A paradigm-shift to individualized & digitized thermal comfort

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Personalization:
A ‘mega-trend’ of the 21st century

- We personally curate our **information and news** - the ‘echo chambers’
- We curate our **cultural and entertainment diets**
- We even curate our own **reality,** only believing what we want to believe in this ‘post-truth’ era
- The phenomenal success of **work-from-home** since early 2020 is owed to personalization of the the home workplace – “*our home is our castle*”
- Individualized, Personalized, Customized, Bespoke, Granular, Curated! All these buzzwords of the 21st century are pointing in one direction – towards **individual control.**
- So it should come as no surprise to learn of a recent research trend towards bespoke thermal environments **– Personal Comfort Systems** (PCS)

The "*One-Size-Fits-All*" Delusion

- For last 50 years comfort standards (ISO-7730, ASHRAE-55) have labored under the misconception that ***quality*** equates to ***temperature uniformity*** throughout a building.
- Yet field studies in *real* buildings with *real* occupants have shown, over and over again, that this ***one-size-fits-all*** approach doesn't work quite as well as we assumed.

The "*One-Size-Fits-All*" Delusion

The *ISO 7730 comfort standard classes*

Class	PMV	Temperature range at typical *clo* and *met*	% acceptability
A	-0.2 < PMV < +0.2	2°C	90
B	-0.5 < PMV < +0.5	4°C	80
C	-0.7 < PMV < +0.7	6°C	65

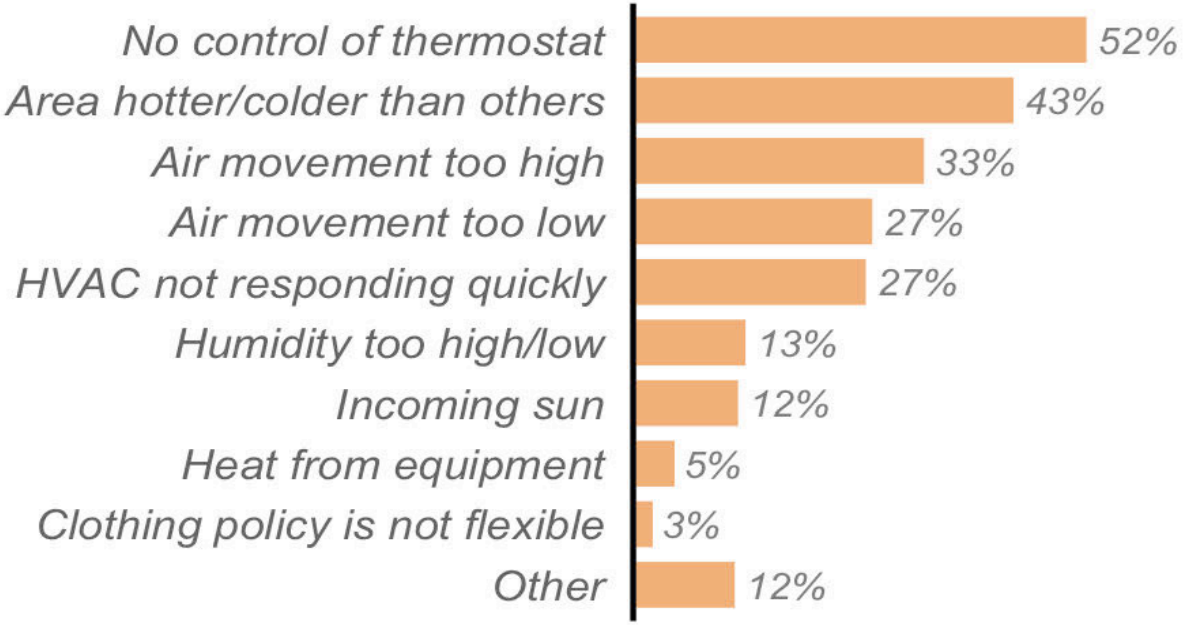
Office Rating	*PMV* Range	Townsville Summer Wet Season	Townsville Summer Dry Season	Kalgoorlie-Boulder Summer Season	Kalgoorlie-Boulder Winter Season
Class A	± 0.2	80% accept (n = 121)	77% accept (n=90)	84 % accept (n=49)	84% accept (n=84)
Class B	± 0.5	78% accept (n=340)	79% accept (n=264)	86 % accept (n=204)	83% accept (n=216)
Class C	± 0.7	78% accept (n=468)	77% accept (n=358)	86 % accept (n=306)	84% accept (n=285)

~80% acceptability is about as good as it gets

Arens, Humphreys, de Dear & Zhang 2010 "Are 'class A' temperature requirements realistic or desirable?" Building and Environment, V 45(1), 4-10

The reasons office occupants give for being thermally ***dis***satisfied

These data came from the UC Berkeley post-occupancy evaluation survey database with over 90,000 questionnaire responses collected from predominantly US office workers over the last 20 years

