Thermal physiology and comfort

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Presentation outline

1) Distributions and characteristics of thermoreceptors of human body

2) “Alliesthesia”

3) The CBE advanced thermal comfort model
1) Distributions and characteristics of thermoreceptors of human body
Thermoreceptors – source of thermal sensation

Skin temperature

Impulse frequency (firing rate, imp./sec)

<table>
<thead>
<tr>
<th>°F</th>
<th>32</th>
<th>41</th>
<th>50</th>
<th>59</th>
<th>68</th>
<th>77</th>
<th>86</th>
<th>95</th>
<th>104</th>
<th>113</th>
<th>122</th>
<th>131</th>
<th>140</th>
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Depth of cold and warm thermoreceptors

Cold thermal receptors: 0.15 – 0.17 mm, immediately beneath the epidermis

Warm receptors: 0.3 – 0.6 mm, upper layer of the dermis

Schematic representation of a cold receptor (Hensel, 1974)
Thermoreceptors distributions

Cold receptors and warm receptors mapping over 100 cm² of the dorsal side of the forearm (Strughold, 1931)

### Warm receptors (from Strughold 1931)

<table>
<thead>
<tr>
<th>Area</th>
<th>Cold receptors</th>
<th>Warm receptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead</td>
<td>3.5–6</td>
<td>1</td>
</tr>
<tr>
<td>Nose</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Lips</td>
<td>16–19</td>
<td></td>
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<tr>
<td>Other parts of face</td>
<td>8.5–9</td>
<td>1.7</td>
</tr>
<tr>
<td>Chest</td>
<td>9–10.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Abdomen</td>
<td>8–12.5</td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>Upper arm</td>
<td>5–6.5</td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>6–7.5</td>
<td>0.3–0.4</td>
</tr>
<tr>
<td>Back of hand</td>
<td>7.4–7.5</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>Palm of hand</td>
<td>1–5</td>
<td>0.4</td>
</tr>
<tr>
<td>Finger dorsal</td>
<td>7–9</td>
<td>1.7</td>
</tr>
<tr>
<td>Finger volar</td>
<td>2–4</td>
<td>1.6</td>
</tr>
<tr>
<td>Thigh</td>
<td>4.5–5.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Calf</td>
<td>4.3–5.7</td>
<td></td>
</tr>
<tr>
<td>Back of foot</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Sole of foot</td>
<td>3.4</td>
<td></td>
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</tbody>
</table>

Cold receptors (from Rein 1925)

Number of cold and warm spots per cm² in human skin

from Strughold from Rein
Dynamic response of thermoreceptors
2) “Alliesthesia”
Word created by Cabanac in 1970s

Alliesthesia: esthesia (sensation) and allios (changed)

Animal behavior is triggered by internal signals “milieu interieur”
What is alliesthesia

- Sensory pleasure with variation. In transient or non-uniform environments, an environmental stimulus that has the prospect of restoring body to thermal comfort, that is perceived as very pleasant (positive alliesthesia)
Testing sensitivities of cooling/heating on each of 16 body parts
What we saw in our lab studies

Neutral condition

- warm body applying foot cooling
- cold body applying foot heating
- cold body applying foot cooling

Foot Sensation vs. Foot Comfort chart

- very comfortable
- comfortable
- just comfortable
- just uncomfortable
- uncomfortable
- very uncomfortable

Ranges:
- Foot Sensation: -6 to 4
- Foot Comfort: -6 to 4

November 12 2013, ARPA-E Workshop
Comfort in transient conditions

comfort overshoot - alliesthesia

Temperature (°C)

Troom = 28°C
Tsupply = 23°C

Face cooling

November 12 2013, ARPA-E Workshop
A paradigm shift in the notion of comfort

A word that might fundamentally change the approach to providing thermal comfort

• Static and isothermal neutral environments are energy intensive and incapable of satisfying more than 80% of an occupancy

• A more thermally dynamic and non-uniform environment would satisfy more, even to the point of delight, and focus energy use where it is needed
Two types of alliesthesia

• Temporal (transients); deDear at Sydney
• Spatial (non-uniformities across the body); CBE at Berkeley

• Personal comfort systems address:
  o Local body segments
  o Spot heating/cooling within those segments
  o Dynamic stimuli; rates of change at neural sensor sites
Temporal alliesthesia
Pleasure under thermal transients

Japanese hot spa

Turkish bath

Image courtesy of Kuno
Preference for natural over constant wind

Air supply terminals.

Airspeed turbulence testing at Tsinghua University 2000-2012

Fig. 5 Percentage of preferred airflow patterns.
Spatial alliesthesia
Pleasure from non-uniform thermal stimuli
CBE spot heating chair

- Heating: 5% of the seat area
- Can maintain comfort conditions at 60.5°F

Max heating power: 14 W

Control panel and occupancy sensor
A planned lab study: to apply spot heating/cooling alliesthesia

- Effective regions
- Effective spot heating/cooling sizes
- Effective thermal stimulus temperatures
3) The UCB multi-segment thermal comfort model
UCB comfort model

- 16 body segments
- Transient
- Blood flow model
- Heat loss by evaporation (sweat), convection, radiation, and conduction
- Clothing model (including heat and moisture transfer)
Radiation calculation
Solar load on the body
Extremity blood flow model

Upper Arm

Lower Arm

Hand
The UCB “Body Builder” will translate simple parameters (height, weight, gender, age, body fat) into physiological parameters for the thermal comfort model (blood volume, surface area, thermal conductivity, basal metabolic rate, etc.).

Differences in Physiology
The UCB Comfort Model predicts *local* sensation and comfort as well as overall sensation and comfort.
Local comfort model for each body part

Local Thermal Comfort Model

- Warmer overall thermal state
- Cooler overall thermal state

Local Thermal Comfort

- Very cold
- Cool
- Neutral
- Warm
- Very hot

Local Thermal Sensation

very comfortable
comfortable
just comfortable
just uncomfortable
uncomfortable
very uncomfortable
Impact of local body part cooling/heating on whole-body sensation – an alliesthesia model

\[ S_{\text{whole-body}} = S_{\text{whole,bigger-group}} + \left[ \Delta S_{\text{overall,max}} + 10\% \Delta S_{\text{overall,second max}} \right] \]
Local body parts cooling/heating

• Independent heating and cooling of 16 body parts using air sleeves

• 109 tests performed

Validation test in Delphi Wind Tunnel
Subjective voting scales

Sensation and comfort votes were collected for each body part as well as for the whole body (‘overall’).
Skin temperature measurements

Figure 4.18: Twenty-two skin temperature measurement locations
CorTemp wireless system provides continuous core temperature measurement.

Actual Size: L 22mm X Dia. 9mm
Conclusions

- Local body part (or even spot) cooling/heating could provide comfort (thermal pleasure, alliesthesia).

- Research needed to examine effective spot cooling/heating areas for different body parts; the results can be directly applied to local alliesthesia-based personal comfort devices.
Questions?