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Overheating in vulnerable and non-vulnerable households

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Abstract

As the 2003 European heat wave demonstrated, overheating in homes can cause wide scale fatalities. With temperatures and heat wave frequency predicted to increase due to climate change, such events can be expected to become more common. Thus, investigating the risk of overheating in buildings is key to understanding the scale of the problem and in designing solutions. Most work on this topic has been theoretical and based on lightweight dwellings that might be expected to overheat. By contrast, in this study temperature and air quality data were collected over two years in vulnerable and non-vulnerable UK homes where overheating would not be expected to be common. Overheating was found to be occurring, and disproportionally so in households with vulnerable occupants. Since the summers in question were not extreme and contained no prolonged heat waves this is a significant and worrying finding. The vulnerable homes were also found to have worse air quality and this suggests that some of the problem might be solved by enhancing indoor ventilation. Finally, the collected thermal comfort survey data were validated against the European adaptive model. Results suggest that the model underestimates discomfort in warm conditions, having implications for both vulnerable and non-vulnerable homes.

Keywords: Overheating, indoor air quality, vulnerability, thermal comfort, adaptive model

1. Introduction

Although there is not yet a universal definition of what constitutes a heat wave, they can be described as periods in which high outdoor temperatures persist for several consecutive days and night temperatures do not drop enough to allow buildings to cool down. The European heat wave of August 2003 is estimated to have caused 70000 excess deaths in Europe (Robine et al., 2007), including 2000 in the UK (Johnson et al., 2005), with the majority of the victims being among the elderly and long-term sick people.

Global average surface temperatures are predicted to rise up to 5°C by 2100 (IPCC, 2013) and heat waves are expected to increase in intensity, frequency and duration (Murphy et al., 2009; Meehl and Tebaldi, 2004; Jones et al., 2008). In dense urban environments, the consequences of global warming will be exacerbated by the urban heat island effect (Laaidi et al., 2012; Smargiassi et al., 2009; Hondula et al., 2012; Gabriel and Endlicher, 2011). All together this could severely increase levels of thermal discomfort and could lead to an increase in heat-related morbidity and mortality - even in temperate climates such as those normally experienced in the UK.

At the same time, concerns over climate change and the need to implement mitigation strategies are driving the call for a more energy efficient built environment. The UK Committee on Climate Change has set a target of a 20% reduction in energy consumption for space heating by 2030 (CCC, 2012). As a result, super-insulated and airtight houses are currently being built, or existing dwellings are being refurbished to higher thermal standards, in order to reduce winter space heating demand and associated greenhouse gas emissions (Hamilton et al., 2014). So far, much of the adoption of such domestic energy efficiency measures in the UK has been achieved in newly-built homes or refurbished social dwellings, which are supposed to be driving the changes to the UK built environment (McManus et al., 2010; DBIS, 2010; Hamilton et al., 2014).

There is already some evidence of overheating happening in British and Northern European homes that have been refurbished or newly built in order to comply with the new energy efficiency and zero carbon standards such as, for example, passive social housing flats in Coventry, UK (Tabatabaei Sameni et al., 2015), passive houses in Linköping, Sweden (Rohdin et al., 2014) and low-energy single-family houses in Pays-de-la-Loire, France (Derbez et al., 2014a). To some, the evidence is so clear that a UK national report has been written describing interventions to improve energy efficiency that can prevent overheating in the future (Dengel and Swainson, 2012). However, it is still unclear if any such overheating is due to increases in insulation and airtightness, rather than increases in solar gains (from larger windows) and lower thermal mass. Most importantly, it is not known if it is just a question of occupant behaviour and could therefore be mitigated by educating occupants on the better use of windows and/or by installing mechanical ventilation.

A plethora of studies have used dynamic thermal simulation in order to see how different energy refurbishments might affect building overheating in current and future weather scenarios (Mavrogianni et al., 2012; Tillson et al., 2013; Porritt et al., 2011; Porritt et al., 2012; McLeod et al., 2013; Oikonomou et al., 2012; Ji et al., 2014; Barbosa et al., 2015). However, most of these studies use simple statements of ventilation patterns, for example, ventilation commencing when the room operative temperature reaches an assumed threshold temperature (Mavrogianni et al., 2012; Tillson et al., 2013; Porritt et al., 2011; Porritt et al., 2012). This is not representative of how windows are used in reality by occupants in homes, since it is based on studies in offices.

The literature offers only a small range of long-term monitoring studies and, therefore, little is known about the current situation of retrofitted ‘energy-efficient’ buildings (Vardoulakis et al., 2015). The most relevant studies are: (Tabatabaei Sameni *et al.*, 2015; Lomas and Kane, 2013; White-Newsome *et al.*, 2012; Beizaee *et al.*, 2013; Sakka *et al.*, 2012; Willand *et al.*, 2016; Wells *et al.*, 2015; Wright *et al.*, 2005). Apart from the link between overheating and ventilation, ventilation is important of itself. With increased airtightness there is a risk of poor indoor air quality unless occupants respond appropriately (Yu and Kim, 2012). Again few data on indoor air quality in energy-efficient buildings exist (Derbez et al., 2014b) and this risk is still poorly understood (Wells et al., 2015).

Even less is known about any distinctions between vulnerable and non-vulnerable households, in terms of either the temperatures within their homes, or the ventilation patterns they choose (van Hoof *et al.*, 2010; Tweed *et al.*, 2015; White-Newsome *et al.*, 2012).

In this study, vulnerable households included one or more occupants falling into one or more of the following categories:

- older than 65 years old,
- disabled,
- with long-term illnesses.

This classification reflects the household types defined in the English Housing Survey (DCLG, 2015b).