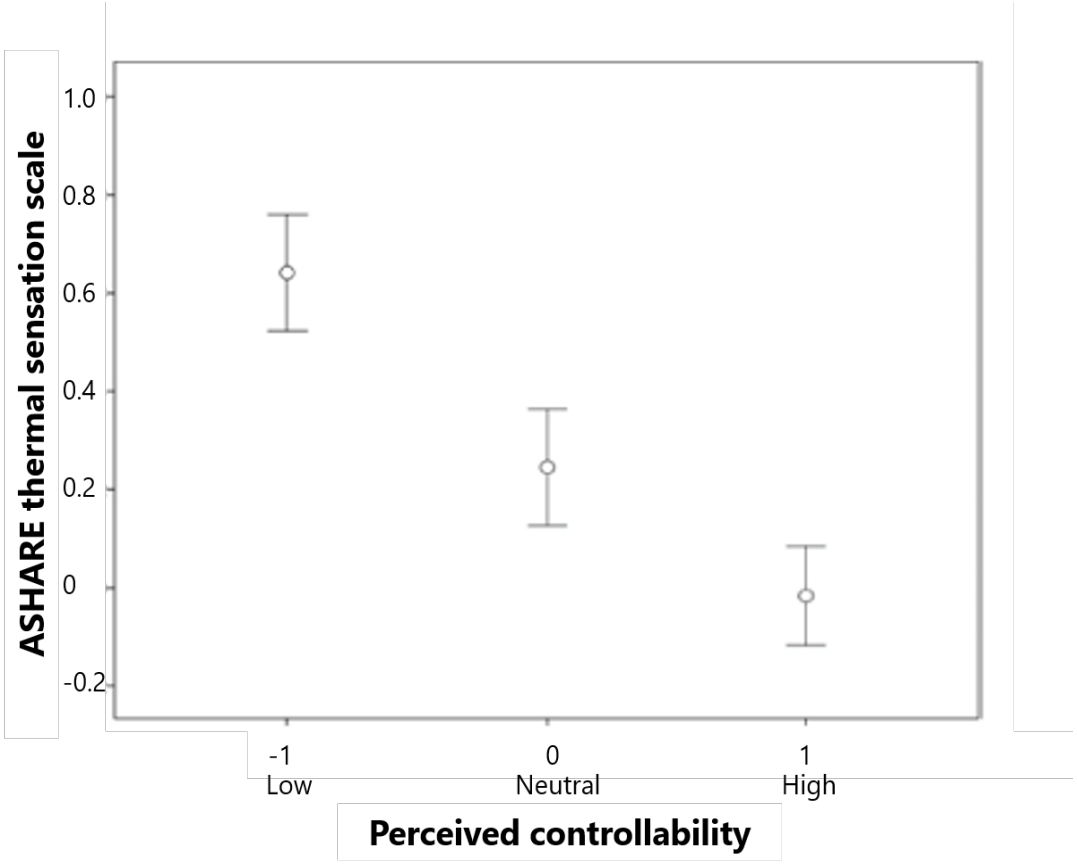


Graham, L.T., Parkinson, T. and Schiavon, S., 2021. Lessons learned from 20 years of CBE's occupant surveys. Buildings and Cities, 2(1).

What's wrong with the *one-size-fits-all* approach?

Perceived Control

- Seven air-conditioned buildings with various levels of adaptive opportunity were selected for a summertime field survey in **South Korea**
- Perceived control on 7pt Likert Scale re-coded (-3,-2,-1) (0) (+1,+2,+3)
  Low Neutral High
- The **high perceived control group felt cooler** (ASHRAE 7pt) in summer than the low perceived control group, despite no difference in operative temperatures. Kruskal-Wallis χ^2 2(2)=16.83, P<0.001
- The summer **comfort temperature** (Griffiths Method) for the high perceived control group was ~ 1◦C warmer than that for the group with low perceived control.
  F(2,171)= 3.62, P = 0.029



Yun, G.Y., 2018. Influences of perceived control on thermal comfort and energy use in buildings. *Energy and Buildings*, 158, pp.822-830.

The Future of HVAC is **Personalization**: 4 Key Developments Driving It

1. First is the advent of very **low-watt and affordable PCS** devices

2. The second is a new framework of thermal perception termed **alliesthesia** to explain why PCS paired with wide ambient dead-band control actually improves comfort

3. The third is the advent of low-cost **sensor technology** (IoT) coupled with **artificial intelligence** (AI) methods, making it now feasible to embed sensors and smart algorithms into PCS to learn preferences and elicit alliesthesia

4. The global climate crisis is pressing us to **decarbonize** our economy. This translates to **reducing energy demand** across the buildings sector – urgently!

