Understanding the dynamics of residential energy consumption in the UK: Mapping occupants thermal discomfort responses

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Abstract
Attempts to reduce the energy consumed in UK homes have had limited success. One reason for this has been identified as the 'rebound effect', where the occupants' responses to their thermal environment change in unexpected ways after interventions. Although much of the research on heating patterns in dwellings has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Using empirical methods drawn from social and cognitive sciences, this paper proposes a set of tools, implemented in a pilot study, carried out on a small sample of UK households during winter of 2010. One of the tools used, the SenseCam facilitates an electronic diary collection by logging occupants' responses in a systematic approach. Preliminary monitoring works 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. These results suggest that future samples may be examined to gain further insights about the development of ideas in this field.

Introduction
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 percent 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 a dwelling's thermal comfort system is conceptualised and understood by its occupants. This paper presents findings from a pilot study comparing methods to capture the diversity of occupants' mitigation responses toward thermal discomfort. The research engages with users through an inductive method drawn from social and cognitive sciences during winter of 2010. As a small sample of UK households were monitored, findings indicate how, when and where discomfort occurs. These outcomes play a key role in mapping occupiers' responses and translating them to several occupant mental models of home thermal comfort systems.

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.

Background

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. For instance Bedford's series of interviews in 1936 did establish a linear relationship between response types and recorded temperature. This research concluded by setting out an optimum temperature for comfort.

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 choose 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 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.

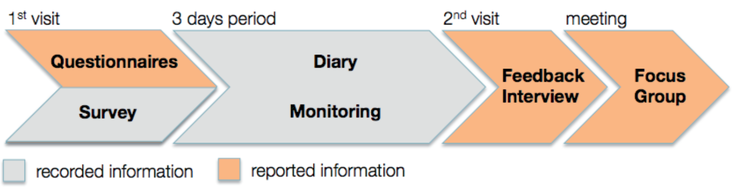

Figure 1. Data collection sequencing Used for the pilot study.

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. 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, (1) activity level and (2) thermal resistance of clothing 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 prescribe 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.

Methodology

The aim of this chapter is to present a practical set of methods used to map occupant thermal discomfort responses. The study was carried out in London, UK, over winter 2010. Using a descriptive 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.

Although the primary research objective is to map peoples thermal discomfort responses, the underlying objective is to fit into existing methods and collect 'benchmark' parameters, such as dwelling type and number of occupants. Consequently the significance of the results can be evaluated against existing predictive models, to acknowledge the limitations of existing methods.

SAMPLING METHOD

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).These household characteristics are summarised in Table 1. 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 retrofitted central, communal or district heating system.

METHODS SELECTION

The purpose of the monitoring study is to collect sufficient data to provide information to address the research objectives. Focusing on the aims of the research, five methods were selected.

Table 1. Household characteristics.

Household Characteristics (per dwelling)	P01	P02	P03	P04	P05	P06	P07& P11	P08	P09	P10
Nb. of occupants	2	2	7	1	2	2	7	2	3	4
Nb. of children (<16yrs)	–	–	–	–	–	–	–	–	–	2
Tenure	Rent	Own	Rent	Rent	Rent	Rent	Rent	Rent	Rent	Rent
Type of dwelling	Flat	Flat	House	Flat	House	Flat	House	Flat	Flat	House
Year dwelling built	1850-1900	1870	1901-1930	2008	1850-1900	1850-1900	1850-1900	1850-1900	1965-1980	1945-1964
Floor area (m2)	58	64	182	62	90	54	220	52	72	92
Bedrooms	1	2	6	2	2	2	7	1	3	3
Heating system	Communal	Central	Central	District	Central	Central	Central	Central	Central	Central

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 (ASHRAE RP-884 project). This approach allows us to collect a wide range of information, which can be compared, to current benchmarks and other studies.

Reported information

Questionnaires
First, two questionnaires were completed with the householders using recognised templates. The questionnaires topics included:

- Socio-demographic variables including household characteristics, housing history, general health and economic activity status, using the questions taken from the original survey and standard questionnaire from the Survey of English Housing 2007/8 (DCLG, 2010);
- Thermal environment variables, using a combination of standard questions taken from ASHRAE standard 55-2004, EN ISO 10551:2001 and RP-884 database. The sensation is rated on the ASHRAE 7 points scale. Metabolic rate and Clo value are established, using EN ISO 7730:2005.

Focus group
At the end of the pilot study nine participants joined a focus group. This session facilitates the gathering of reported information on thermal discomfort response. Using open-end questions on responses to thermal discomfort, on associated thresholds and on influencing factors, enable the researcher to gain insight on the participant's relationship with their dwellings' thermal comfort system.

Recorded information

Building survey
A visual inspection of the property is conducted both internally and externally, using RdSAP worksheet version 9.83 (DECC, 2010). Data collected includes construction type, amount of electrical equipment and details of heating system.