Additionally, non-vulnerable homes were classified, based on the number of occupants, in overcrowded (more than or equal to 5 occupants) and non-overcrowded homes (fewer than 5 occupants). This definition of overcrowding is related to the number of occupants rather than to the density of occupants in each dwelling. The monitored dwellings were quite homogenous in terms of kitchen and living room floor areas and, therefore, the number of occupants was considered better suited to characterize internal heat gains in these spaces. Defining overcrowding in the monitored bedrooms was more difficult since their occupancy (how many people were sleeping in each bedroom) could not be assessed. Therefore, for the bedrooms, overcrowding was also defined based on the total number of occupants in each dwelling.

Reduced physical mobility, social isolation and security concerns are some of the reasons that might impede the response of vulnerable occupants to high indoor temperatures and make them at a higher risk of overheating and poor indoor air quality.

Another issue is that existing thermal comfort standards used to quantify the severity and frequency of overheating have not been derived from direct assessments of homes. The BS EN15251 adaptive thermal comfort model (Nicol and Humphreys, 2010), upon which the overheating recommendation of the UK Chartered Institution of Building Services Engineers (CIBSE) is based, has been deduced from data predominantly obtained from field studies in office buildings where people have less opportunity to adapt. This suggests that the applicability and validity of the BS EN15251 adaptive thermal comfort standard need to be tested with thermal comfort field-studies in homes.

Given this background, this paper attempts to provide data to start answering a series of simple questions:

- Do measured data from social housing in the UK indicate that overheating is already occurring?
- Are there any differences between vulnerable and non-vulnerable households?
- Do vulnerable and non-vulnerable households show different attitudes to ventilation and thermal comfort?
- Might any additional overheating (if there is any) in vulnerable households be explained by reduced ventilation rates, and might increasing the ventilation rate be a potential solution?
- Do long-term measurements of summertime CO_2 in social housing indicate poor air quality?
- Are the existing thermal comfort models able to predict occupants' thermal comfort in residential homes in UK?

In order to do this, temperature and relative humidity of living rooms, kitchens and bedrooms of 55 newly-retrofitted (*i.e.* reasonably well-insulated) low-rise social dwellings in Exeter (UK) were monitored during the summers of 2014 and 2015. Additionally, radiator temperatures were monitored (to see if heating might be the cause of any overheating) and CO_2 levels were also monitored (as indicators of air quality). Occupant thermal comfort was investigated through paper-based questionnaires and telephone interviews.

This study stands out from previous large-scale and long-term monitoring studies of summertime temperatures (Beizaee et al., 2013; Lomas and Kane, 2013) since it collects radiator temperatures, indoor carbon dioxide concentrations and thermal comfort responses along with temperature and relative humidity.

2. Factors affecting overheating

Occupants' behavioural thermal adaptation refers to all the conscious or unconscious actions that a person can take in order to modify the building indoor environment or their personal situation. In reducing temperatures and hours of overheating, (Coley *et al.*, 2012) found, via dynamic simulation, that occupants' behavioural adaptation (for example, night cooling achieved by opening of windows, or closing windows when the external temperature is greater than the internal) is equally important to common structural adaptations (for example, increased thermal mass, external shading above windows, solar-control glasses, and reduced electrical gains by using more energy-efficient items). However, behavioural adaptation is related to the specific characteristics of the occupants; for example, elderly occupants and those with compromised health might have a limited control of ventilation due to restricted possibility of movement. Since overheating depends on both occupants and dwelling characteristics, social and behavioural factors interweave with structural aspects making it particularly difficult to assess its causes. This suggests that it is important to know if there are behavioural differences between different social groups.

Various studies have hinted at reasons why overheating might occur:

- Urbanization and the associated urban heat island effect increases ambient temperatures and prevents the cooling of the buildings at night. It also influences occupant ventilation patterns especially night cooling due to outdoor pollutions, noise and security reasons (Mavrogianni et al., 2012).
- Upper stories, southern orientation and elevated glazing to wall ratio increase the severity of solar gains (McLeod et al., 2013; Porritt et al., 2012).
- The absence of window shading (fixed external shading devices or external shutters) also makes the dwelling more exposed to solar heat gains (McLeod et al., 2013; Porritt et al., 2012).
- Greater overcrowding implies greater internal heat gains while increased insulation and air-tightness and reduced external wall area to volume ratio prevent the release of the accumulated heat (Beizaee et al., 2013).
- Properties of the windows *i.e.* the windows opening type (side hung, bottom hung, sliding, etc), their size and their controllability also influence the effectiveness of natural ventilation in dissipating the accumulated heat (Roetzel et al., 2010).
- If there is a drop in night temperatures and sufficient night ventilation of the building, the use of thermal mass can help to reduce peak daytime temperatures by absorbing heat gains during the day and releasing them during the night (Peacock et al., 2010). In different circumstances, thermal mass can lead to an increase in the length of heat exposure by retaining heat within the dwelling.

The limited empirical evidence indicates that properties with an elevated risk of overheating are: flats (Lomas and Kane, 2013; Beizaee *et al.*, 2013; Wright *et al.*, 2005) and, especially, top floor flats (Beizaee et al., 2013); post-1990 British dwellings and, especially, those having insulated cavity walls (Beizaee et al., 2013); Australian 6-Star rated homes when compared to lower rated homes (Willand et al., 2016). However, it is quite possible that this list is more indicative of what has been studied, rather than where the problem lies. In addition bedrooms have been found to be more susceptible to overheating than living rooms (Firth and Wright, 2008).

The homes used in this study have been selected because they are:

- *medium weight* - insulated external cavity walls of brick, and brick/block internal walls;
- *not over-glazed* - a glazing to wall area ratio for each façade of less than 20%;
- *low-rise* with the tallest apartment block consisting of only 4 floors, and most dwellings being 2 floors (see Section 5.2 for more details);
- *located within a maritime climate and on the outskirts of a small city*, so not greatly affected by an urban heat island (see Section 6 for more details of the climate of the study site).

