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The gap between what is said and what is done: a method for distinguishing reported and observed responses to cold thermal discomfort

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Abstract

The need to identify occupants' behaviour-responses to thermal discomfort during the heating season has become one of the priorities in the quest to reduce energy demand. The current models have long been associated with people's behaviour by predicting their state of thermal comfort or rather discomfort. These assumed that occupants would act upon their level of discomfort through two-types of response set as involuntary mechanisms of thermoregulation, and behaviour-responses. Surprisingly, little research has focused on the behavioural aspect, and one of the key challenges is to gather accurate measurements while using 'discreet', sensor based, observatory methods in order to have minimum impact on people's behaviour. To address these issues, this paper introduces a mixed-methods approach that enabled the establishment of a three-tiered framework mapping behaviour-responses to cold sensations, consisting of *(1)* increasing clothing insulation level (I_{cl}), *(2)* increasing operative temperature by turning the heating system on/up, and *(3)* increasing the frequency, duration and/or amplitude of localised behaviour responses, including for example warm food or drink intake, changing position, changing location within the same room or changing room. Drawing from this framework, this paper introduces an extended model of thermal discomfort response that incorporates a wider range of observed behaviours.

Keywords: Occupant behaviour; thermal comfort; mixed-methods; ubiquitous sensor technologies.

1 Introduction

During the heating season, indoor temperature is one of the strongest determinants of energy used in buildings. As of 2011, the domestic sector was responsible for a large share of the total energy consumption in the UK, approximately *28%* (DECC, 2012). Space heating alone accounted for *63%* of the UK's household energy consumption in 2009 (DECC, 2013). Therefore strategies aiming to reduce domestic heating consumption can make a significant contribution towards the UK's national CO_2 emissions reduction commitments (CCC 2008). As a result, thermal comfort acceptability and practices play a key role in the quest to reduce energy use.

Using a mixed-method framework, this paper seeks to investigate the variability of reported and observed behaviour-responses in residential buildings during the heating season. A number of case study participants were chosen as the focus of the study; however it is believed that the methods could be transferable to all types of buildings.

Drawn from the current methods used to assess occupant's thermal comfort acceptability and from psychological research, this paper introduces a three-tiered methodological framework to identify occupants' responses to cold thermal discomfort. Results of semi-structured interviews revealed three broad categories of occupant behavioural response to cold thermal discomfort:

1. Increasing clothing insulation level.
2. Increasing operative temperature by turning the heating system on/up.
3. Increasing the frequency, duration and/or amplitude of localised behaviour responses, including:
    a. Consuming warm food and/or liquid.
    b. Changing body position, location within the same room, or room within the dwelling.
    c. Opening and closing of curtains and/or windows.
    d. Using a local device: hot-water bottle, having a warm bath, etc.

These categories are then used as an analytical frame for the analysis of automated visual diaries. Surprisingly, the results from the analysis of the semi-structured interviews, and the automated visual diaries, revealed major differences between what occupants self-reported, and what occupants were observed to do, in response to cold thermal discomfort. To complement this finding, clothing thermal insulation levels were monitored using wearable sensors, and compared to living room temperature levels. The mixed methods employed, and the findings of this study, enable the introduction an extended model of thermal discomfort responses that incorporates a wider range of observed behaviours.

2 Methods

Current thermal comfort field studies often involve modelling and analysis at the household level (Oseland, 1994, Crosbie 2006, Hong et al. 2009). Usually, these studies are using mixed methods approaches, which include standard comfort questionnaires, and monitoring of environmental parameters. Their focus is to investigate the relationships between social or technical factors, and participants' thermal comfort level or dwellings' indoor temperatures. Surprisingly, occupant's actual responses to thermal discomfort are not reviewed. Moreover cross-sectional studies and 'static' heat balance models are used to report on a dynamic system. To address these two issues, the research presented in this paper draws methods from psychological and physiological research to monitor people and their environment through continuous periods of time.