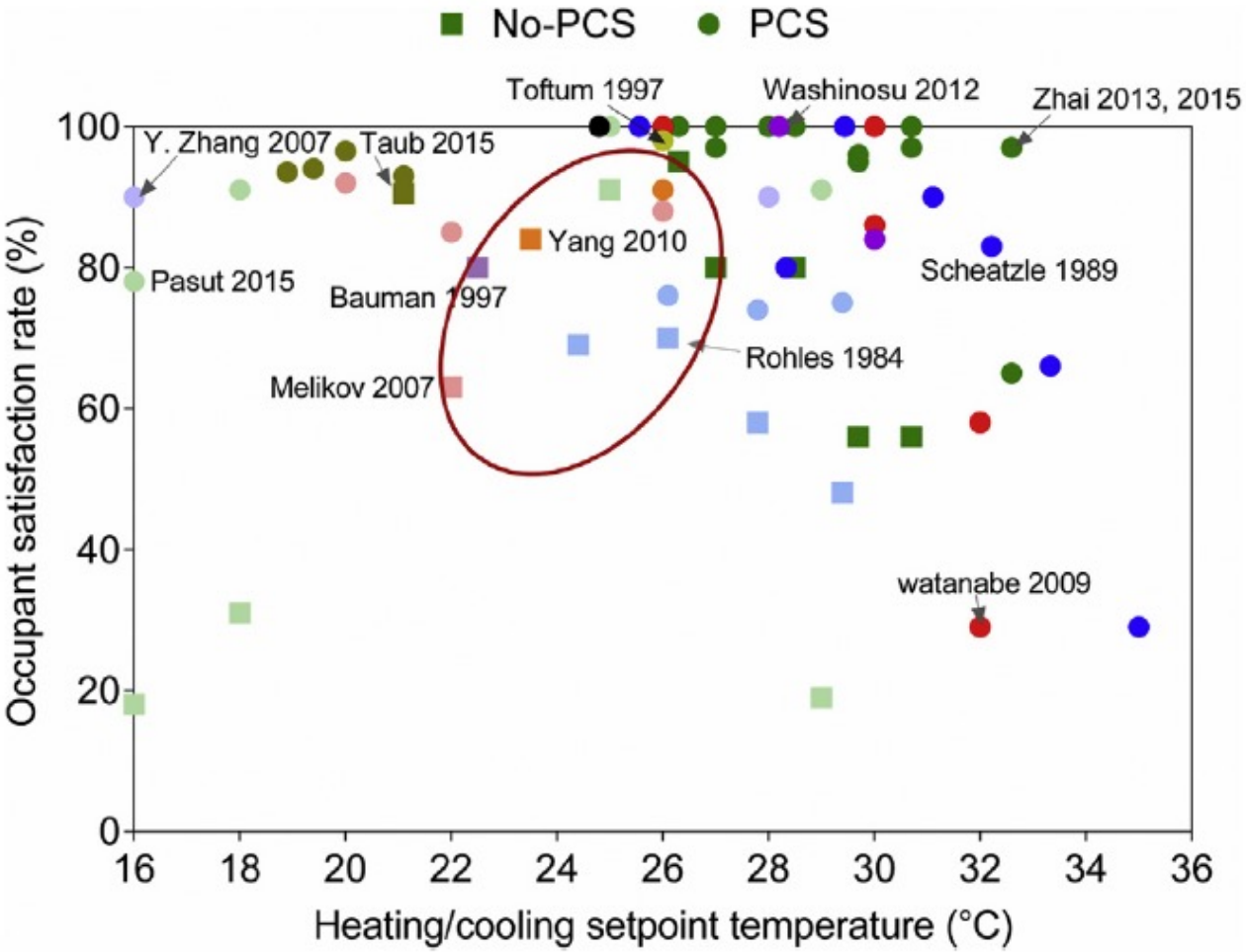
Personal Comfort Systems (PCS) Devices

Thermal PCS devices are usually based on the simple rules of alliesthesia –

"cool the head and warm the feet"

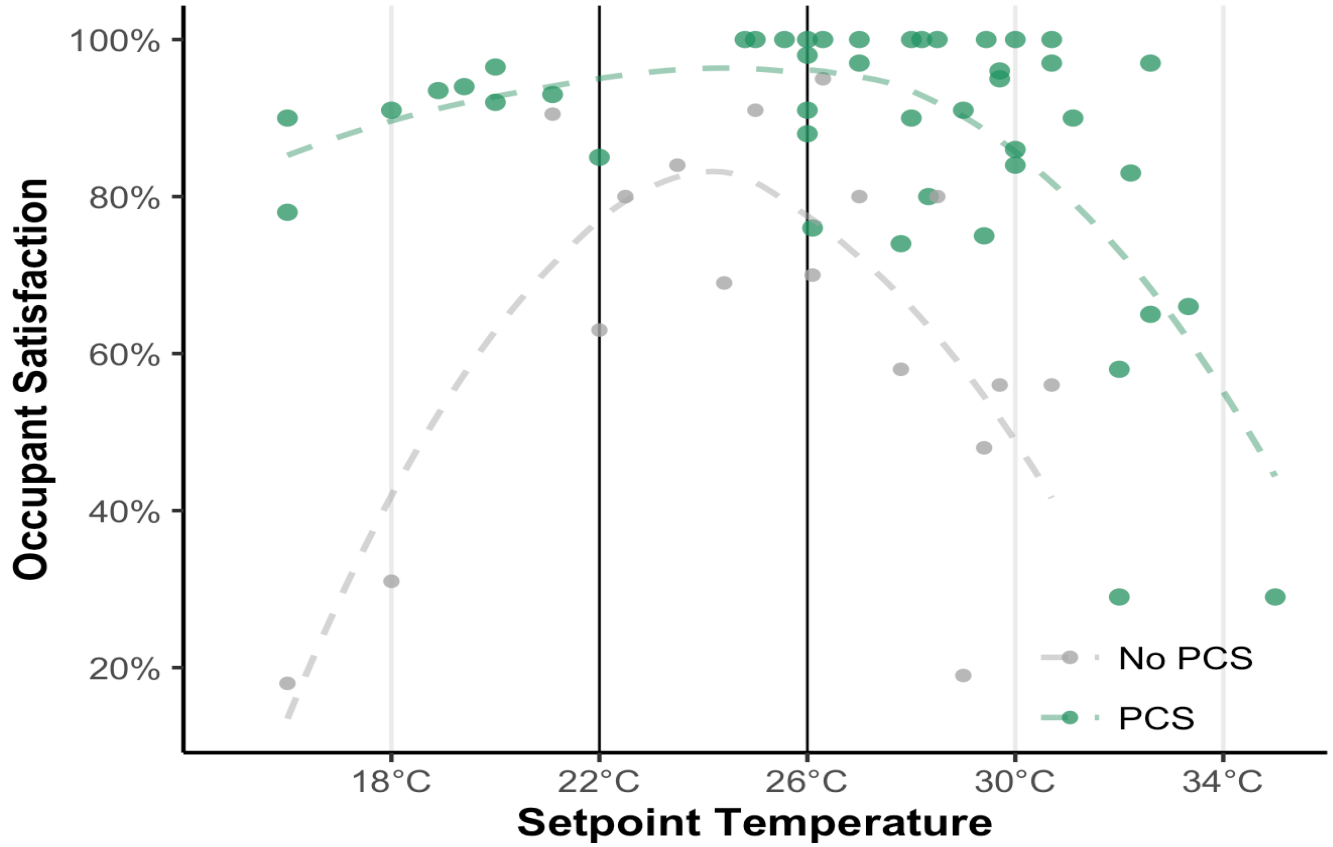
- fans for air movement aimed at head/face/upper body. This includes desk, pedestal, and ceiling fans, small USB fans, nozzles and diffusers in desks and workstation partitions
- regulable conditioned air-outlets in floor or furniture
- misting fans (evaporative-cooling-assisted convection)
- water-conditioned radiant panels (infrared heat gain/loss from occupants)
- electric heating panels/elements (infrared radiant gain by occupants)
- Water/electric conditioned furniture (conductive heat gain/loss from occupants)
- various combinations of these strategies

