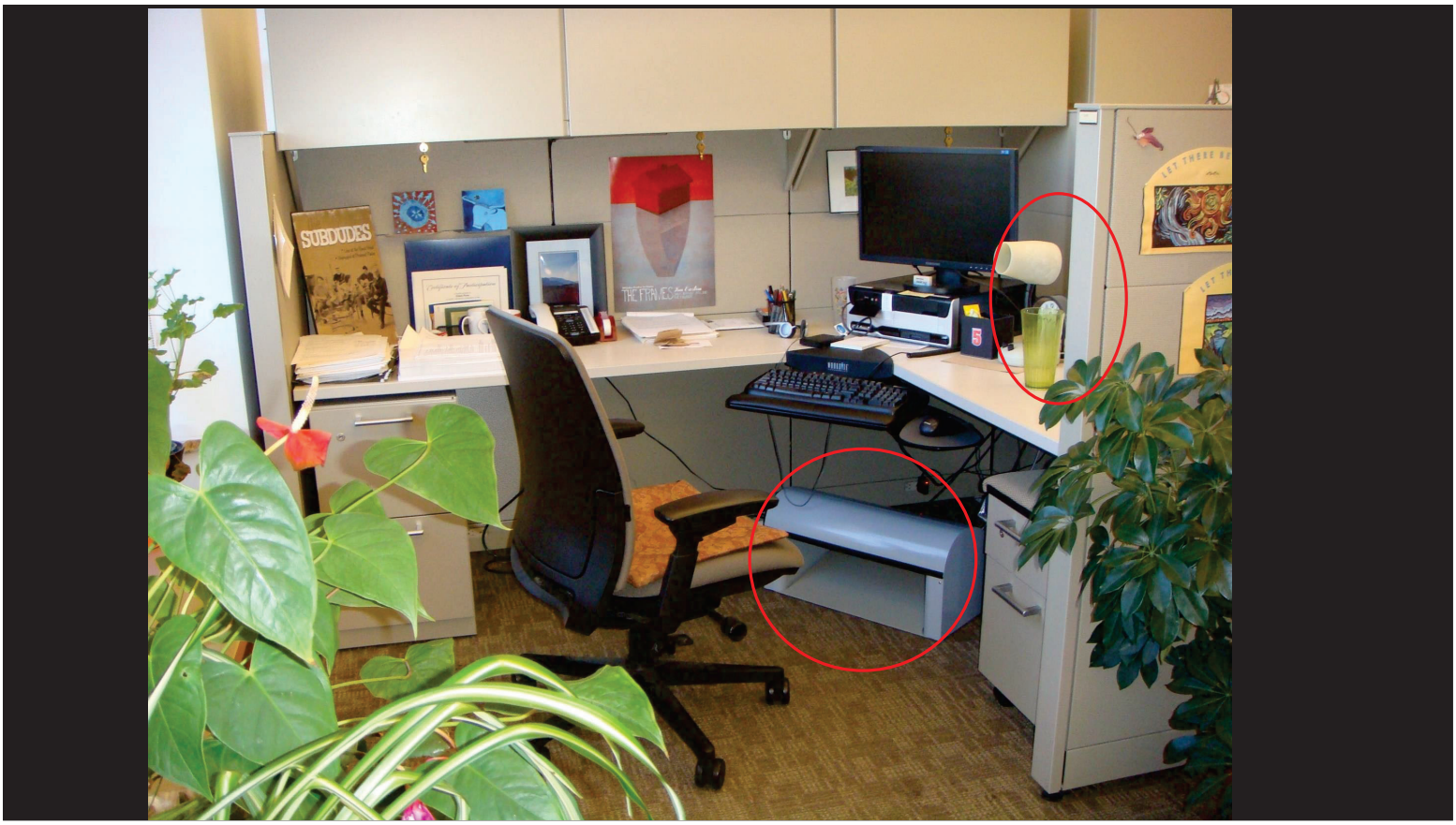
Head cooling and foot warming PCS

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

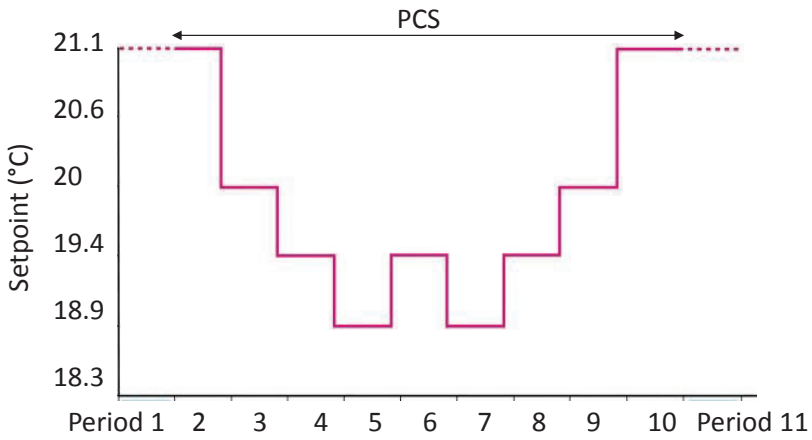
Demonstrate the use of fan/footwarmer over a whole winter

Method

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

Results

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



