Title

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

Author

Gauthier, Stephanie Marie

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Sensing Clothing and Activity Levels Using SenseCam

Stephanie M. Gauthier

University College London, Energy Institute

Author Note

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Abstract

Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings, from modifying the building fabric to upgrading operating systems. To date, these attempts have met with limited success. One reason for this has been identified as the 'rebound effect', where the occupants' respond to their home thermal environment change in unexpected ways after interventions. Often people decide to turn up the heating, to leave it on for longer, or to increase the average spatial temperature by heating more rooms. Although much of the research on heating patterns in dwellings has focused on identifying methods to predict and to assess thermal sensation, less is understood about the way occupants form their responses. Research presented in this paper focuses on mapping householders thermal discomfort responses. Empirical methods, drawn from the social and cognitive sciences, were used in a several studies, which monitored a small sample of UK households during winter of 2010. One of the tools used, the SenseCam, facilitates an automatic electronic diary collection by logging occupants' responses in a systematic approach. SenseCam results enabled the mapping of participants' activities in their home, in particular the estimation of clothing and activity level throughout the record period. The preliminary monitoring results show that different householders are interacting with their home thermal comfort systems in very different ways, and that their responses diverge from the current predictive models. Further analysis examines the factors influencing responses to thermal discomfort and thereby energy consumption of individual in dwellings.

Keywords: Adaptive Behavior; Thermal Discomfort, SenseCam; Household Energy Demand

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Reducing energy consumption in dwellings is an important component of meeting carbon reduction commitments; as the UK is aiming to reduce its overall carbon emissions by 80 per cent from their 1990 levels by 2050 - Climate Change Act, 2008 (c.27). To meet this target, programs of interventions to the existing building stock have been introduced, such as the Green Deal in December 2010 (DECC, 2010). In parallel, more demanding building regulations to new and existing dwellings were introduced in October 2010 (NBS, 2010). Although similar initiatives have been rolled out over the past years, energy consumed in dwellings continues to rise (DECC, 2010). This phenomenon is recognised as the ‘rebound effect’ (Summerfield, 2009), where the expected energy saving does not occur. There are many reason for this effect to occur, one of these is that householders are making their home more comfortable by raising the target temperature, leaving the heating on for longer or increasing the spatial average temperature (Shipworth, 2010).

Consequently it is critical to map-out how people respond to thermal discomfort in their home. Using empirical methods drawn from social and cognitive sciences, this paper proposes a set of tools, implemented in a pilot study which was carried out on a small sample of UK households during winter 2010. This case study research explores the use of SenseCam to map occupants’ clothing and activity levels by logging key variables and generating a visual diary. The aim of this study is to elicit sufficient information to map occupant responses to thermal discomfort.

This paper begins with a brief review of the existing methods used to gather and predict thermal discomfort responses. Next the process of planning the study is described, by translating the research question into a protocol for investigating occupant thermal discomfort responses. The paper concludes with some suggestions on how further research on resident responses could be developed, in particular the estimation of clothing and activity levels.

Current methods used to map and to predict thermal discomfort response

Although much of the research on thermal comfort in dwellings has focused on examining methods for predicting thermal sensation and on assessing acceptability in the field, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field study results. In 1936 Bedford conducted a series of interviews that established a linear relationship between response types and recorded temperature. This research concluded by setting out an optimum temperature for comfort. (Bedford, 1936)

So what is thermal comfort? The ASHRAE standard 55 (2004) defines thermal comfort for a person as ‘that condition of mind which expresses satisfaction with the thermal environment’. This definition touches on psychological or psychosocial issues where people’s opinions validate their state of comfort or discomfort. Responses to this state are of three kinds:

- Involuntary physiological mechanisms of thermoregulation, which aim to maintain the individuals’ body temperature constant (Parson, 2007). These mechanisms form the basis of the heat balance equation (CIBSE, 2006). Although this equation can only be validated steady-state condition, it gives information as to which variables are used and how they are combined to create optimal comfort conditions. The six variables are: air temperature

(1), humidity as water vapour pressure in ambient air (2), mean radiant temperature (3), relative air velocity (4), thermal resistance of clothing (5) and activity level (6).