1 – Low Energy Personal Comfort Technology



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

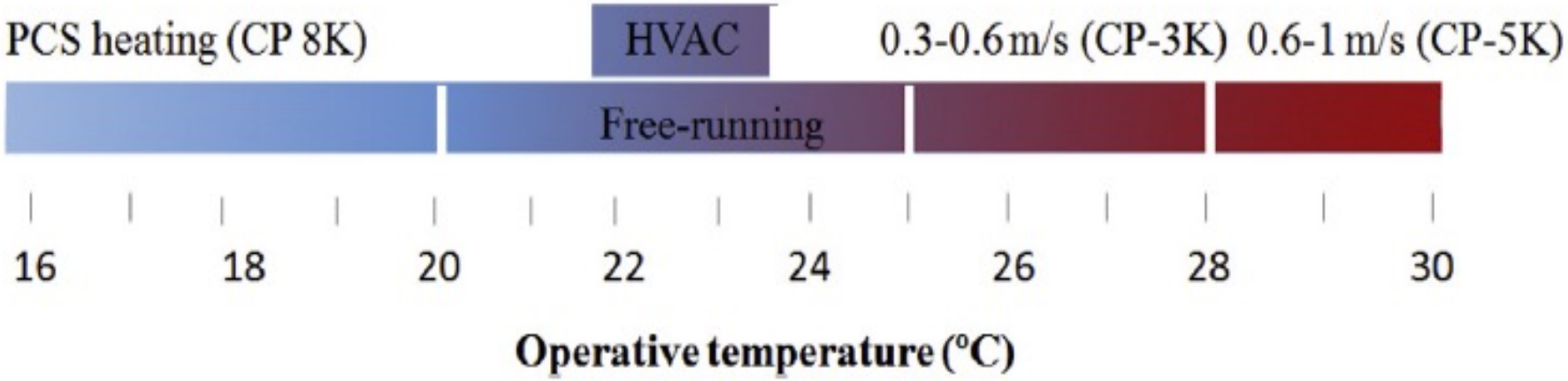
1 – Low Energy Personal Comfort Technology [previous slide redrawn]



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

1 – Low Energy Personal Comfort Technology

"Corrective Power"



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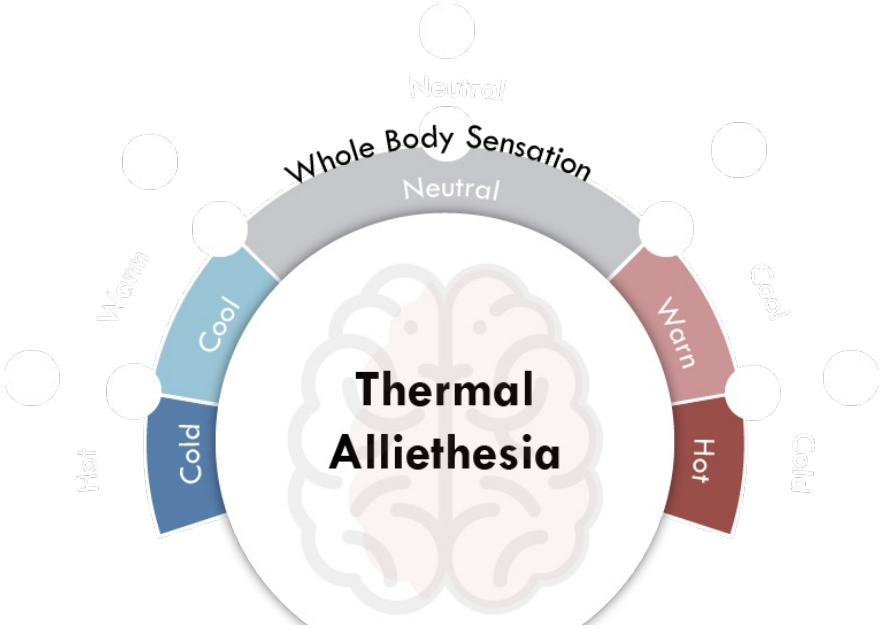
2 - New Thermal Comfort Framework: Alliesthesia