Thus, the study has been designed (unlike others) to make the chances of detecting overheating most unlikely. Therefore if overheating is detected in these properties, it can be reasonably confidently concluded that overheating is more common than previously thought.

3. The social housing context

Social homes represent 17% of the total number of houses in the UK (DCLG, 2015a). There are some characteristics of social houses that might make them at a higher risk of overheating now and in the future, and of the problems that overheating might cause:

- social homes have the highest rate of occupancy in the country (DCLG, 2015a), which implies higher internal heat gains;
- their tenants disproportionally belong to higher age bands; it is estimated that 22% of household with a person aged over 65 lives in social homes (ONS, 2011), which implies they are more vulnerable to heat exposure.

4. The CIBSE TM52 adaptive thermal comfort benchmark

In order to assess overheating it is possible to use either fixed or adaptive criteria. The Passivhaus criterion, for example, assumes a fixed temperature benchmark: it sets an operative temperature limit of 25°C which should not be surpassed for more than 10% of the total annual occupied hours. CIBSE Guide A sets a fixed temperature limit of 26°C for bedrooms which should not be exceeded at night (CIBSE, 2015).

In contrast, the adaptive overheating criteria of the CIBSE Overheating Taskforce (CIBSE TM52) are based on the European Standard EN15251 adaptive model of thermal comfort (Nicol and Humphreys, 2010) and are valid for habitable rooms other than bedrooms.

According to the adaptive model, the range of acceptable temperatures in naturally-ventilated buildings is larger than in conditioned ones and comfort temperatures are a function of the outdoor air temperatures. The adaptive model is driven by the idea that in free-running buildings there exists a wide band of temperatures within which an occupant can find his/her own optimum given sufficient adaptive opportunities, such as taking off excess clothing, taking in cold food or drinks, opening/closing windows or doors, and drawing curtains. While sleeping, occupants have limited abilities to adapt to temperatures higher than 26°C and, therefore, the adaptive model is not applicable to bedrooms.

Within the European adaptive model, the maximum allowable operative temperature T_{max} depends on the outdoor temperature (Nicol and Humphreys, 2010). Two maximum operative temperature limits are given depending on the degree of vulnerability of the occupants:

$$T_{max\ (Cat\ I)} = 0.33 * T_{rm} + 20.8$$

$$T_{max\ (Cat\ II)} = 0.33 * T_{rm} + 21.8$$

Here,

T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature:

$$T_{rm} = (1 - \alpha) * \{T_{-1} + \alpha * T_{-2} + \alpha^2 * T_{-3} \dots\}$$

Where α is a constant and T_{-1} is the mean outdoor temperature of the day before, T_{-2} for the day before that and so on. The recommended value for α is 0.8.

Cat(egory) I includes particularly fragile and vulnerable occupants.
Cat(egory) II is for normal occupants in new and retrofitted buildings.

According to CIBSE TM52, a room is considered to overheat if any two of the following three criteria fail. Each criteria uses the difference between the actual operative temperature (T_o) and the maximum operative temperature (T_{max}), expressed as ΔT.

Criterion C1 (frequency of overheating):

$$H_e \leq 3\% \text{ of summer occupied hours}$$

Where summer is defined as May to September, and H_e is the Hours of Exceedance, given by:

$$H_e = \sum_{i=1}^{h} \begin{cases} 1 \text{ if } \Delta T_i \geq 1°C \\ 0 \text{ otherwise} \end{cases}$$

Where h is the total number of occupied hours over the summer period.

Criterion C2 (severity of overheating):

$$W_e \leq 6 \text{ in any one summer day}$$

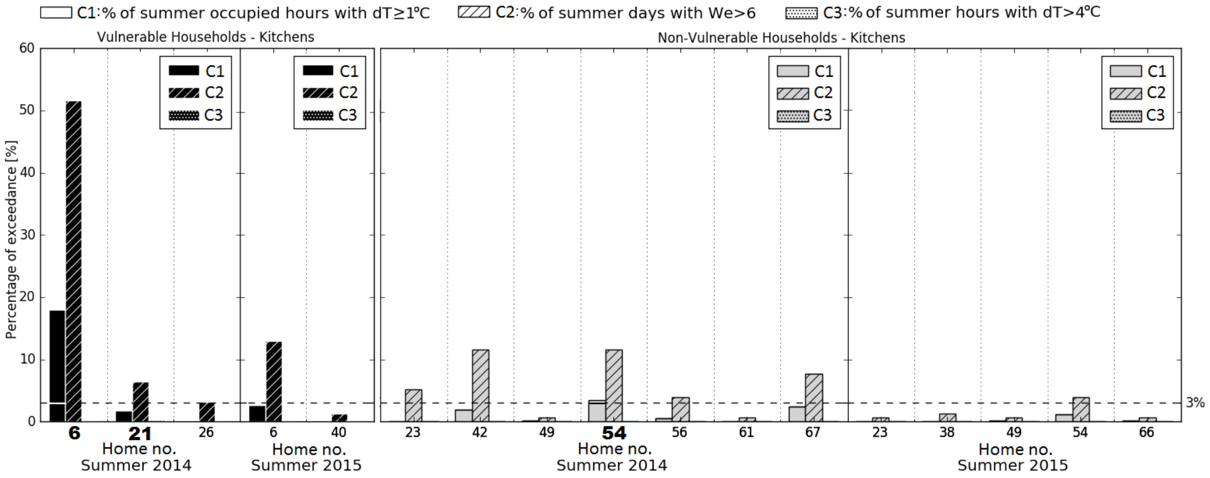
Where W_e, the Weighted Exceedance, is given by:

$$W_e = \sum_{i=0}^{3} h_{ei} * \Delta T_i$$

Here, h_{ei} is the number of hours for which each ΔT_i (i.e. $\Delta T = 0°C$, $\Delta T = 1°C$, $\Delta T = 2°C$ and $\Delta T = 3°C$) is experienced.

