What Are People's Responses to Thermal Discomfort?
Sensing Clothing and Activity Levels Using SenseCam

Behavior, Energy and Climate Change Conference
November 2011
16% of total ENERGY consumption in the UK is used for SPACE HEATING.
Introduction | Context

Climate Change Act, 2008 (c.27)

AIM reduce energy consumption in dwellings

Programs of Interventions
- improve building fabric
- upgrade services
- integrate renewable energy technologies

Energy continues to rise

‘re-bound effect’

How dwelling thermal comfort systems are conceptualised and understood by their users / occupants?
What is thermal comfort?
‘that condition of mind which expresses satisfaction with the thermal environment’

Involuntary physiological mechanisms: \textbf{thermoregulation}
Basis of the \textbf{heat balance equation}
Fanger (1970)

Voluntary behaviour or \textbf{action response}
Brager (1998)

Habituated behaviour Glaser (1966)

Current models:

[+]
- Identify issues within the thermal environment

[+]
- Predict and assess thermal sensation

[-]
- How occupants form their responses
b | Field Study | Methods selection

Aim: Test methods to gather and analyse information
What: Mapping occupants thermal discomfort responses
How: Mixed methods approach

- **Observation Checklist**
  - Building location
  - Building age
  - Building fabric
  - Heating system
  - Hot water system

- **Monitoring**
  - Temperature
  - Relative humidity
  - Illuminance

- **Questionnaire**
  - Socio-demographic
  - Thermal environment

- **Diary**
  - User interactions
  - Temperature
  - Illuminance

- **Focus Group**
  - Responses
  - Thresholds
  - Influencing factors

- **Building Survey**
- **Occupant Survey**

- recorded information
- reported information

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Field Study | Method: Diary - SenseCam
Field Study

Method: Diary - SenseCam

Output 1: Log of 4 main variables

<table>
<thead>
<tr>
<th>VER</th>
<th>28/10/2010 17:38</th>
<th>4</th>
<th>0</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIL</td>
<td>28/10/2010 17:38</td>
<td>11:00:00</td>
<td>Sep 29 2010</td>
<td></td>
</tr>
<tr>
<td>SYS</td>
<td>28/10/2010 17:38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC</td>
<td>28/10/2010 17:38</td>
<td>0.369</td>
<td>0.8</td>
<td>0.426</td>
</tr>
<tr>
<td>TMP</td>
<td>28/10/2010 17:38</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLR</td>
<td>28/10/2010 17:38</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIR</td>
<td>28/10/2010 17:38</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAT</td>
<td>28/10/2010 17:38</td>
<td>40650</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAG</td>
<td>28/10/2010 17:38</td>
<td>-858</td>
<td>250</td>
<td>246</td>
</tr>
<tr>
<td>CAM</td>
<td>28/10/2010 17:38</td>
<td>10000332.JPG</td>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

1. ACC  Accelerometer: x (R/L), y (Up/Down), z (F/B)
2. MAG  Magnetometer: x, y, z
3. CLR  Colour light sensor: value for white light
4. PIR  Passive infrared detector: 1 triggered, 0 not
5. TMP  Temperature (°C)

Others
- RTC (real-time clock)
- BAT (battery)
- CAM (image capture)
- FIL (filename)
- VER (version of firmware)
- SYS (system info.)

Output 2: Images

- Manually
- Automatically:
  - Timer (1min)
  - Sensors:
    - Temperature sensor;
    - Light level sensor;
    - Passive infrared detector;
    - Multiple-axis accelerometer;
    - Magnetometer.
PARTICIPANT 04
DAY 01
b Field Study | Results

Heat Balance Equation

VBA - BS EN ISO 7730: 2005

Estimation of PMV

Predicted Responses

Diary

Recorded Responses

Questionnaire
Interview
Focus Group

Reported Responses

CIBSE guide A 1.3.1.2 Monitoring Diary (BS EN ISO 7730: 2005)
Field Study | Results

Heat Balance Equation

- Relative Humidity (%)
- Mean Radiant Temp. (°C)
- Ambient Air Temp. (°C)
- Relative Air Velocity (m.s⁻¹)
- Clothing (clo)
- Activity Level (met)

VBA - BS EN ISO 7730: 2005

Estimation of PMV

Predicted Responses

CIBSE guide A 1.3.1.2  Monitoring  Diary (BS EN ISO 7730: 2005)
b | Field Study | Results
Responses to thermal discomfort

<table>
<thead>
<tr>
<th>Daily wear clothing</th>
<th>( \theta_c )</th>
<th>( m^2 \cdot K/W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwear, shirt, trousers, jacket, socks, shoes</td>
<td>0.70</td>
<td>0.110</td>
</tr>
<tr>
<td>Underwear, shirt, trousers, jacket, socks, shoes</td>
<td>0.70</td>
<td>0.110</td>
</tr>
<tr>
<td>Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes</td>
<td>1.30</td>
<td>0.200</td>
</tr>
<tr>
<td>Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes</td>
<td>1.50</td>
<td>0.230</td>
</tr>
</tbody>
</table>
Field Study | Results
Responses to thermal discomfort

SenseCam accelerometer sensor readings to determine cut-in / cut-off points in time