Monitoring
Data loggers recording air temperature, relative humidity and illuminance are compact devices, programmed to start 30 min before the interview and recording a reading every 5 minutes. Each has been labelled with a unique code and their location in the dwelling recorded. For quantifying space-heating demand, the effective internal temperature has been weighted as a combination of average temperature from each zone in the dwelling – these are defined by the home layout and by the occupants living patterns. Typically, the living room and the bedroom were defined as zones. The data-loggers were placed away from potential heat sources and located at waist height. Over the same period external conditions were monitored, using similar data loggers recording air temperature, relative humidity and illuminance levels. The results of this intensive monitoring will be used to model PMV and PPD values during the 3 days study.

Diary
In the field of cognitive psychology, automatic diary methods have been used as external memory aids for patient with neurodegenerative disease and brain injury (Berry, 2007). Using a wearable device, the SenseCam, episodic memories grounded on personal experiences are recalled. This tool was selected as the diary collection method. Of similar size to a badge, this recording device takes photographs when triggered manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared detector and a multiple-axis accelerometer. This device provided a visual diary of participants' where-abouts in their home and a record of measurements taken by each sensor, but excludes audio recording. The recording period runs through three consecutive days, which generated around 3,200 images for each participant.

In Summary, this study proposes to use a set of methods, with the intention to create links between the different approaches and their output. The core background theory applies a 'user-centred' approach in which the residents and the dwellings' thermal comfort system are in a reciprocal dynamic and interactive relation (Vischer, 2008). The research considers the resident as an active agent who interacts with the dwellings' thermal comfort system. It also looks at the extent of this interaction, associated influencing factors, system boundaries and thresholds. The proposed methodological framework consists of variations in the existing methods used to assess thermal comfort and elicits sufficient information to map occupants' responses to thermal discomfort. Five methods where selected, two related to building's survey and three associated with occupant's survey.

ANALYSIS OF THE RESPONSES

The analysis of the information gathered consists in the review of the households' characteristics and associated reported and recorded information. The analysis of the data collected is structured in three steps:

- (A) Initial results of the focus group were used to characterise reported responses, as well as the keywords used in defining those.
- (B) Also the analysis of the information gathered in the focus group consists in the review of household's characteristics and associated reported information.
- (C) Finally a comparison was made of residents reported and predicted responses as a cross-sectional study at the time of questionnaire A. Likewise a comparison was made of residents observed and predicted responses throughout the recording period using diary images.

With regards to the analysis of focus group results (A) and (B), the observation schedule and the transcript of the discussion were coded using qualitative data analysis software, Nvivo. Content analysis was the method applied later to gather an understanding of the participants' responses to thermal discomfort and associated influencing factors.

Part of the analysis of participants' actual and predictive responses (C) consisted in applying the PMV and PPD models and comparing their results against observed information. To use these models, six parameters need to be ascertained, these are accounted 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 HOBO 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 a basis that in winter openings tend to stay close;
- Insulation of clothing (5) and activity patterns (6); these were estimated based on two types of data entry:
  - Questionnaire A, the respondents were asked to select the appropriate clothing description and activity level, using EN ISO 7730:2005 checklists.
  - 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 calculated for each home then PMV was computed using EN ISO 7730:2005 Visual Basic algorithm. Then a comparison of reported and predicted responses was carried out.

Results

The study is providing an opportunity to investigate responses to thermal discomfort and their implication on energy consumption. As described above the results are presented in two parts to follow analysis (A), (B) and (C).

HOUSEHOLD'S CHARACTERISTICS AND ASSOCIATED REPORTED INFORMATION (A) AND (B)

Using content analysis, focus group's transcripts were first coded by 'cases nodes', where each participant was given a set of attributes; then portion of the text was attributed to each participant. To follow the discussions guide theme, the transcript was then coded by 'tree codes', as 'responses', 'thresholds' and 'influencing factors'.

The results of this analysis revealed that the most likely responses to thermal discomfort for the sample group are:

- Interacting with the heating system via thermostatic radiator valve, room stat or programmers (44 %);
- Layering as putting clothes on or off, thermal insulation (38 %).

Also some socio-demographic variables, such as gender, age, household composition, dwelling size and energy efficiency rating (EER), may need to be investigated further as significant factors should be analysed. Interestingly, the influencing factors to thermal discomfort are varied and included 14 elements see Table 2. This suggest that home thermal comfort systems may not be restricted to the dwelling's mechanical system but include behaviours of 'friend & family' and 'neighbours', as well as 'household characteristics'.

ACTUAL AND PREDICTED RESPONSES TO THERMAL DISCOMFORT (C)

Participants self-reported comfort vote in questionnaire A are first compared to their predicted vote computed from monitoring results, see to Table 3. This evaluation shows that the predicted PMV are lower than the reported comfort vote by an average of 0.9 units. The low air speed of 0.1 m/s specified for the PMV model can not explain the discrepancy between the two scores as greater air speed would have resulted in even lower predicted PMV scores. Further studies should include a differential sensitivity analysis of each six variables taking the reported vote as base case.

From the results of questionnaire A, it is worth noting that although comfort perception was relatively narrow on the thermal comfort scale, comfort vote varied from 'slightly cold' to 'slightly warm', most participants reported being comfortable.