Criterion C3 (upper temperature limit):

$$\Delta T \leq 4°C \text{ in any one summer hour}$$



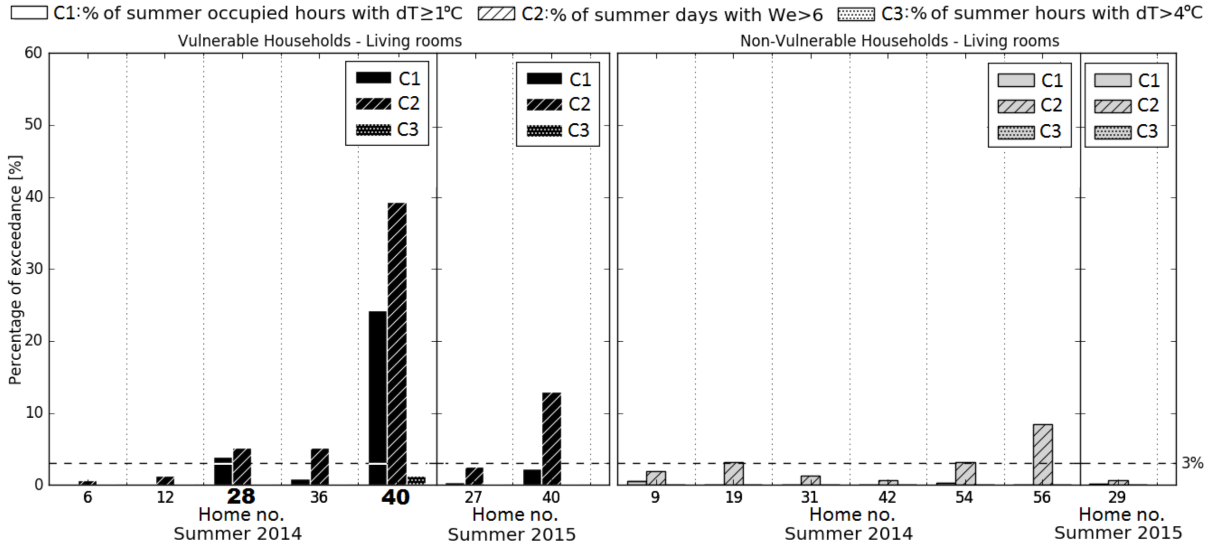


Figure 9 and Figure 10 show the overheating analysis results for kitchens and living rooms. The percentages of exceedance shown in the three bars are based on the three overheating criteria explained above:

- The first bar represents the percentage of summer occupied hours during which $\Delta T \geq 1°C$. This percentage shall be less than 3%, otherwise the criterion C1 fails.
- The second bar represents the percentage of summer days during which $W_e > 6$. This percentage shall be 0, otherwise the criterion C2 fails.
- The third bar represents the percentage of summer hours during which $\Delta T > 4°C$. This percentage shall be 0, otherwise the criterion C3 fails.

According to CIBSE TM52, a room is considered to overheat if any two of the three criteria fail.

The adaptive overheating criteria are based on the operative temperature T_o. In this study, as in other monitoring studies (Tabatabaei Sameni et al., 2015; Lomas and Kane, 2013; White-Newsome et al., 2012; Beizaee et al., 2013; Sakka et al., 2012; Willand et al., 2016; Wells et al., 2015), only the dry bulb air temperature has been measured due to the difficulties of long-term monitoring of the radiant temperature and air speed. It is therefore assumed that the dry bulb temperature is equal to the radiant temperature, but this assumption is not always met in indoor spaces, particularly those with a high thermal mass.

Also, although occupancy was detected by using passive infrared (PIR) sensors, it was not possible to reliably infer occupancy profiles for all the monitored rooms since many of the PIR sensors were not working at times or were covered. Therefore, in common with other monitoring studies (Tabatabaei Sameni *et al.*, 2015; Lomas and Kane, 2013), occupancy for living rooms and kitchens was assumed to be from 9 a.m. to 10 p.m., while for bedrooms occupancy was estimated to be from 11 p.m. to 8 a.m..

5. Study methodology

5.1. Physical measurements

Wireless temperature, humidity, CO_2 and motion sensors reported data to a university-hosted database every 5 minutes for over 2 years. The manufacturer-stated accuracy of the sensors is given in Table 1. This paper investigates the data monitored during the summers of 2014 and 2015 (from 1st of May to 31st of September 2014, and from 1st of May to 31st of September 2015).

In common with other experimental studies in occupied homes (Lomas and Kane, 2013), there were occasional issues with wireless connections and/or due to inappropriate siting of sensors (for example near sources of heat, such as fridges, TVs), etc. Thus, the recorded data needed to be cleaned and validated. This involved both automatic and human inspection which resulted in a loss of 42% of the available sensors during summer 2014 and 41% of the available sensors during summer 2015 (see Appendix) with the majority of the losses being in the kitchens. Similar loss rate have been reported in other long-term monitoring studies (*e.g. see* (Lomas and Kane, 2013)).

Post-processing of the data comprised three main steps: (i) Filtering and smoothing the raw time series in order to eliminate outliers and errors due to the influence of nearby appliances. (ii) Visually inspecting the time series by comparing hourly indoor temperatures with hourly radiator temperatures, hourly outdoor air temperatures, hourly solar irradiation, indoor CO_2 concentration and occupancy (as given by the PIR sensors, where available). This allowed us to also determine if sensors were irreversibly affected by heat sources and/or solar radiation, or if they were erroneously placed on the floor. In all cases all data from the sensor was discarded for the whole experiment, not just for the affected period. (iii) Only those sensors reporting more than 80% of the time during the hottest months of June, July and August were selected for the analysis. Post-processing of the CO_2 time series consisted of both step 1 and step 3.