The sampling frame was defined by the 3-physiological attributes prescribed by ISO 8996: 2004 Annex C, as gender, age and weight. The sample frame was populated across combinations of categories using a mixture of convenience and snowball sampling with, 20 participants living in 19-different dwellings. The study was carried out in the South-East of England, during the winters of 2012 and 2013, monitored external temperatures were below the degree-day threshold of $15.5^{o}C$ for 99.8% of the recording period, and low enough to require space heating (CIBSE, TM41, 2006). Each participant was monitored over a period of 10-consecutive days; concurrently environmental variables were recorded, and semi-structured interviews conducted at the end of each monitoring period; see Figure 1.

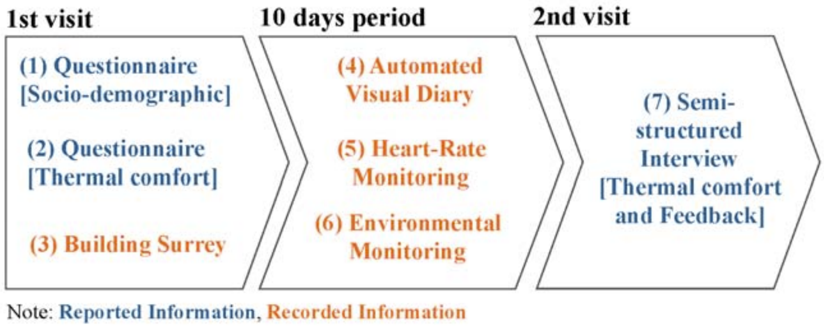

Figure 1. Individual case study data collection sequencing.

Environmental monitoring took place throughout the 10-days. Three sets of 4-dataloggers were placed in the home in living rooms and in bedrooms to record ambient air temperature (T_a) and relative humidity (*RH*). These devices were programmed to start 30-minutes before the first interview, and recorded a reading every 5-minutes. The 4-dataloggers were fastened to wooden-pole and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by ISO 7726:2001.

Concurrently, an automated visual diary was recorded using a SenseCam (Vicon Motion Systems, Microsoft, UK). This wearable recording device took photographs manually when triggered by the user, and automatically when triggered by a timer or by changes in sensors' readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared detector, a tri-axis accelerometer, and a magnetometer (Gauthier and Shipworth, 2013). In total 146,284 images were generated for the 20-particpants, which represents an average of 7,314 pictures for each participants. These pictures enabled participants' whereabouts to be mapped, and in particular their food and drink intake, their activity, and thermal insulation levels to be identified. In addition to the SenseCam, a chest strap and logger was handed out. This compact device recorded heart rate, which was used to evaluate the participants' activity level.

Ten days after the first visit, the researcher returned to the dwelling to collect the equipment, and to conduct a semi-structured interview with the participant. The aim of this interview was to gather feedback on the monitoring methods employed, and reported information on thermal discomfort responses. Open-ended questions addressing typical responses to thermal discomfort, associated thresholds, and influencing factors, enabling insight to be gained into the participant's relationship with their home's thermal comfort system. Content analysis was used to analyse interview transcripts in order to gain an understanding of the participants' responses to thermal discomfort and associated influencing factors.

In summary, this mixed-method framework was established in order to map a rich picture over a continuous timeframe of people's variability in daily activity in order to capture and categorise participants' behaviour-responses to thermal discomfort.

3 Results

The results of the semi-structured interviews, the visual diary, and of the monitoring were analysed separately, and then compared and contrasted. Surprisingly there is large variation between what occupants say and what occupants do with respect to their thermal discomfort responses.

3.1 Reported responses to thermal discomfort

Using content analysis, the semi-structured interviews were partially transcribed focusing on the three discussions guide themes: 'typical responses', 'thresholds' and 'influencing factors' to thermal discomfort. The results of this analysis summarised in Figure 2 reveal that the most frequently reported responses to thermal discomfort for the sample group were:

- Layering through putting on clothes and increasing their thermal insulation (*47%*).
- Interacting with the home heating system, using TRVs, room thermostat, or programmers (*24%*).