- Voluntary behaviour or action response, where the occupant chooses to act upon their level of discomfort, for example one might decide to put a jumper on, to have a warm drink, to close the window or to turn the room thermostat up (Brager, 1998). The action's outcome or level of thermal comfort will serve as a starting point in the response process. The occupants' dwelling or setting will provide different opportunities and constraints, which will influence the type of response(s) (Humphreys, 1994).
- Habituated behaviour, which influence occupants' perception of and reaction to thermal comfort (Glaser, 1966). For example, external condition can have a direct effect on thermal responses, as these may be conditioned by passed experiences. In Helson's review of adaptation-level theory (1964), habits may be the result of three different sets of operations: bipolar response (1), set of assumption (2) or judgement based on a 'skew' level of central tendency or anchor (3). Habituated behaviour and expectation act as 'by-pass' for the choice of responses. These choices are reinforced by the degree of performance of the outcome.

To record these three forms of responses, a combination of qualitative and quantitative methods are commonly used. It includes measuring physical parameters and carrying out questionnaires and observations (BS EN ISO 7730). These studies have been completed in two types of settings:

- Climate chamber studies, generally used as laboratory bench studies;
- Field studies, where environmental monitoring, details building and social surveys are carried out.

The results of these studies are compared against benchmarks. Used as design comfort criteria and developed by Fanger (1970), the Predicted Mean Vote (PMV) evaluates the average vote of a large group of persons exposed to the same conditions on a 7 points thermal comfort scale. This predictive model is based on climate chamber studies where two variables, thermal resistance of clothing (5) and activity level (6) cannot be measured with accuracy (Brager, 1993). PMV is often translated into Predicted Percentage Dissatisfied (PPD), which is a measure used for benchmarks. The current standard prescribes that optimum environments should achieve a PPD inferior to ten per cent, the equivalent of one in ten people been dissatisfied (CIBSE, 2006). In summary, the current model can identify issues within the thermal environment, but occupant's predicted level of comfort and associated responses are less actuate.

Study design

The aim of this chapter is to present a set of methods used to map occupant thermal discomfort responses. The study was carried out in London, UK, over winter 2010. Because this investigation was a pilot study, sample size was limited. The sample of interest was defined by selected criteria such as location, dwelling type and construction, tenure, number of occupants, based on precedent studies (Heijs, 1988 and Hong, 2009). Twenty people were contacted of which eleven, living in ten different dwellings, took voluntary part in the study. Located in London, UK, the dwellings were built at different periods, dated from 1850 to 2008. Some incorporate features such as a retrofitted central, communal or district heating system.

Using a case study approach, ten dwellings were each monitored over a period of three consecutive days, two weekdays and one weekend day. This six week study was followed by a focus group, which was attended by nine of the eleven participants. The data collection sequencing is summarised in figure 1. Focusing on the aims of the research, five methods were selected. In making these choices, there are questions raised about the validity of mixed methods to gather information, however these are often the norm in build environment field studies (De Dear et al. 1997). This approach allowed for the collection of a wide range of information, which can be compared to current benchmarks and other studies.