5.2. House and household information

Out of a total of 68 monitored dwellings, only 55 homes had at least one sensor reporting during one of the two summers. These 55 dwellings constitute the monitored sample. House and household information for these homes were collected through questionnaires administered to the participants, and by consulting the Exeter City Council database and directly surveying the dwellings (see Appendix).

Among the 55 monitored homes, there were a total of 76 rooms (41 living rooms, 17 kitchens and 18 bedrooms) monitored during summer 2014 and 72 rooms (31 living rooms, 16 kitchens and 25 bedrooms) monitored during summer 2015.

The group of vulnerable households represents 31% of the monitored sample. Non-vulnerable overcrowded homes constitute 18% of the monitored sample. The remaining 51% of the monitored homes includes non-vulnerable and non-overcrowded homes.

Out of 55 dwellings, 52 were built with cavity walls. Unfortunately, there was no information available for the remaining 3 homes. Also, all the residences were refurbished with double-glazed windows and, when possible, with loft and cavity wall insulation. They were all low-rise dwellings with the tallest apartment block consisting of only 4 floors. None of the houses were air-conditioned and none of their windows were shaded (neither fixed external shading devices nor external shutters). All the residences were naturally-ventilated and all the rooms in which data was gathered for the study were equipped with openable windows. Cross ventilation was theoretically possible in all the dwellings.

Overall, the sample is composed of 22 low-rise flats, 17 semi-detached houses/bungalows, 3 detached houses, 9 mid-terrace houses/bungalows and 4 end-terrace houses. A total of 18 dwellings were built in the period between 1920 and 1939, 12 between 1940 and 1959 and 24 between 1960 and 1990. The floor area of the dwellings ranges between 42 and 112 m^2 with an average value of 84 m^2.

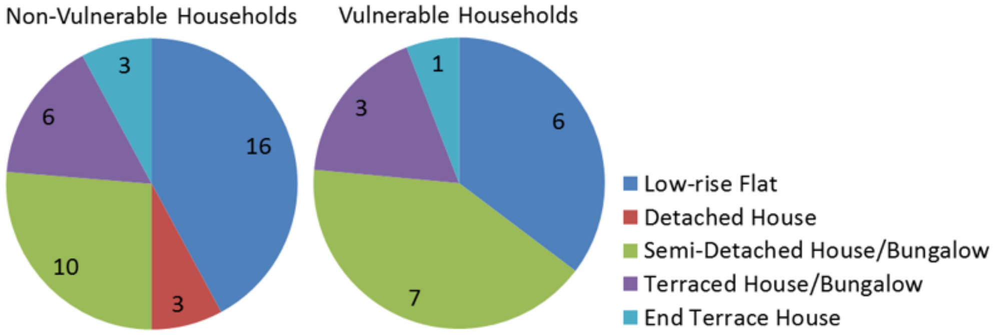


Figure 1 shows the distribution of the dwellings type. Figure 2 gives details of the demographic of the occupants.

5.3. Occupant survey

Occupant surveys were carried out at the end of summer 2014 and during summer 2015. The paper questionnaire administered at the end of summer 2014 included one question about the perceived subjective temperature in summer and two additional questions assessing ventilation and cross ventilation habits as reported in

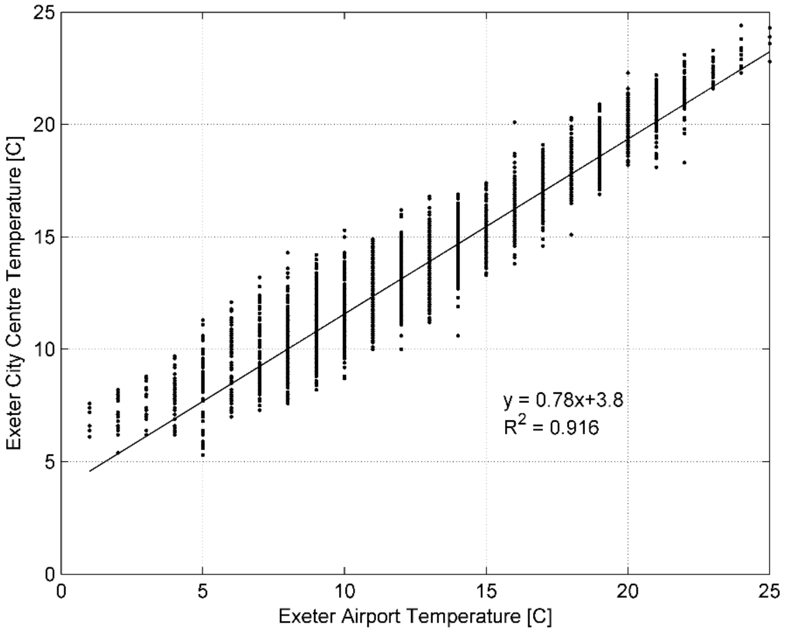
Table 2. A total of 50 paper questionnaires (16 from vulnerable and 34 from non-vulnerable households) were collected from the monitored homes, *i.e.* a response rate of 91%.

Additionally, telephone interviews were carried out throughout the months of July and August 2015. The telephone questionnaire was adapted from (ASHRAE, 2013) and ISO 7730 (ISO, 2005) and included the information reported in Table 3. The 20 households who participated in the telephone interviews consisted of 10 vulnerable and 10 non-vulnerable households. Each household was repeatedly surveyed and provided between 1 and 7 questionnaires, for an average of 3.5 responses per household and a total of 70 questionnaires collected.

6. Climate of the study site

The city of Exeter has a population of about 125000 and a surface area of 47.6 km^2. The Köppen-Geiger climate classification for Exeter is Cfb (Kottek, 2006).