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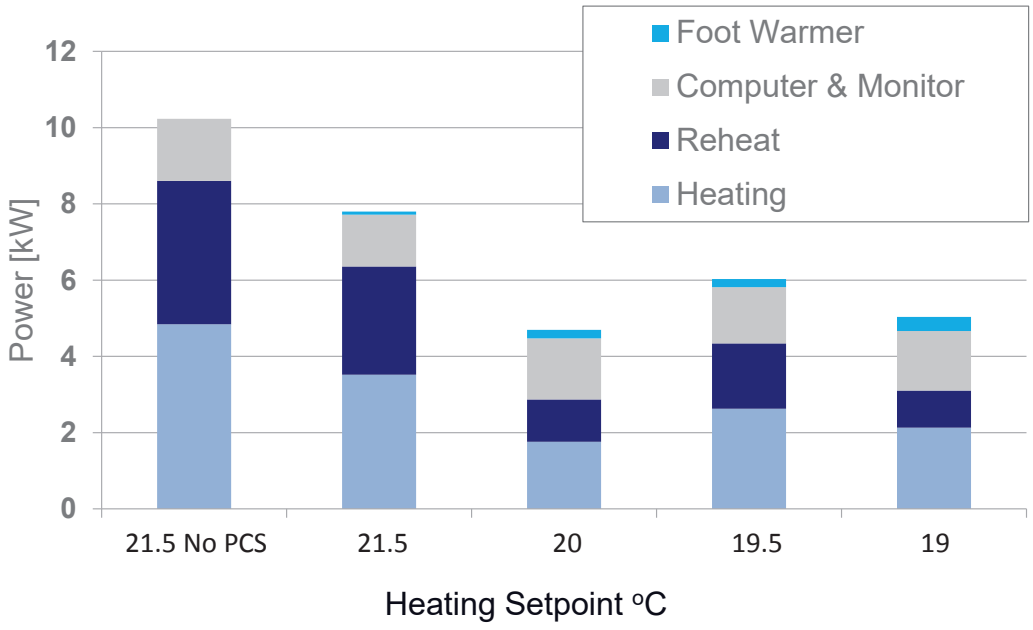
Measured power usage by footwarmer is negligible



Thermal perception at a more detailed scale

Thermal sensitivity: test method

Neutral ambient temperature

- 25ºC, 40%RH

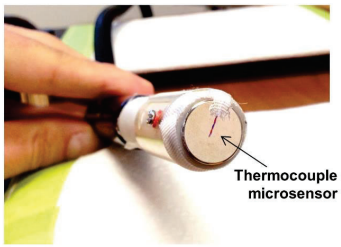
Thermal probe

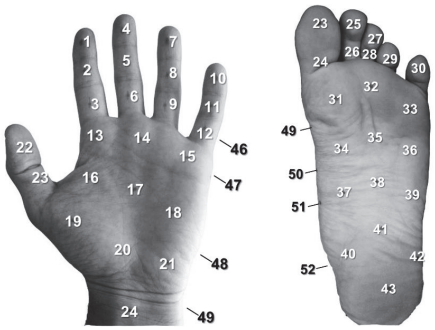
- PhysiTemp, 14mm probe
- 50 test points on hand, 50 on foot