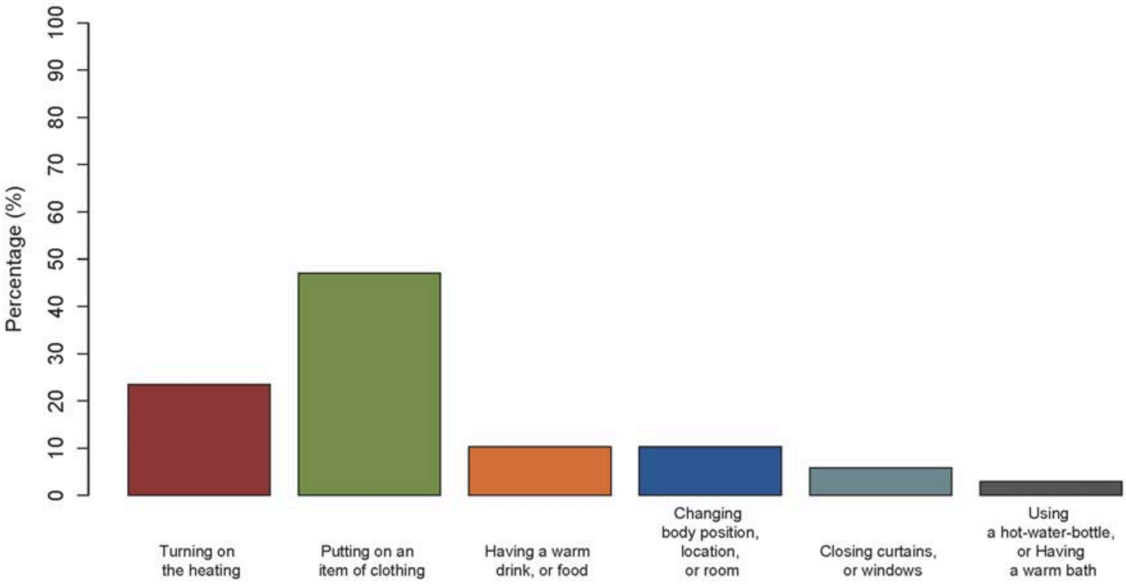

Figure 2. Semi-structured interview results - Reported responses to thermal discomfort.

Interestingly, the influencing factors to thermal discomfort are varied and responses suggest that a dwelling comfort system may not be restricted to the mechanical system but include 'friend and family', 'neighbours' and 'household characteristics'.

3.2 Observed responses to thermal discomfort

Through the diary collection, the SenseCam device captured automatically up to 24,306 images, and an average 7,314 images per participant over a monitoring period of 10-days or more. This yields to a very large collection of images. To process this information, automatic segmentation was used in a 5-steps sequence:

- Formatting - After uploading the SenseCam data, the images and the output from the temperature sensor were extracted from the diary-log. This temperature entry gives an estimation of the temperature at the surface of the clothing on the participants' chests, and is refer to as T_{clo} expressed in degree Celsius (^{o}C).

- Formatting - T_{clo} readings were then averaged over the chosen time-unit of analysis set as a 1-minute epoch.
- Normalising – While reviewing T_{clo} time-series profiles, temperature rises were observed each time a participant put-on the SenseCam. These artefacts are unwanted information contained within T_{clo} reading profiles. Prior to carrying-out the analysis, the profiles were reviewed, and these artefacts discounted; this process is called normalising. The method consists in identifying the temperature rise-time due to the resistance of the device and/or to changes in the environment. To do so, a software filter was written which identify the lagged differences between consecutive readings. The filter boundary condition was set to T_{clo} being stable during a 5-minutes period.
- Structured-query - Consecutive normalised T_{clo} readings were compared, and if those increased or decreased by 1°C or more, associated images were identified.

This structured data-query process enabled filtering of the images to those in close proximity to observed changes in T_{clo} making manual inspection of the remaining images possible. Inspection of the images then allowed for identification of the reasons for changes in T_{clo}.