SenseCam Diary Images

EN ISO 7730: 2005 Table B.1
Metabolic rates

<table>
<thead>
<tr>
<th>Metabolic rate</th>
<th>met</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>0.8</td>
</tr>
<tr>
<td>58</td>
<td>1.0</td>
</tr>
<tr>
<td>70</td>
<td>1.2</td>
</tr>
<tr>
<td>93</td>
<td>1.6</td>
</tr>
<tr>
<td>116</td>
<td>2.0</td>
</tr>
<tr>
<td>110</td>
<td>1.9</td>
</tr>
<tr>
<td>140</td>
<td>2.4</td>
</tr>
<tr>
<td>165</td>
<td>2.8</td>
</tr>
<tr>
<td>200</td>
<td>3.4</td>
</tr>
</tbody>
</table>
b | Field Study | Results
PMV and PPD models (through recording period)

- **83% of monitored time outside of the comfort zone** set by ANSI/ASHRAE standard 55-2004, table 5.2.1.2 acceptable thermal environment for general comfort

- Most participant should be feeling ‘slightly cool’ (-1), ‘cool’ (2) and ‘cold’ (-3)
b Field Study Results

Heat Balance Equation

- Relative Humidity (%)
- Mean Radiant Temp. (°C)
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- Relative Air Velocity (m.s\(^{-1}\))
- Clothing (clo)
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Field Study  |  Results

- Diary
  - Recorded Responses
Field Study

Responses to thermal discomfort

3 days - SenseCam recording - 1500 to 6300 images

Events Segmentation Process

Event A – TRVs

Event B – Putting a jumper on

Event C – Eating
Event Segmentation **Approach 1** (manual) ‘1-2-3 analysis’

- **Stage 1**: setting out the criteria where differences may indicate events

<table>
<thead>
<tr>
<th>Picture nb</th>
<th>When</th>
<th>Where</th>
<th>Who</th>
<th>Clo</th>
<th>Met</th>
<th>What Semantic concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>333</td>
<td>28/10/2010 17:38</td>
<td>Living room</td>
<td>2</td>
<td>0.7</td>
<td>1</td>
<td>Sitted on sofa, carrying out the questionnaire</td>
</tr>
<tr>
<td>347</td>
<td>28/10/2010 17:41</td>
<td>Living room</td>
<td>2</td>
<td>0.7</td>
<td>1</td>
<td>Sitted on sofa, mobile phone</td>
</tr>
<tr>
<td>352</td>
<td>28/10/2010 17:43</td>
<td>Living room</td>
<td>2</td>
<td>0.7</td>
<td>1</td>
<td>Sitted on sofa, carrying out the questionnaire</td>
</tr>
<tr>
<td>440</td>
<td>28/10/2010 18:04</td>
<td>Living room</td>
<td>2</td>
<td>0.7</td>
<td>1.2</td>
<td>Standing up, in front of kitchen door</td>
</tr>
</tbody>
</table>

- **Stage 2**: comparison of adjacent images
- **Stage 3**: comparison every 2\textsuperscript{nd} images
Event Segmentation **Approach 1** (manual) ‘1-2-3 analysis’

- LR, standing-up: 17.60%
- Kitchen, standing-up: 16.80%
- LR, seated, laptop: 11.20%
- LR, phone: 7.20%
- Bathroom, standing-up: 7.20%
- LR, seated, drink: 7.20%
- Black: 7.20%
- LR, seated, TV: 6.40%
- LR, seated, eating: 5.60%
- LR, seated on sofa, questionnaire: 4.80%
- Bedroom, standing-up: 4.00%
- Hallway, standing-up: 1.60%
- LR, standing-up, TV: 0.80%
- Hallway, standing-up: 0.80%
- LR, seated, reading: 0.80%
- LR, seated, table: 0.80%
Responses to thermal discomfort

Event Segmentation **Approach 2** (automatic)

**STAGE 1**
SenseCam Images
Segmentation

**STAGE 2**
40 Events Detected
Segmentation

**STAGE 3**
22 Events Represented
Event Segmentation **Approach 2** (automatic)

Software developed by Dublin City University (DCU)

- **Stage 1**: MPEG-7 features
  - Scalable Colour
  - Colour Structure
  - Colour Moments
  - Edge Histogram

- **Stage 2**: Metadata information
  - Light level
  - Temperature
  - Accelerometer

- **Stage 3**: Group Image into classes:
  static person, moving person, static camera
b  Field Study  Results

Responses to thermal discomfort

Event Segmentation **Approach 2** (automatic)

- SenseCam Images
- Segmentation
- 40 Events Detected
- Segmentation
- 22 Events Represented

- [?] image clustering
- [?] parameter threshold level, events’ boundaries
Field Study | Responses and PMV model

- Relative Humidity (%)
- Mean Radiant Temp. (°C)
- Ambient Air Temp. (°C)
- Relative Air Velocity (m.s⁻¹)
- Clothing (clo)
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Field Study | Responses and PMV model


-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0

Change activity & location | Change location | Change activity

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To develop an automatic segmentation method

Possible method: images // metadata

- **When**  
  Time stamping
- **Where**  
  Accelerometer and Magnetometer sensors
- **Clo**  
  Temperature sensor and Infra-Red Camera
- **Activity**  
  Accelerometer sensor and Heart Rate Monitor
Any questions?

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