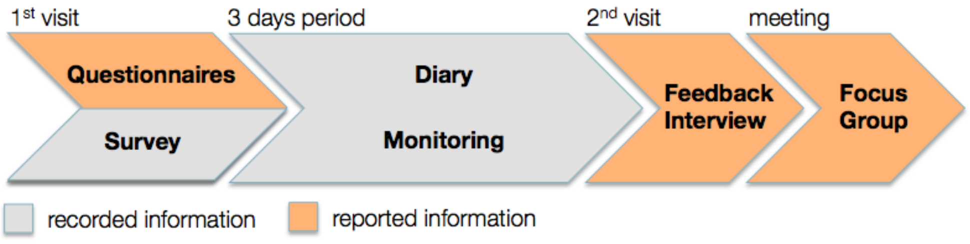

Figure 1. Data collection sequencing Used for the pilot study

While participants' reported information on thermal discomfort responses, on associated thresholds and on influencing factors were noted, recorded information was collected. The study used a building observation checklist, monitoring devices and a SenseCam. Throughout the three days monitoring period, compact dataloggers recorded ambient air temperature and relative humidity in the dwellings. The mean internal temperature was weighted as a combination of average temperature from each zone in the dwelling – these were defined by the home layout and by the occupants living patterns. Typically, the living room and the bedroom were defined as zones. Over the same period external conditions were monitored, using similar dataloggers recording air temperature and relative humidity. The results of this monitoring were later used to evaluate PMV and PPD values during the three days study. Alongside monitoring internal and external conditions, the occupants were asked to wear a SenseCam. As referred to in the previous section, two variables used to assess thermal comfort, thermal resistance of clothing (5) and activity level (6), are difficult to evaluate with accuracy. Most thermal comfort studies only assess these two variables a one point in time using questionnaires or written diaries (Hong et al. 2009). However this research aimed to address both variables throughout the three days experiment to engage with the dynamic state of thermal comfort. The challenges of providing continuous PMV and PPD values in field experiments have been reviewed in adaptive comfort literature (Brager 1993). The use of SenseCam as an automatic diary has been tested in this study to support the mapping of occupants' thermal discomfort and associated responses. In the field of cognitive psychology, this automatic diary tool has been used as external memory aids for patient with neurodegenerative disease and brain injury (Berry et al. 2007). Of similar size to a badge, the SenseCam takes photographs when triggered manually and automatically by a timer or by changes in the sensors readings. The camera trigger options and list of six sensors are summarized in Figure 2.

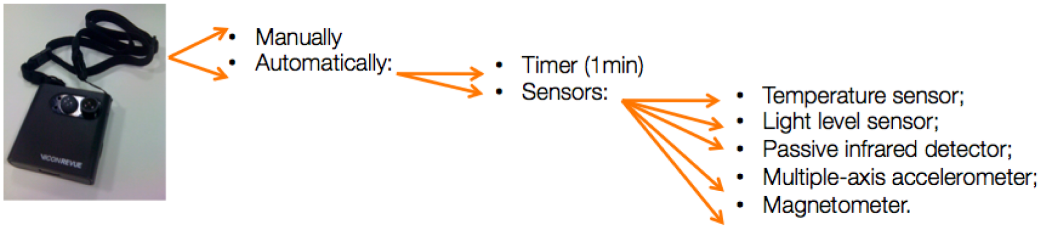

Figure 2. SenseCam image recording triggers

The Sensecam provides two types of outputs: (1) a record of measurements taken by each sensor and (2) a visual diary of participants' whereabouts in their home, but excludes audio recording. The recording period ran through three consecutive days, which generated around 3200 images for each participant.

Although the primary research objective was to map peoples thermal discomfort responses, the underlying objective was to gather continuous and systematic information on the occupants' clothing and activity levels. Consequently the results can be brought into existing predictive models.

Analysis

Through the analysis reported and recorded information are reviewed. SenseCam sensor recordings and visual diaries were used to identify clothing and activity pattern continuously though the recording period.

Part of the analysis of participants' actual and predictive responses consisted in applying the heat balance model and comparing PMV and PPD values against observed information. To use this model, six parameters required to be ascertained; these are accounted for and estimated as follow:

- Indoor air temperature (1) and relative humidity (2), were accounted for as the mean air temperature and as the mean relative humidity for each zone in the dwelling monitored using dataloggers;
- Mean radiant temperature (3), no mean radiant temperature was measured as part of the pilot study; instead it was assumed that this variable was of equal value to the monitored mean indoor temperature (Humphreys, 1976);
- Relative air velocity (4), no air movement was measured as part of the pilot study; instead a minimum air velocity of 0.1m/s was assumed for all cases on the basis that in winter openings tend to stay close (Hong et al. 2009);

- Insulation of clothing (5) and activity patterns (6); these were estimated based on the SenseCam's diary. The researcher estimated the participants clothing and activity level from the image series, using EN ISO 7730:2005 checklists.

As described above the six parameters of the heat balance model were either recorded or estimated for each dwelling then PMV was computed using EN ISO 7730 Visual Basic algorithm. Initial PMV values were compared against three benchmark categories A and B according to table A.1 (EN ISO 7730), where:

- Category A: $-0.2 < PMV < +0.2$
- Category B: $-0.5 < PMV < +0.5$

Results

The study is providing an opportunity to investigate responses to thermal discomfort and their implication for energy consumption. The results are presented in two parts.

Sensing clothing and activity levels using SenseCam

The SenseCam device captured automatically up to 6300 images per participant. This yields to a very large collection of images and extensive visual diary. To process this information, two approaches were used manual and automatic segmentation techniques.