Test procedure

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

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

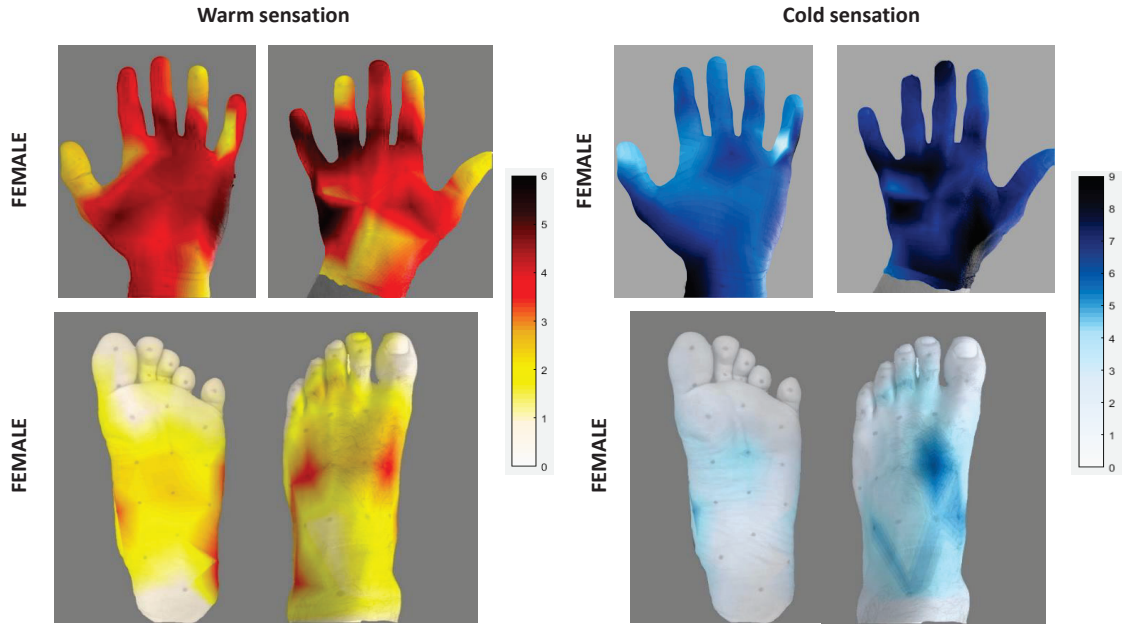




Very Hot	10	Very Cold
	9	
	8	
	7	
	6	
	5	
	4	
	3	
	2	
	1	
Not hot at all	0	Not cold at all

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

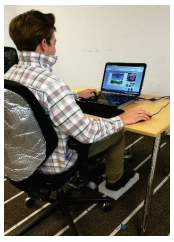
Warm/cool sensitivity maps of hands and feet

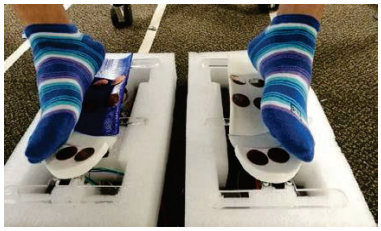


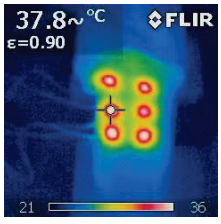
Filingeri, D., H. Zhang, E. Arens. 2018. Thermosensory micromapping of warm and cold sensitivity across glabrous and hairy skin of male and female hands and feet, Journal of Applied Physiology, 125: 723–736

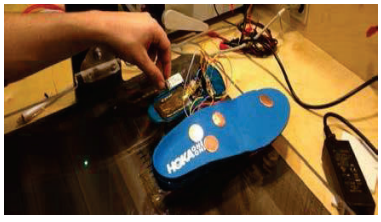
Tests of spot-heated insoles on foot sensation