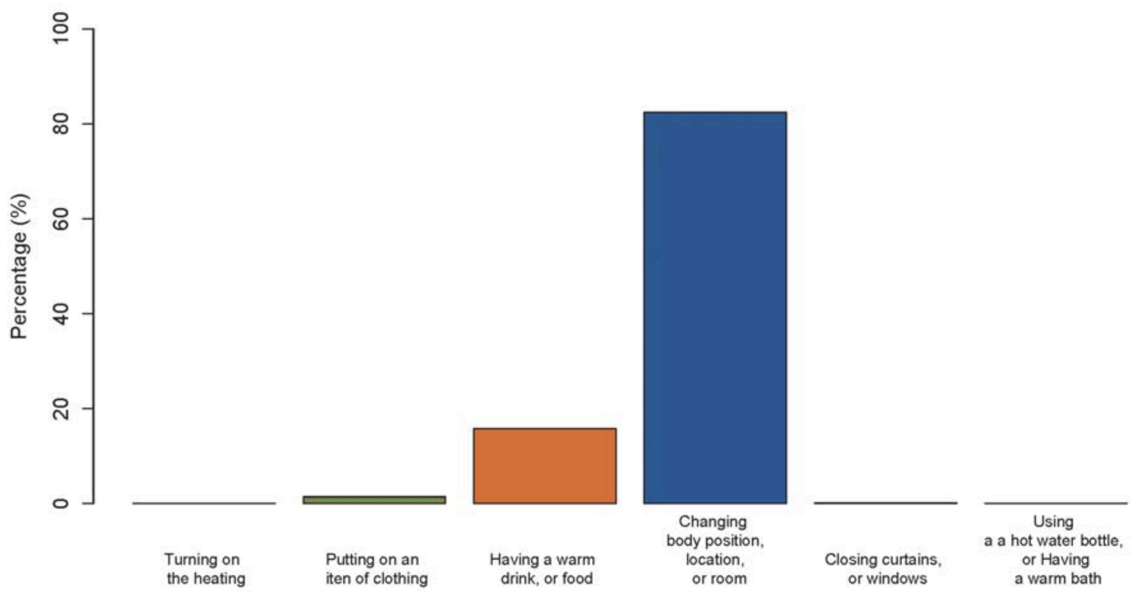

Figure 3. Automated diary results - Observed responses to thermal discomfort.

Through this approach participants responses to changes in T_{clo} were identified, and the results are summarised in Figure 3. Interestingly, the frequencies of observed responses differ greatly to the reported responses. It is important to note that the localised behaviour responses observed in the SenseCam images are not necessarily thermal discomfort responses; they may arise for a range of other reasons. To explore this issue, regression analysis between indoor monitored temperature (T_a) and the most frequently reported response (clothing insulation levels) and the most frequently observed response (motion), are carried out in the next section.

3.3 Predicted responses to thermal discomfort

Predicted responses are drawn from the framework of the predictive indices. Developed from laboratory experiments in climate chambers, this framework combines knowledge of the human body physiology and of the heat-transfer theories in which 6-variables are accounted for (ISO 7730:2005), including:

- 4-environmental variables: ambient air temperature (T_a), mean radiant temperature (T_r), relative humidity (*RH*) and air velocity (v_a).
- 2-personal variables: thermal insulation of clothing (I_{cl}) and metabolic rate (*M*).

Focusing on thermal insulation of clothing (I_{cl}), this personal variable was estimated as continuous, objective and quantitative using ASHRAE 55:2013, Appendix B, 'First guess for surface temperature of clothing', where:

$$T_{cloa} = T_{aa} + \left[(35.5 + T_a) \div \left(3.5 \times (6.45 \times I_{cl} + 0.1)\right)\right] \quad (1)$$

$$I_{cl} = [([(35.5 - T_a) \div (T_{cloa} - T_{aa})] \div 3.5) - 0.1] \div 6.45 \quad (2)$$

where T_{cloa} is the surface temperature of clothing in Kelvin, T_{aa} is ambient air temperature in Kelvin, T_a is ambient air temperature in Celsius, and I_{cl} is thermal insulation of clothing in m^2K/W.