Through the manual segmentation approach, each image is visually inspected and labeled using six criteria; which included: (1) image number, (2) when and (3) where the image was taken, (4) how many persons where in the room, (5) clothing and (6) activity levels. While reviewing the images, participants' clothing insulation was estimated directly from the typical combinations of garments presented in Table C.1 of BS EN ISO 7730. These varied between 0.7

and 1 clo or 0.11 and 0.16 m2K/W. A similar process was used to determine the participants' metabolic rate as a function of their activity levels. This was estimated by using the typical activities presented in Table B.1 of BS EN ISO 7730. The recorded metabolic rates varied between 1 and 1.6 met or 58 to 93 W/m2. To add to this visual inspection, a review of the SenseCam accelerometer recording was analyzed to confirm the cut-in and cut-out points when participants were:

- Seated or standing (vertical axis);
- Static or moving (horizontal axis).

Then for each participant, all the images collected were visually inspected by playing them sequentially. Adjacent images were compared. If a change in criteria (3), (4), (5) or (6) occurred, a new 'event' was identified. In addition, images before and after this 'event' were reviewed as a confirmatory process (Smeaton et al. 2006). An 'Event' often occurs when the participant left one room, went into another room and came back to the first room, as occurred in Figure 4. Through this analysis sixteen 'events' where identified for a single participant (P01), of which 'living room / standing-up' (18%), 'kitchen / standing-up' (17%) and 'living room / seated / laptop' (11%) were the most frequent 'events'. Although providing interesting insights, this segmentation approach is time consuming and there could be bias in the observation. For these reasons an automatic segmentation approach was tested.

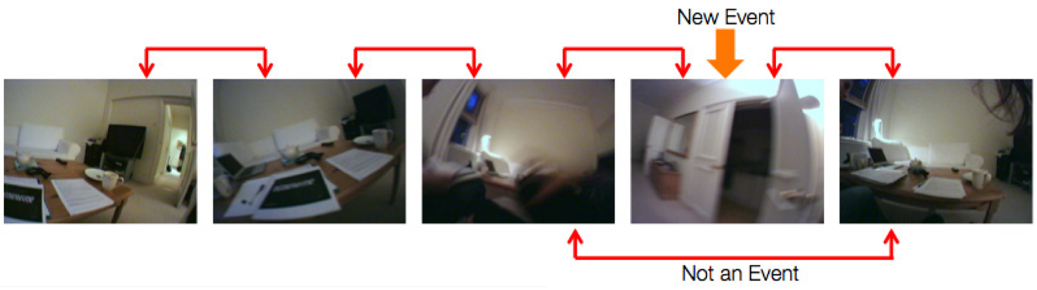

Figure 3. Manual 'event' segmentation process

The automatic segmentation technique was carried out in three stages. After uploading, the SenseCam images were automatically processed using a software developed by Dublin City University (DCU). It uses content-based image analysis techniques to structure the images into a list of ‘events’, referred to as the index (Lee et al. 2008). Each image has a level of MPEG-7 visual features, including scalable color, edge histogram, color structure and moments. These features are used for the first stage of segmentation, then for the second stage the metadata information of the log is reviewed, including light level, temperature and accelerometer. Finally for the third stage of segmentation, each ‘event’ is associated to a class, ‘static person’, ‘moving person’ and ‘static camera’. Through this approach twenty-two ‘events’ were identified for the same participant (P01). The results of this analysis were less successful than the manual segmentation, as the natures of the ‘events’ were repetitive and not representative of the participant activities. Further work needs to be carried out for this automatic segmentation approach to be reliable, starting with image clustering and reviewing the threshold level for each visual feature.

Estimated predicted levels of thermal comfort vote

Participants’ comfort votes were computed from monitoring and SenseCam results. Figure 3 illustrates the variability of PMV for all participants throughout the monitoring period. Although being a purposive sample, this analysis shows that 83% of the monitored period was outside of the comfort zone set by ANSI/ASHRAE standard 55-2004 and category B of the EN ISO 7730, the lower threshold being ‘-0.5’ and the higher one being ‘+0.5’ (i.e. the shaded part of Figure 3). The participants’ scores ranged from ‘-3’ (cold) to ‘+0.5’ (neutral / slightly warm) (i.e. the bars in Figure 3). Most participants should be feeling ‘slightly cool’ (-1) and ‘cool’ (2) in their dwelling given the choice of clothing and activity patterns. The low air speed of 0.1 m/s specified for the PMV model cannot explain these results, as greater air speed would have resulted in even lower predicted PMV scores. Further studies should include a comparison between residents' PMV and actual responses throughout the recording period using SenseCam diary images.