10 female, 10 male, 18°C, 40%RH

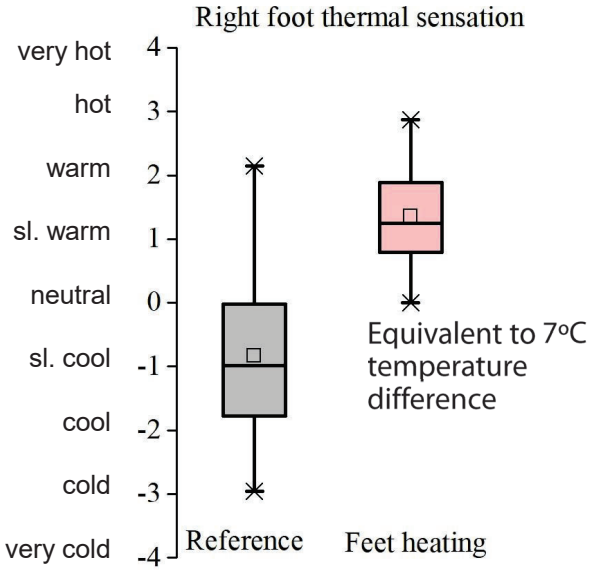








1.2 Watts



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.

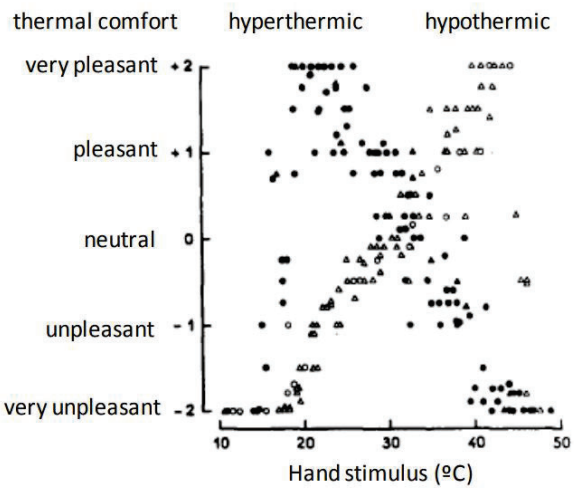
de Dear RJ. Revisiting an old hypothesis of human thermal perception: Alliesthesia. Building Research & Information, 2011, 39(2):108-117.

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.

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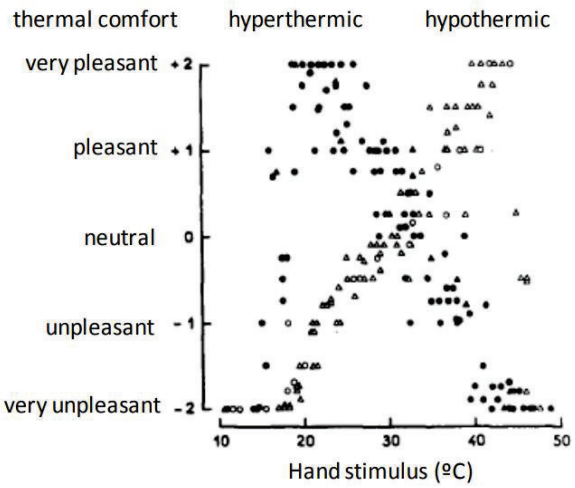
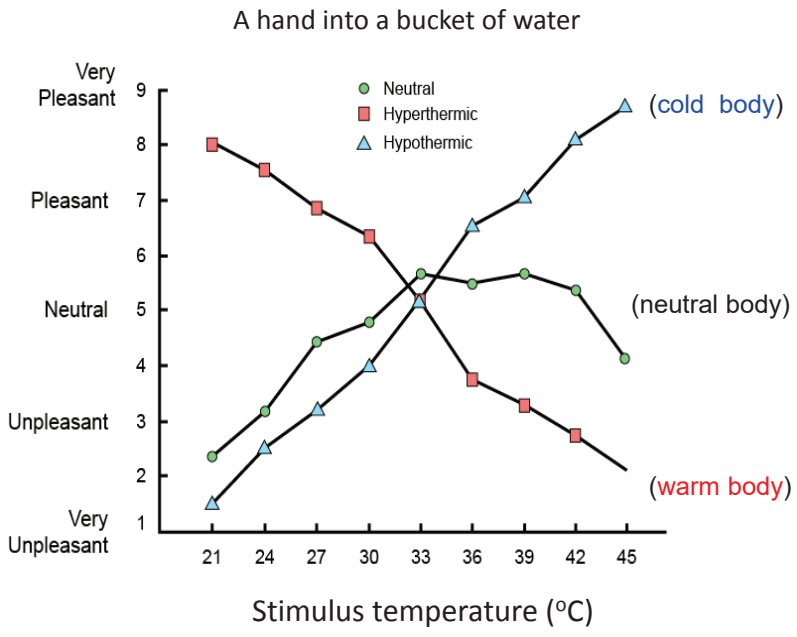
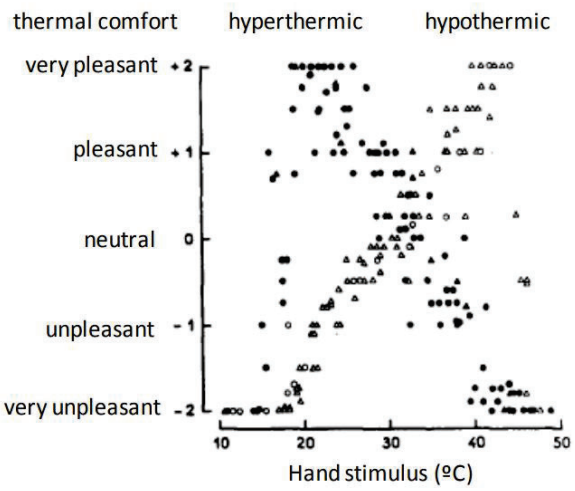