To resolve this equation, T_a and T_{clo} are estimated as follow. Ambient air temperature (T_a) was measured using HOBO U12-012 dataloggers. Three set of 4-dataloggers were placed in living-rooms and in bedrooms, fastened to wooden-poles and positioned at *0.1m*, *0.6m*, *1.1m* and *1.7m* from the ground to comply with the requirements set by ISO 7726:2001. For the purpose of the analysis, T_a accounts for the temperature monitored in living room while standing or the mean temperature over 3-heights - *0.1m*, *0.6m* and *1.7m*. As the monitoring frequency was set at 5-minutes, a step-function was applied to generate a 1-minute sampling rate.

Relative air velocity (v_a) was measured during the first visit. For all participants, the results were equal to or below *0.1m/s*. Therefore a relative air velocity of *0.1m/s* was assumed for all cases on a basis that in winter openings tend to stay close (Hong et al., 2009). As relative air velocity was equal to or below *0.1m/s*, the surface temperature of clothing (T_{clo}) may be estimated using the SenseCam temperature recordings. The data processing was similar to the observed-responses segmentation method. First, readings were averaged over the chosen time-unit of analysis set as 1-minute. Then a normalising process was carried out to identify and discount four artefacts, including:

- Temperature rise-time as a function of the observed resistance temperature of the SenseCam when switched-on and worn.
- Participants in motion.
- SenseCam been taken-off but left switched on.
- SenseCam been worn under an item of clothing.

As the monitoring was carried-out on the chest, only the upper-body thermal insulation level was estimated; therefore a constant value of *0.3 clo* or *0.0465* m^2K/W, as the aggregation of lower-body garments, including underwear, trouser or skirt and socks, was added to the final I_{cl} value (ISO 9920: 2007). The final sample size amounts to 18,559 data-points. The estimated range of *0.43* to *1.99 clo* is within the expected standard values as described in ISO 9920: 2007. However the estimated mean value of *0.82 clo* is lower than the usually assumed winter value of *1* clo given as constant in building energy simulation (Schiavon and Lee, 2013).

Having estimated thermal insulation of clothing (I_{cl}) as a quantitative, objective, and continuous variable, its relationship with ambient temperature (T_a) may be evaluated using regression analysis. If participants were to always adjust their thermal insulation level by adding more clothing items as a response to colder temperatures, then the correlation coefficient should be close to *-1*. However the results show a very weak relationship between measured indoor air temperature and estimated clothing insulation (R=0.0134), which is in agreement with the observed response to thermal discomfort described in section 3.2. However this result might be due to the analysis design as all participants were grouped in one sample. Further analysis of the data on a participant-by-participant basis revealed within-subject variations. Figure 4 shows that one half of the participants slightly increases clothing level as indoor air temperature decreases; however the other half of the participants decrease their clothing level as indoor air temperature decreases.