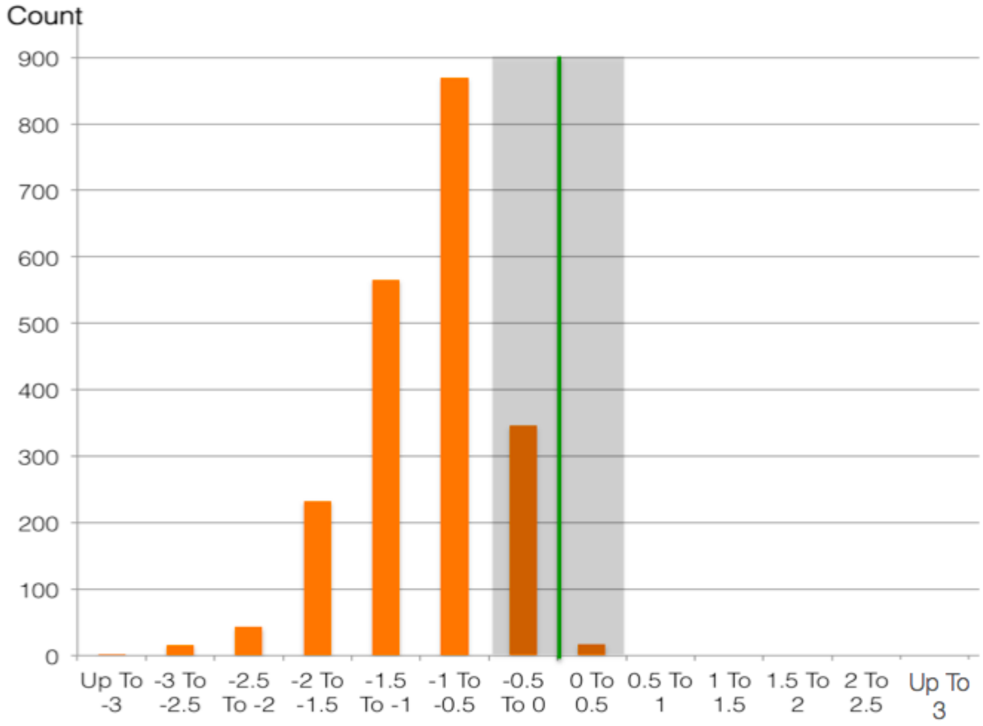

Figure 4. Predicted Mean Vote (PMV) for all participants during the entire study

Discussion and Conclusion

This case-study research included the collection of questionnaires, transcripts of focus group, physical surveys, monitoring data and diaries. The results of these methods provided insight in estimating PMV in a dynamic mode and in identifying the predictive responses to thermal discomfort in dwellings. The study illustrates a number of potential benefits for the use of SenseCam as a wearable automatic diary. Preliminary results showed low PMV scores where

83% of the monitored period was outside of the comfort zone. SenseCam results enabled the mapping of participant's clothing and activity level in their home. However the main analysis used manual segmentation techniques. Further works should focus on developing automatic segmentation, which may include:

- Estimation of clothing insulation level: The use of an infrared camera within the SenseCam may be explored, although calibration may be an issue.
- Estimation of activity level: SenseCam's accelerometer and magnetometer recordings could be combined with an external heart rate sensor. The relationship between heart rate and metabolic rate can be measured though methods described in EN ISO 8996.

The dynamic between people and their dwellings' thermal comfort system forms a complex framework, for which the awareness and understanding level is only part of the response. Residents' responses may be influenced by a range of other factors, including demographics, context, environmental interactions and cognition (Brager and De Dear 1998). Besides, this study carries the following limitations, which may be answered by future research:

- Sample: non-probability, small - Recruitment of participants remains a barrier due to the amount of monitoring. For this reason the follow-up research may be constructed conjointly with other projects.
- Location: London, UK, temperate climate - The results may differ for other countries, nonetheless the set of methods used may apply elsewhere.
- Season: winter, heating season - Divergence may be expected between seasonal results; the study should be repeated in summer and in mid-season.
- Response bias: review the confounding factors to each type of responses - are people more forgiving for certain types of building, 'old and beautiful'?

Although not representative of UK dwelling stock, this study has suggested directions to map resident thermal discomfort responses. It has also confirmed the need for further research, including reviewing current automatic segmentation approach, followed by a comparison between residents' PMV and actual responses using SenseCam sensors and diary images. The outcomes could provide insights on the energy used within a dwelling and its impact on energy consumption.