Cabanac M. Plaisir ou deplaisir de la sensation thermique et homeothermie. Physiology and Behavior 1969;4: 359-364.

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



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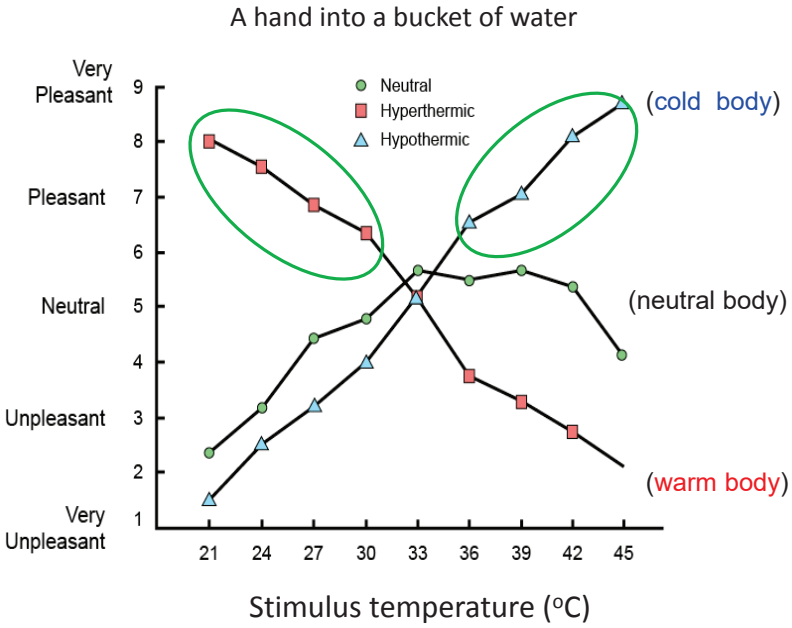
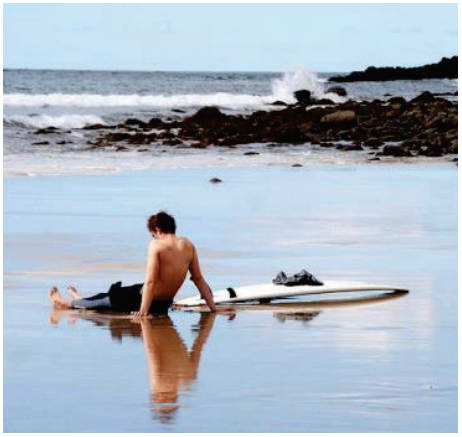


Adapted from Mower DM. Perceived intensity of peripheral thermal stimuli is independent of internal body temperature. Journal of Comparative and Physiological Psychology 1976;90(12):1152–5

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

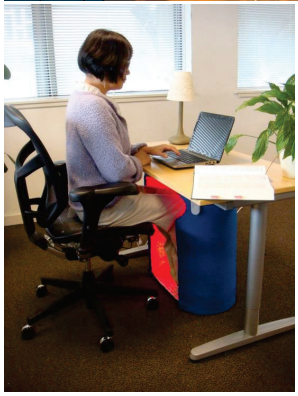
We can provide better comfort with PEC or PCS (Personal comfort systems)

- 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!