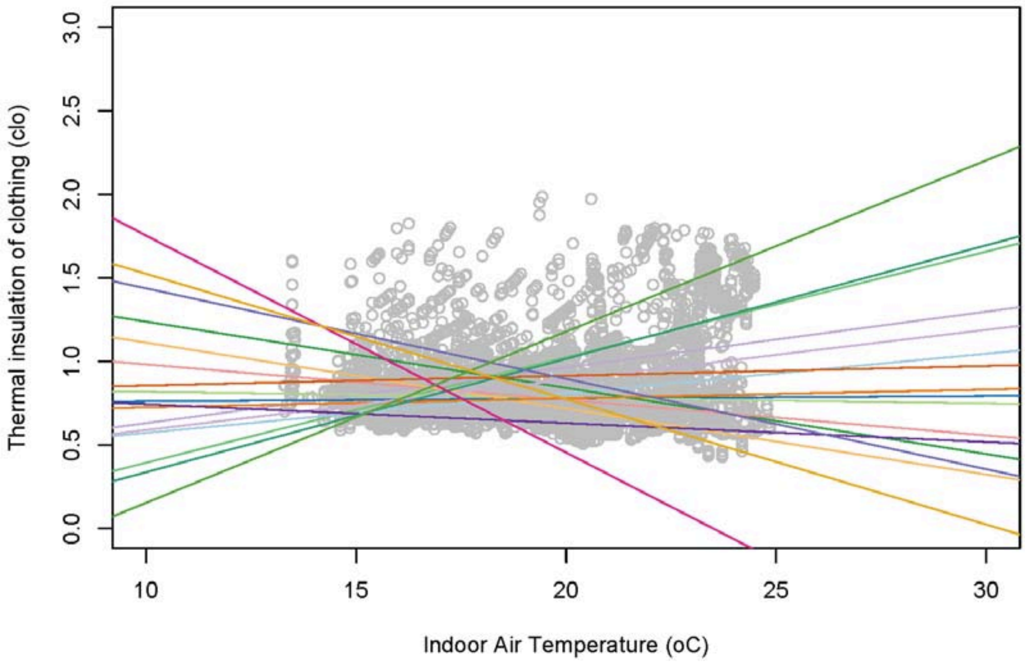

Figure 4. Monitored results – Regression analysis between monitored ambient air temperature and estimated thermal insulation of clothing for all participants with the fitted linear regression lines for each participants.

These findings establish that there is a gap between participants self-reported and sensor-observed use of clothing as a response to cold thermal discomfort. While participants reported putting on clothes when they were cold – this was not observed for half of the participants. Therefore this suggests that other behaviour-responses may be being employed, such as turning-on/up the heating or localised behaviour responses.

Following this analysis, the most frequently observed response - participants' activity level (motion) was estimate from the output of the SenseCam tri-axis piezoresistive accelerometer. Participants' total acceleration (TA) was calculated as the normalized magnitude of the acceleration vector including the earth's gravity (Shala and Rodriguez, 2011):

$$TA = \sqrt{(x^2 + y^2 + z^2)} = Linear\ Acceleration + g \tag{3}$$

where TA is the total acceleration in m/s^2, x is acceleration in the x-axis in m/s^2, y is acceleration in the y-axis in m/s^2, z is acceleration in the z-axis in m/s^2, and g is the earth's gravity of *9.81* m/s^2.

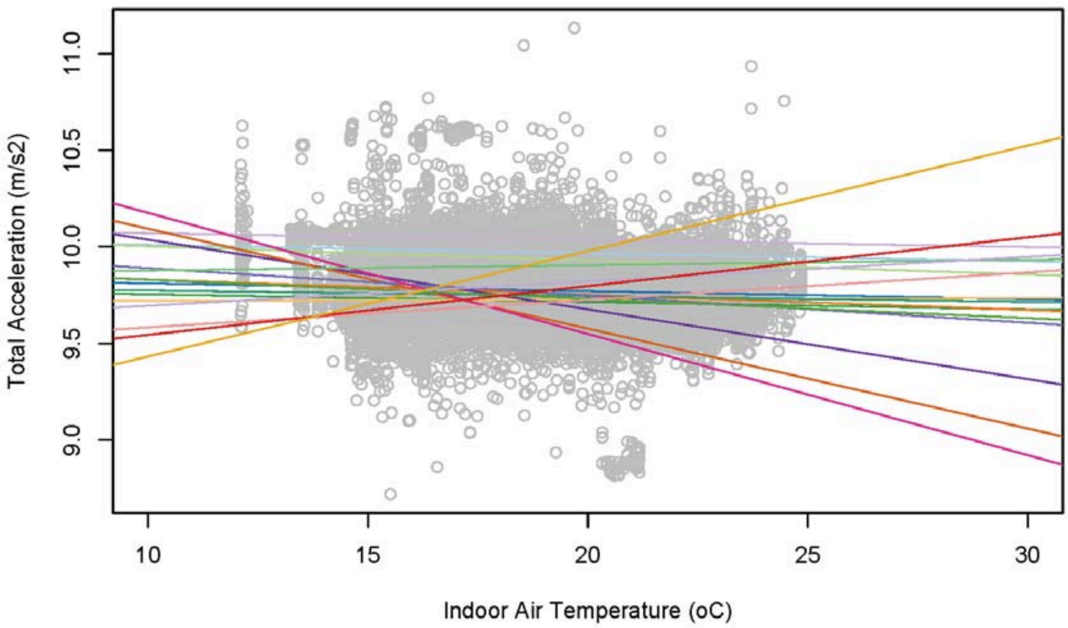

Figure 5. Monitored results – Regression analysis between monitored ambient air temperature and estimated total acceleration for all participants with the fitted linear regression lines for each participants.