- Conventional thinking about thermal comfort is about uniform conditioned affecting the **whole body**.
- But PCS applies heating or cooling to **specific body regions**, so it demands a fundamentally different framework for thinking about thermal comfort.
- **Alliesthesia** – is a term coined by a physiologist (Cabanac 1971) and refers to the hedonic tone (pleasure/displeasure) of an environmental stimulus as deriving from whether it will **restore (+ve)** or **perturb (-ve)** internal equilibrium.
- Cabanac hedonic theory is applicable to all of the body's homeostatic systems (hunger, thirst, temperature). **Why?**
  -ve alliesthesia – unpleasant feeling, **discouraging** maladaptive behavior
  +ve alliesthesia – pleasant feeling, **encouraging** adaptive behavior
- -ve thermal alliesthesia – local discomforts (draft, asymmetry, stratification)
- +ve thermal alliesthesia – localized heating/cooling (PCS)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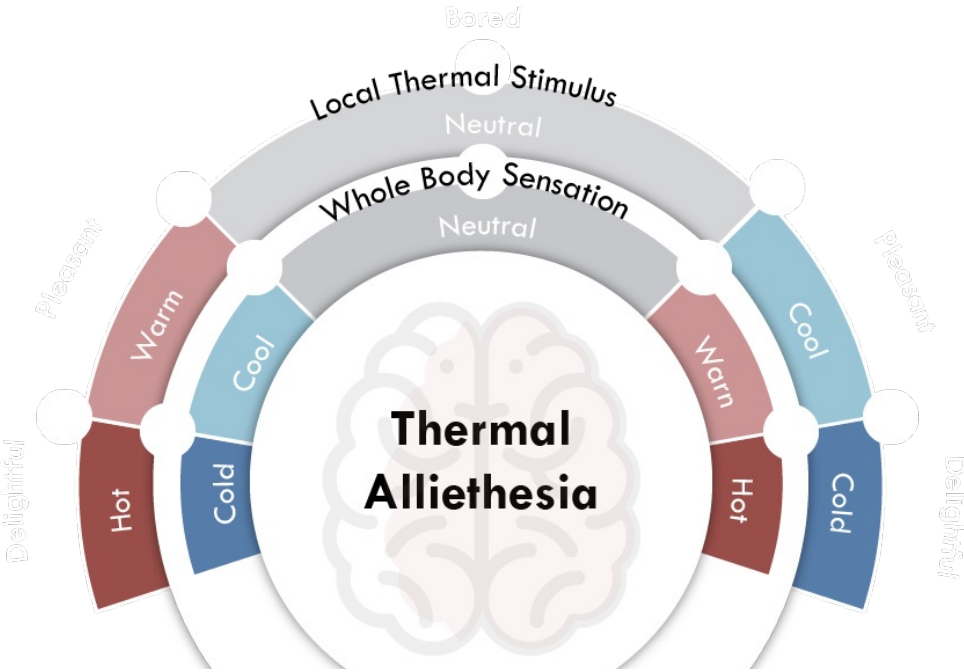
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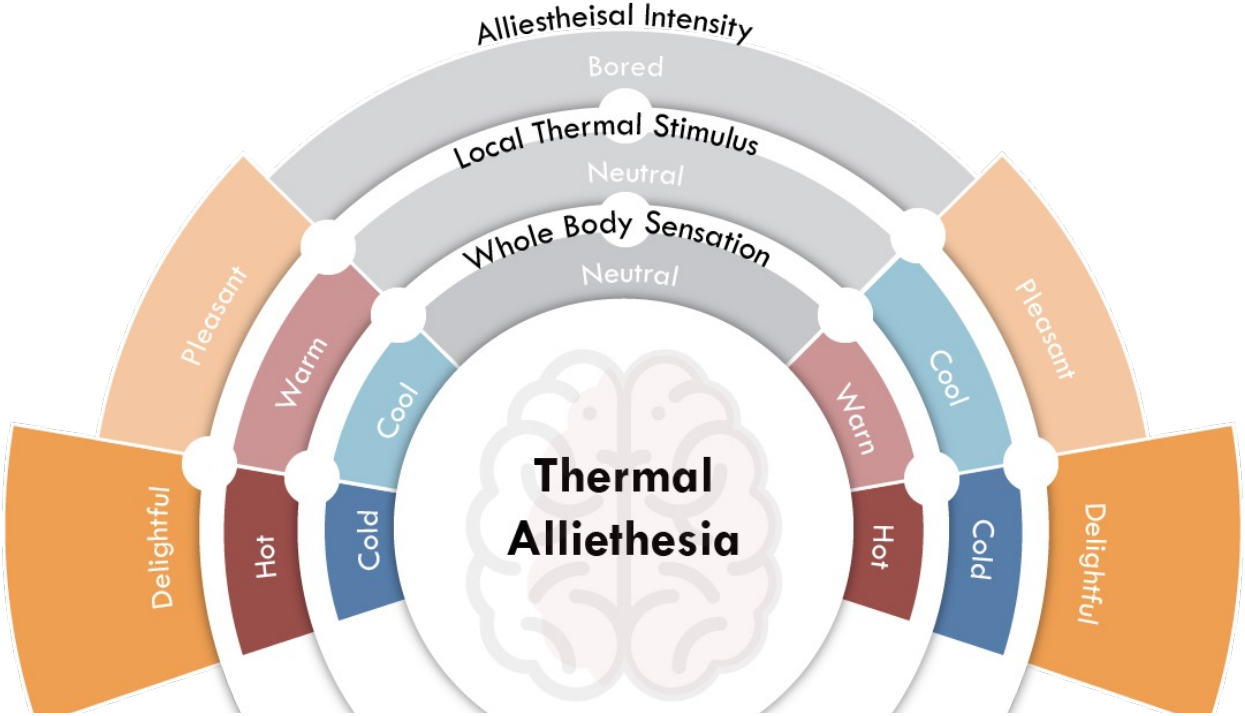
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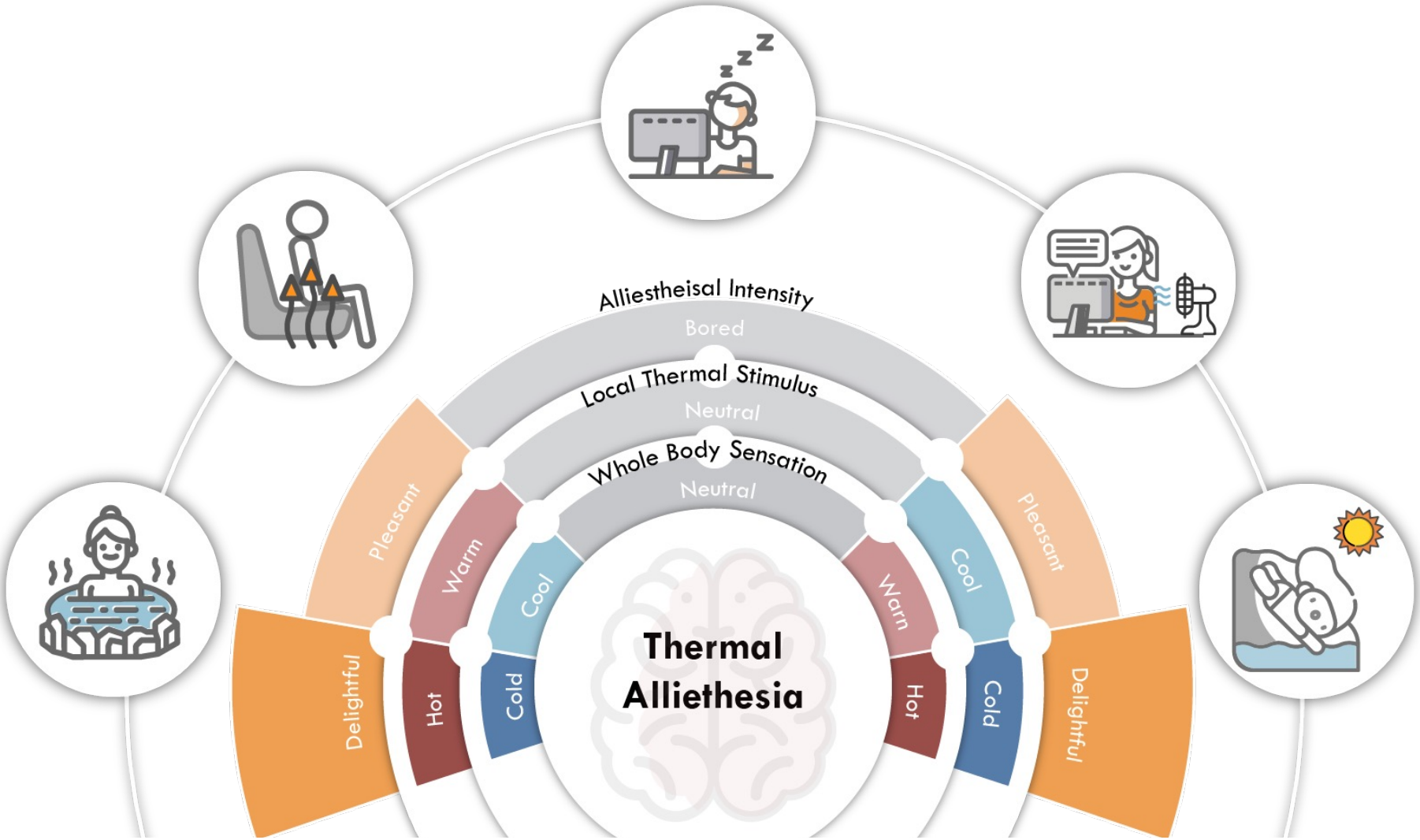
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2 - New Thermal Comfort Framework: Alliesthesia