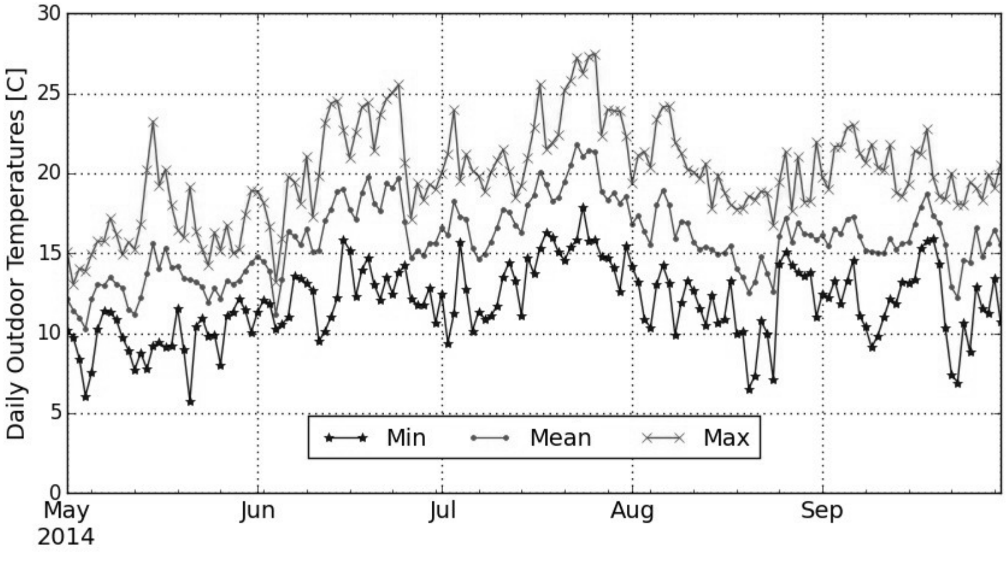
For the summer of 2014, the outdoor temperature was obtained from a mean of the hourly temperatures monitored at 6 different weather stations located within 5 km from the city centre of Exeter (blue dots in Figure 3). For the summer of 2015, the outdoor temperature was directly measured at a station mounted on the roof of a building around the study area (green dot in Figure 3). For any time steps when data were not available from the above stations, temperature data from the weather station situated at the Exeter Airport (9 km from the city centre - red dot in Figure 3) were used. In order to take into account any impact of the urban heat island effect, the data from the airport were corrected using the regression line shown in Figure *4* which was obtained by correlating the airport temperatures with the temperatures monitored at our weather station within the study area. The regression line shows that, when the temperature is low, there are higher temperatures in the city than in the airport. This aligns well with an urban heat island effect. However, when the temperature is high, the temperatures in the Airport are higher than the temperatures in the city. This is in contrast with a normal urban heat island effect. Many local effects could be responsible for the temperature being slightly lower in the city than in the airport. Examples of these are the proximity of a large river (river Exe) and green spaces, or the fact that the station is at a higher altitude than the airport, 60.3 and 26.8 meters above mean sea level respectively.



	Could you generally describe what are you currently wearing?
Activity level	In the last 30 minutes before we started this conversation, how would you describe what you were doing?
Occupied room	In the last 30 minutes before we started this conversation, which room of your home were you in for most of that time?

Thermal sensation vote (TSV)	How are you feeling right now? Measured on the ASHRAE seven-point Likert scale.
Thermal preference vote (TPV)	If you could change the current temperature in your home, what would you prefer it to be? Reported on Nicol's scale: -1 (much cooler), -0.5 (a bit cooler), 0 (no change), 0.5 (a bit warmer), 1 (much warmer).
Thermal acceptability vote (TAV)	What do you think about the temperature of your home right now? Reported in the scale: 1 (clearly acceptable), 2 (just acceptable), 3 (just unacceptable), 4 (clearly unacceptable).
Perceived temperature control	How well do you feel that you can control the temperature in your home right now? Reported in the scale: 1 (no control), 2 (light control), 3 (medium control), 4 (high control), 5 (total control).
Sleep quality	At night-time, do you find that it is difficult to sleep because the temperature in your bedroom is too high? Reported in the scale: 1 (not difficult at all), 2 (slightly difficult), 3 (very difficult).

Table 4 reports the 30-year averages, covering the period 1981-2010, for the temperatures recorded at the weather station at *Exeter airport (MetOffice).* While the summer of 2015 was generally slightly cool compared to the long-term record and 2014 slightly warm, neither could be consider atypical or extreme. According to the definition of the World Meteorological Organization, a heat wave happens 'when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5°C, the normal period being 1961-1990'. Based on the records of the (MetOffice) and the definition of the World Meteorological Organization, neither summer 2014 nor summer 2015 included a heat wave.



Daily mean, maximum and minimum outdoor temperatures recorded during the period May to September 2014 are shown in Figure *6*. It is noteworthy that minimum outdoor temperatures always fell below 18°C, and normally below 15°C. In addition the mean temperatures, with the exception of a few days, were below 20°C. This suggests that natural ventilation had clear potential for preventing overheating in the study area. This further suggests that any observed overheating is likely to imply low indoor ventilation rates. The exponentially weighted running mean of the daily outdoor air temperature (T_{rm}) and the maximum allowable temperature (T_{max}) for Category I and II are shown in