The estimated total acceleration (*LA*) was then compared to the measured ambient air temperature (T_a) for each participant, see Figure 5. The overall sample size amounts to 31,540 data-points. The results show that most participants tend to be slightly more active as ambient temperature gets colder. Only 4-participants were less active in colder temperature; this is may be due to the fact that these 4-participants lived in relatively warmer environments and did not experience temperature below 19^{o}C. These findings establish that there is some agreement between participant diary-observed and sensor-observed motion level as a response to cold thermal discomfort. As participants feel colder, they may chose to adjust their position, their location within the room, or to change room; this form part of the localised behaviour responses.

4 Thermal response model

This paper compares and contrasts occupant-self-reported and observed responses to thermal discomfort and finds a marked difference between them. Most participants reported that if feeling cold they would put on an item of clothing. In contrast, observed responses identified through the automated visual diary are very different, as participant increased clothing only in *1.4%* of the observations made. This observed result is confirmed by the very weak relationship between measured air temperature (T_a) and estimated clothing insulation (I_{cl}), which was estimated from measured temperature at the surface of the clothing on participants' chests (T_{clo}) and measured air temperature (T_a). These findings establish that there is a gap between [reported] and [observed & monitored] responses in the use of clothing as a response to cold thermal discomfort. This suggests that other behaviour-responses may be employed by the occupants, including turning-on/up the heating and localised behaviour responses.

From this interpretation, one might consider the heat flow around the body as a simple one-dimensional system (see Figure 6); where the temperature at the surface of the clothing is function of skin temperature (T_{sk}), ambient temperature (T_a), temperature derived from localised behaviour (T_{bev}) and the resistances in between.

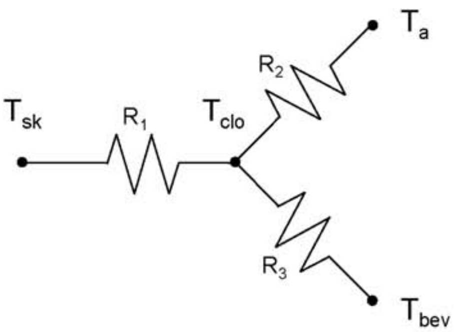

Figure 6. Diagram of heat flow around a human body – *Thermal Response Model (TRM)*.

The reduction of the inputs and associated resistances to a single node may be represented as an application of the Millman's Theorem, where:

$$T_{clo} = \frac{\frac{T_{sk}}{R_1}+\frac{T_a}{R_2}+\frac{T_{bev}}{R_3}}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}} \quad (4)$$

Findings from this study suggest that all three resistances in the model, including R_1, the resistance of clothing, remain largely constant. This leaves variation of T_a (through controlling heating systems) and variation of T_{bev} (through a range of local behavioural responses) as the observed mechanisms for cold thermal discomfort alleviation.

In practice, further studies could explore different practical scenarios, including:

- Localised action – if all input variables stay constant but T_a decreases, one response could be to 'have a warm drink' then T_{bev} increases and T_{clo} increases as a proportion of T_{bev} and R_3.
- Heating – if all input variables stay constant but T_a decreases, one response could be to 'put the heating on' then T_a increases and T_{clo} increases as a proportion of T_a and R_2.
- Changing room – if all input variables stay constant but T_a decreases, one response could be to 'move to a warmer room' then T_a increases and T_{clo} increases as a proportion of T_a and R_2.

5 Conclusions

This paper compares and contrasts occupant-self-reported and observed responses to thermal discomfort and finds a marked difference between them. This led to the development of a *thermal response model* as a simple one-dimensional system in which the skin surface temperature is assumed to be constant. Future work should include heat flow within the human body.

Theoretically, this paper introduces an extended model of discomfort response that incorporates a wider range of observed behaviours. Methodologically, this paper demonstrates the efficacy of multi-method observational approaches for understanding discomfort responses. Substantively, this paper highlights the need for researchers working in this field not to fall into the gap between what occupants say and what occupants do.

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