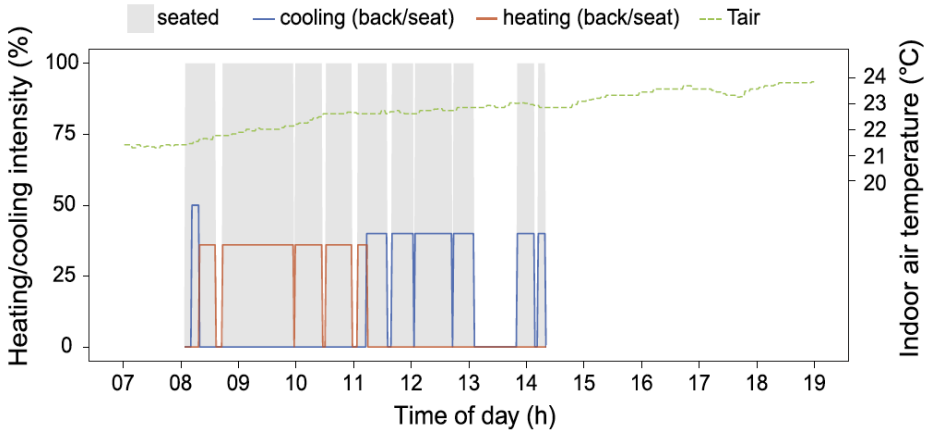
- How are thermal sensory signals coming from different body parts integrated? Hui Zhang argues that comfort follows a '**complaint' process**. Uncomfortable body segments 'complain' and override signals from other segments in creating overall comfort perception (Zhang et al., 2015).
- PCS can flip this complaint into pleasure by **applying heating or cooling directly onto the plaintive segment**. This restores comfort, and in the process, provide positive alliesthesia, because the restorative thermal stimulus puts the local part on the opposite side of neutrality from the rest of the body.
- **It's the squeaky wheel gets the oil!** Effective PCS should target the main 'plaintive' segments
  - **Core segments**, especially head and trunk are most sensitive to warm discomfort in warm environments so cooling them is particularly effective in warm and neutral environments
  - **Extremities** of hand and feet are most sensitive to cool discomfort in cool environments, so warming them and lower body segments are particularly effective in cool environments
  - Hence the old thermal comfort aphorism: "***Cool the head and warm the feet***"

3 - Combining Sensors with AI to create Personal Comfort Models

- Low-cost **sensing** thanks to the IoT enable collection of ubiquitous **environmental data** plus continuous occupant **comfort feedback data** (perceptual, physiological, behavioral).
- Simple **artificial intelligence** tools easily applicable to the paired environmental and comfort feedback data. In effect "learning" our "**thermal comfort signature.**"
- Once trained the Personal Comfort Model can then **predict what the individual wants, when they want it**, without requiring any further input from them.