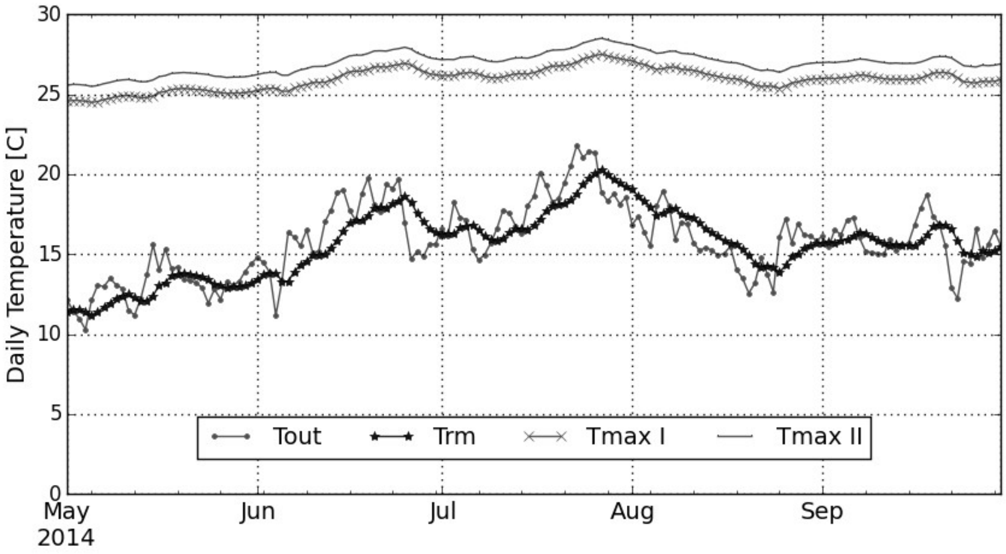


Figure *7*.

7. Results

7.1. Indoor temperatures and overheating risk

Different room characteristics (roof exposure and façade orientation) and occupant variables (occupant vulnerability and number of occupants per dwelling) were used to conduct the analysis of the temperatures monitored in the different rooms: living rooms (Lr), kitchens (K) and bedrooms (Br). An unbalanced design four-way ANOVA was performed across the mean of the mean daily temperatures recorded from 9 a.m. to 10 p.m. during the hottest months of June, July and August for the summers of 2014 and 2015. The four factors included in the ANOVA analysis were: roof exposure, façade orientation, occupant type and room type. Roof-exposed rooms (RE) were tested against the remaining rooms in the lower floors (LF). Regarding the occupant type, temperatures recorded in rooms of vulnerable and non-vulnerable overcrowded households (V-O) were tested against temperatures monitored in rooms of non-vulnerable non-overcrowded households (nV-nO).

Results of the four-way ANOVA for summer 2014 are graphically presented in

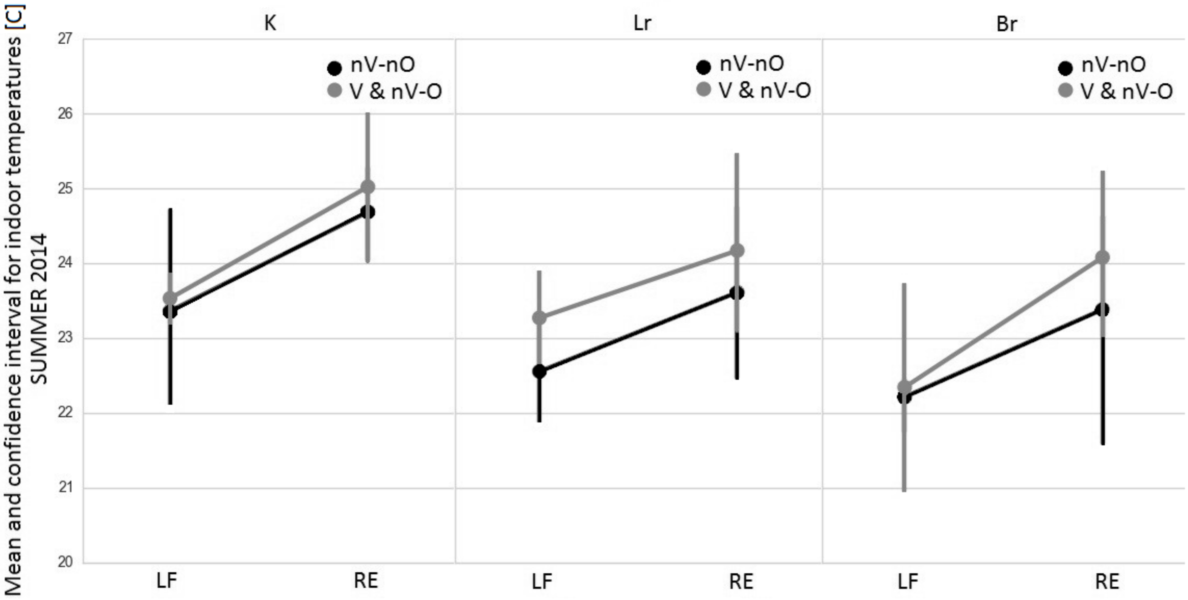


Figure 8, the three factors shown in the plot are: roof exposure (RE vs. LF), occupant type (V-O vs. nV-nO) and room type (K vs. Lr vs. Br). Descriptive statistics for the mean temperatures monitored during the two summers and results of the ANOVA test are reported in

Month	Averages for 1981-2010			2014	2015
	Max (°C)	Min (°C)	Mean (°C)	Mean (°C)	Mean (°C)
May	16.8	7.6	12.2	13	12.4
June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5. The significance level α is set at 0.1. If the p-value is above 0.1 then the evidence is not statistically significant. Thus, if the p-value is between 0.1 and 0.05 the evidence is weak, while if the p-value is below 0.05 the evidence is strong. It is to be noted that the small size of some of the subsets (see

Month	Averages for 1981-2010			2014	2015
	Max (°C)	Min (°C)	Mean (°C)	Mean (°C)	Mean (°C)
May	16.8	7.6	12.2	13	12.4
June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5) have likely had an impact on the statistical power of the ANOVA test.

Roof-exposed (RE) rooms were found to have statistically significantly higher mean daily temperatures than lower-floor (LF) rooms ($p < 0.01$, see

Month	Averages for 1981-2010			2014	2015
	Max (°C)	Min (°C)	Mean (°C)	Mean (°C)	Mean (°C)
May	16.8	7.6	12.2	13	12.4

June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5) during summer 2014 but not during the comparatively cooler summer of 2015. This result is in agreement with the results from other monitoring studies which show that top floor flats are at a higher overheating risk than lower floor flats (Beizaee et al., 2013). South-facing rooms (i.e. rooms with at least 1 window façade facing south, between 90 and 270°) were not found to have statistically significantly different mean temperatures than north-facing rooms in either of the two summers.