References

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (2004). Thermal environment conditions for human occupancy, Standard 55, Atlanta.

Bedford, T. (1936). The warmth factor in comfort at work, MRC Industrial Health Board Report No. 76, HMSO.

Berry, E., et al. (2007). The use of SenseCam as a pictorial diary to improve autobiographical memory in a patient with limbic encephalitis. Neuropsychological Rehabilitation.

Brager, G. Fountain, M. Benton, C. Arens, E. and Bauman, F. (1993). A comparison of methods for assessing thermal sensation and acceptability in the field. In: Oseland, N. and Humphreys, M. Thermal comfort: past, present and future, BRE, Watford.

Brager, G. S. and De Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review, Energy and Buildings, 27, 83-96.

The British Standards Institution (2002). BS EN ISO 7730:2005, Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort, BSI, London, UK.

The British Standards Institution (2006). BS EN ISO 8996:2004, Ergonomics of the thermal environment – Determination of metabolic rate, BSI, London, UK.

The British Standards Institution (2006). BS EN ISO 10551:2001, Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales, BSI, London, UK.

The Chartered Institute of Building Services Engineers (CIBSE) (2006). Environmental Design Guide A, London, UK.

Climate Change Act 2008 (c.27), London, UK. http://www.statutelaw.gov.uk. Accessed 8th January 2011.

De Dear, R. Brager, G. Cooper, D. (1997). Developing an Adaptive Model of Thermal Comfort and Preference, Final Report ASHRAE RP- 884, 1997. http://sydney.edu.au/architecture/staff/ homepage/richard_de_dear/index.shtml. Accessed 8th January 2011.

Department of Energy and Climate Change (DECC) (2009). The Government's Standard Assessment, Procedure for Energy Rating of Dwellings, BRE, Watford.

Department of Energy and Climate Change (DECC) (2010). Energy Consumption in the UK Domestic data tables 2010 Update, 10D/802, London, UK. http://www.decc.gov.uk/ Accessed 8th January 2011.

Department of Energy and Climate Change (DECC) (2010). The Green Deal, A summary of the Government's proposals, 10D/996, London, UK.

Department for Communities and Local Government (DCLG) (2010). Survey of English Housing, 2007-2008, Colchester, Essex: UK, Data Archive, SN: 6399.

Fanger, P.O. (1970). Thermal Comfort, Danish Technical Press, Copenhagen.

Glaser, E. (1966). The Physiological Basis of Habituation, O.U.P., London.

Heijs, W. and Stringer, P. (1988). Research on residential thermal comfort: some contributions from environmental psychology. Journal of Environmental Psychology, 8, 235-247.

Helson, H. (1964) Current trends and issues in adaptation-level theory. American Psychologist, Vol. 19, Issue 1.

Hong, S. H., Gilbertson, J., Oreszczyn, T., Green, G. & Ridley, I. (2009). A field study of thermal comfort in low-incomedwellings in England before and after energy efficient refurbishment. Building and Environment, 44, 1228-1236.

Humphreys, M.A. (1976). Field studies of thermal comfort compared and applied. Building Services Engineer. Volume 44, Issue 1.

Humphreys, M.A. (1994). Field Studies and climate chamber experiments in thermal comfort research. In: Oseland, N. and Humphreys, M. (Eds.) Thermal Comfort: Past, Present and Future, BRE, UK.

Lee, H. et al. (2008). Constructing a SenseCam visual diary as a media process. Multimedia Systems Journal, 14 (6). pp. 341-349.

Natinoal Building Specification (NBS) (2010). Approved Document L1A: Conservation of fuel and power, London, UK.

Parsons, K. (2007). Human Thermal Environments, 2nd Edition, Taylor & Francis, London, UK.

Shipworth, M. et al. (2010). Central heating thermostat settings and timing: building demographics, Building Research & Information, 38, 50 – 69.

Smeaton, A. et al. (2006). SenseCam Work at Dublin City University (presentation) Center For Digital Video Processing, Dublin City University, Ireland. http://research.microsoft.com/apps/video/default.aspx?id=104217. Accessed 15th March 2011.

Summerfield, A. (2009). Occupant Behaviour and Energy Use. In: Mumovic, D. Santamouris, M. A handbook of sustainable building design and engineering, Earthscan, London, UK.