3 - Personalised Comfort Models

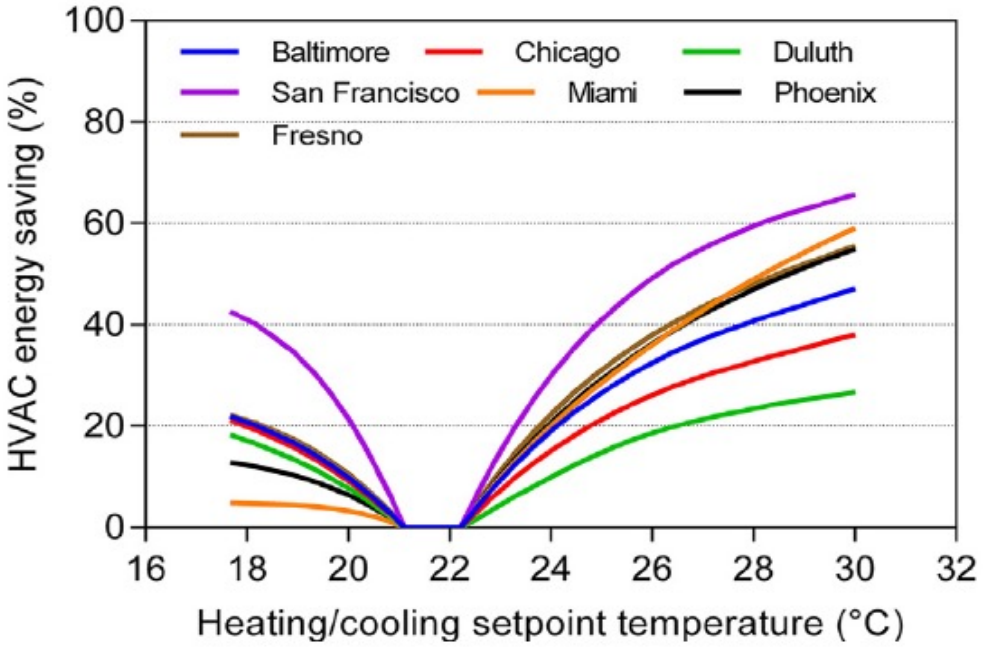
- **Example # 2:** This PCM development draws from **field data** including:
  - 38 occupants in an office building in California
  - PCS control behavior (‘electric chair’)
  - time-of-day, day-of-week
  - subjective survey data (questionnaire)
  - workstation environmental conditions
  - mechanical system settings (BAS)
  - local weather data
- Various machine learning algorithms used
- PCM based on all field data produced the median accuracy of 0.73 among all subjects and improved predictive accuracy compared to conventional (population) comfort models (PMV, adaptive) which produced a median accuracy of 0.51



Kim, J., Zhou, Y., Schiavon, S., Raftery, P. and Brager, G., 2018. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment*, 129, pp.96-106.

4 The Energy Savings of PCS

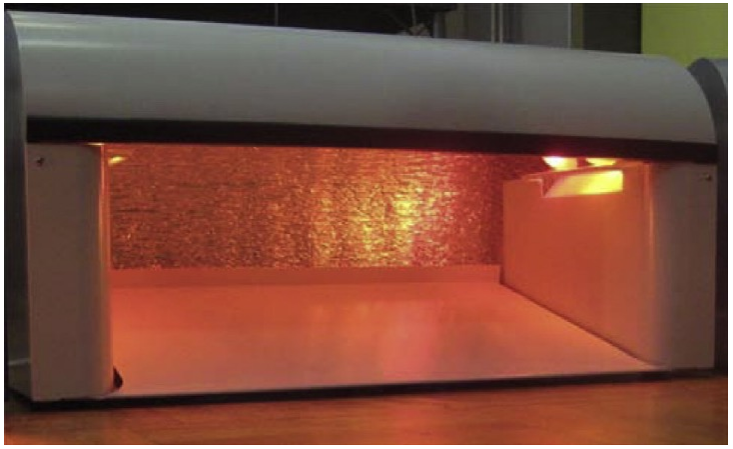
- HVAC represents ~20% of total energy use in developed countries.
- Cooling demand is growing at alarming rates everywhere (IEA 2018 *Future of Cooling*).
- Relax the indoor temperature control deadband, total HVAC energy is reduced by ~10% $^{o}C^{-1}$
- Occupants require less energy to heat/cool than the rooms they occupy