The boxplots in Figure 2, illustrate the variability of predicted PMV for each participant throughout the monitoring period. This analysis shows that 83 % of monitored times are outside of the comfort zone set by ANSI/ASHRAE standard 55-2004 (table 5.2.1.2 acceptable thermal environment for general comfort). Also most participants should be feeling 'slightly cool' (-1), 'cool' (2) and 'cold' (-3) in their dwelling given the choice of clothing and activity patterns.

In Figure 3, the same results are displayed as histograms showing the frequency of predictive PMV for all participants throughout the monitoring period. This shows that on average 80 % of the participants should be uncomfortable as their predictive votes are outside the benchmark comfort range, set as [-0.5/+0.5].

Table 2. Focus group results.

Responses (50)		Thresholds (10)		Influencing Factors (43)	
Heating	44%	Cold Feet	50%	Friend & Family	28%
Clothes (Clo.)	38%	Draught	30%	Neighbours	19%
Food & drink (Met)	12%	Cold Hand	20%	Household characteristics	16%
Blanket (Clo)	10%	Shivering	10%	Outside environment	7%
Change room or location	8%			Clothing	2%
Opening	6%			Activity	2%
Hot water bottle	6%			Energy conscious	2%
Body position (Met)	4%			Cost of energy	2%
Shoes (Clo)	2%			Upbringing	2%
Blinds	2%			Natural preference	2%
				Habit	2%
				Expectation - 'homely'	2%
				Sensation - Visual	2%
				Sensation - Draught	2%

Table 3. Reported and predicted vote compared.

Participants' Characteristics	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	MEAN
Reported PMV Questionnaire A	slightly warm 1.0	slightly warm 1	slightly warm 1	neutral 0	slightly cool -1	warm 2	neutral 0	slightly cool -1	slightly cool -1	warm 2	neutral 0	0.4
Predicted PMV Monitoring	-0.2	0.0	1.0	-0.8	-0.9	0.4	-1.3	-0.8	-1.9	-0.9	-0.6	-0.5
ΔPMV	1.2	1.0	0.0	0.8	0.1	1.6	1.3	0.2	0.9	2.9	0.6	0.9

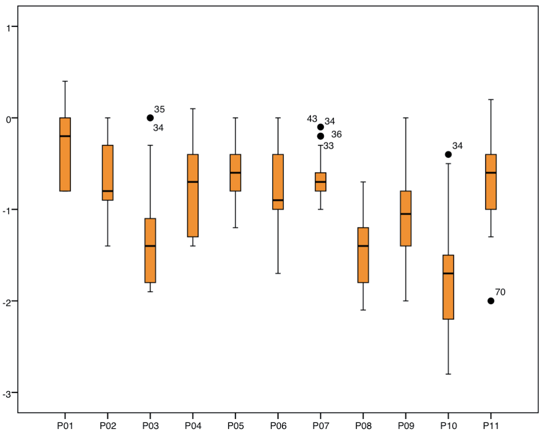

Figure 2. Predicted PMV for each participants throughout the monitoring period.

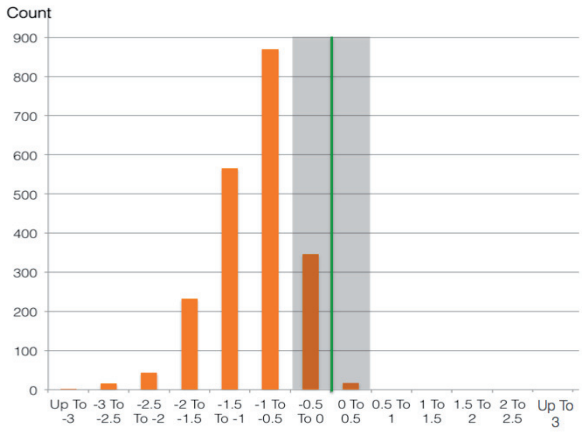

Figure 3. Predicted PMV for all participants throughout the monitoring period.

Discussion and conclusion

This detailed case study analysis is based on empirical data. It includes the collection of questionnaires, monitoring data, physical surveys and diaries. This information provides insight into identifying the responses of most importance to thermal discomfort in dwellings. The purpose of this study is to map how people respond in everyday contexts to thermal discomfort. The dynamic between people and their dwellings' thermal comfort system forms a complex framework, for which awareness and understanding level is only part of the response, as shown in the focus group results. Residents' responses may be influenced by a range of other factors, including demographics, context, environmental interactions and cognition (Brager, 1998).

In addition preliminary results between reported and predicted thermal sensation, shows great disparity in PMV scores. These outcomes highlight the limitation of the heat balance model, when used as comfort criteria and design tool.

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 future 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 - It is expected that there may be some divergence between seasonal results; therefore the study should be repeated in summer and 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 on people's responses, on where energy is used within their homes and the impact on energy consumption. In summary, the case study has provided an illustration for some of the issues and possibilities of energy and environmental research in the domestic sector. This study has outlined the various considerations that need to inform the planning process of further studies by describing in some detail the range of responses associated with each household. This paper has also highlighted the importance of referring to existing methods of data collection and classification.

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