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

4 The Energy Savings of PCS

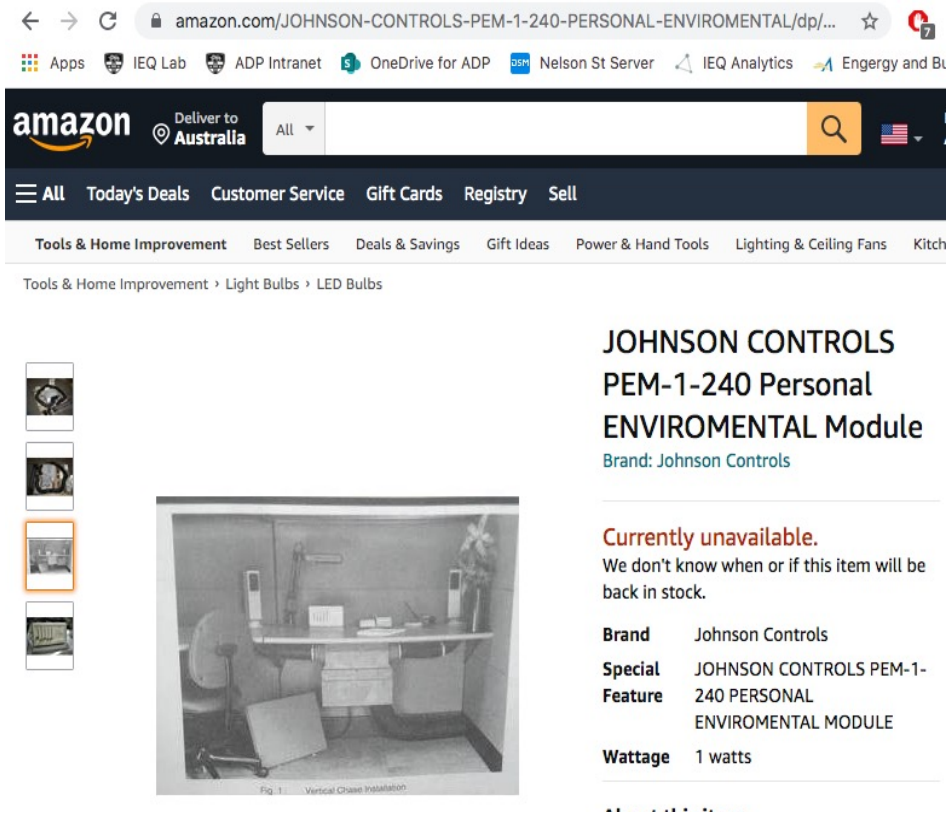
- Example study from Berkeley Cal.
- **PCS** was a “dimmer-controlled IR **footwarmer** (max 160 W)
- **Building** was University of California Berkeley library 2012/13 winter.
- **Baseline** (w/out PCS) room temp 21◦C
  PCS intervention room temp 19◦C
- **16 subjects** (8 females and 8 males)
- **Equal thermal comfort** levels between the baseline and intervention phases
- Central heating energy dropped 38–75%
  The incremental plug load energy from the footwarmers was much less than the central heating energy saved by lowering the heating set point (**3–21 W vs 500–700 W** average power per occupant during occupied hours).



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

Future of PCS Research and Practice: Commercialization of PCS

- The Johnson Controls' Personal Environment Module was ahead of its time
- Jettisoning temperature control of supply air, the basic concept of PCS could reduce to:-
  - Radiant heating panels underneath desk surface
  - Fans for cooling above the desk surface
- This would dramatically
  - reduce unit costs
  - enlarge potential market because UFAD no longer required
- The time is now right for the commercialization of an 'aesthetically appropriate' PCS



References

- Auffenberg, F., Stein, S., Rogers, A. (2015) A personalised thermal comfort model using a Bayesian Network, *Proc. Twenty-fourth Int. Joint Conf. Artif. Intell. IJCAI*, vol. 2015, pp. 2547–2553.
- Baker, N. and Standeven, M., (1997) A behavioural approach to thermal comfort assessment. *International Journal of Solar Energy*, 19(1-3), pp.21-35.
- Boerstra, A., Beuker, T., Loomans, M. and Hensen, J., 2013. Impact of available and perceived control on comfort and health in European offices. *Architectural Science Review,* 56(1), pp.30-41.
- Ghahramani, A., Castro, G., Becerik-Gerber, B. and Yu, X., 2016. Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort. *Building and Environment*, *109*, pp.1-11.
- Jung, W. and Jazizadeh, F., 2019. Comparative assessment of HVAC control strategies using personal thermal comfort and sensitivity models. *Building and Environment*, *158*, pp.104-119.
- Kim, J., Schiavon, S. and Brager, G., 2018. Personal comfort models–A new paradigm in thermal comfort for occupant-centric environmental control. *Building and Environment*, 132, pp.114-124.
- Kim, J., Zhou, Y., Schiavon, S., Raftery, P. and Brager, G., 2018. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment*, 129, pp.96-106.
- Langevin, J., Wen, J. and Gurian, P.L., 2012. Relating occupant perceived control and thermal comfort: Statistical analysis on the ASHRAE RP-884 database. *HVAC&R Research*, 18(1-2), pp.179-194.
- Lee, S.Y., and J.L. Brand. 2005. Effects of control over office workspace on perceptions of the work environment and work outcomes. *Journal of Environmental Psychology,* 25, pp.323–3.
- Liu, S., Schiavon, S., Das, H.P., Jin, M. and Spanos, C.J., 2019. Personal thermal comfort models with wearable sensors. *Building and Environment*, *162*, p.106281.
- Salamone, F., Belussi, L., Currò, C., Danza, L., Ghellere, M., Guazzi, G., Lenzi, B., Megale, V. and Meroni, I., 2018. Integrated method for personal thermal comfort assessment and optimization through users' feedback, IoT and machine learning: A case study. *Sensors*, 18(5), p.1602.
- Warthmann, A., Wölki, D., Metzmacher, H. and Van Treeck, C., 2019. Personal Climatization Systems—A Review on Existing and Upcoming Concepts. Applied Sciences, 9(1), p.35.
- Wang, Z., de Dear, R., Luo, M., Lin, B., He, Y., Ghahramani, A. and Zhu, Y., 2018. Individual difference in thermal comfort: A literature review. *Building and Environment*, 138, pp.181-193.
- Yun, G.Y., 2018. Influences of perceived control on thermal comfort and energy use in buildings. *Energy and Buildings*, 158, pp.822-830.
- Zhang, H., Arens, E. and Zhai, Y., 2015. A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Building and Environment,* 91, pp.15-41.
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