The highest mean temperatures were recorded in the kitchens during both summers. The difference in the mean temperatures for the three types of rooms is statistically significant for both summer of 2014 and 2015, see

Month	**Averages for 1981-2010**			**2014**	**2015**
	Max (°C)	**Min (°C)**	**Mean (°C)**	**Mean (°C)**	**Mean (°C)**
May	16.8	7.6	12.2	13	12.4
June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5.

During the summer of 2014, rooms in vulnerable and overcrowded dwellings were found to have significantly higher mean temperatures (about 0.6°C) than rooms in non-vulnerable and non-overcrowded homes (p=0.076, see

Month	**Averages for 1981-2010**			**2014**	**2015**
	Max (°C)	**Min (°C)**	**Mean (°C)**	**Mean (°C)**	**Mean (°C)**
May	16.8	7.6	12.2	13	12.4
June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5).

Overheating in living rooms and kitchens was assessed using the CIBSE TM52 adaptive benchmark. Since many of the monitored kitchens included a dining area, they were considered as habitable rooms. No room was found to overheat during the summer of 2015. During the comparatively warmer summer of 2014, it was found that 18% of the kitchens (i.e. 1 from non-vulnerable and 2 from vulnerable households), and 5% of the living rooms (i.e. 2 from vulnerable households) suffered overheating, see

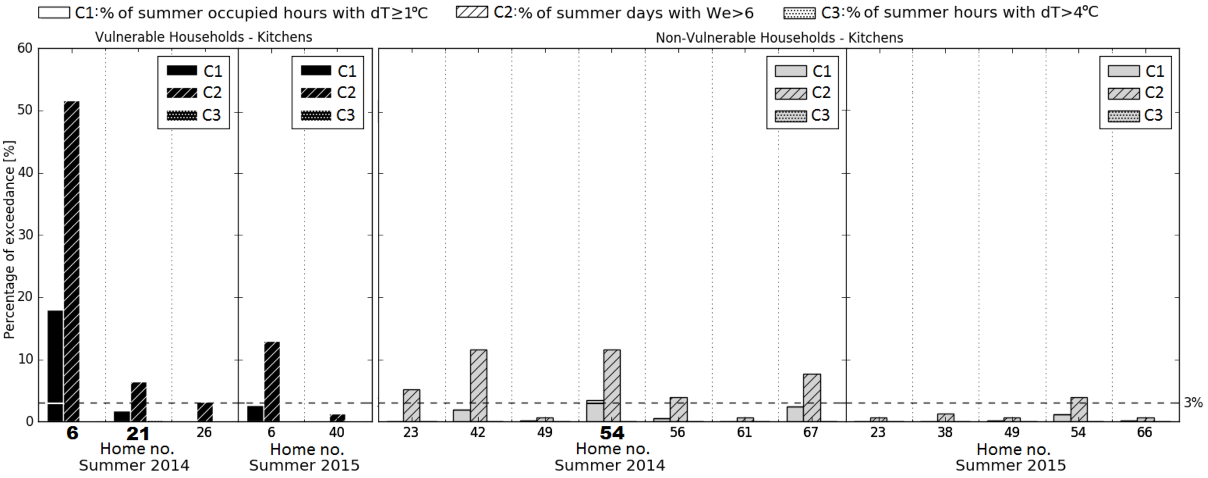


Figure 9 and

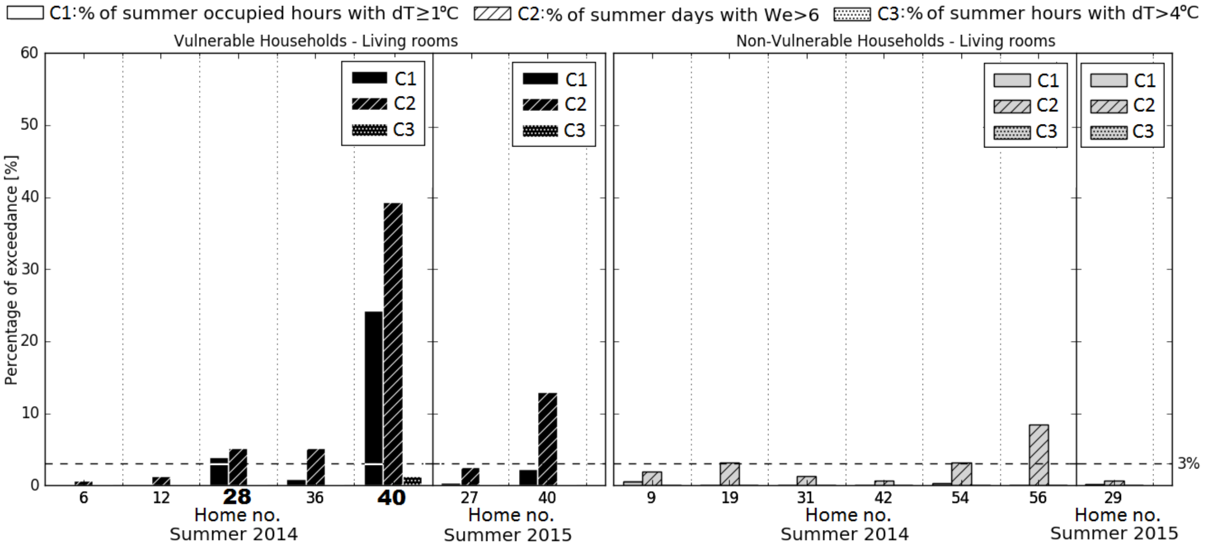
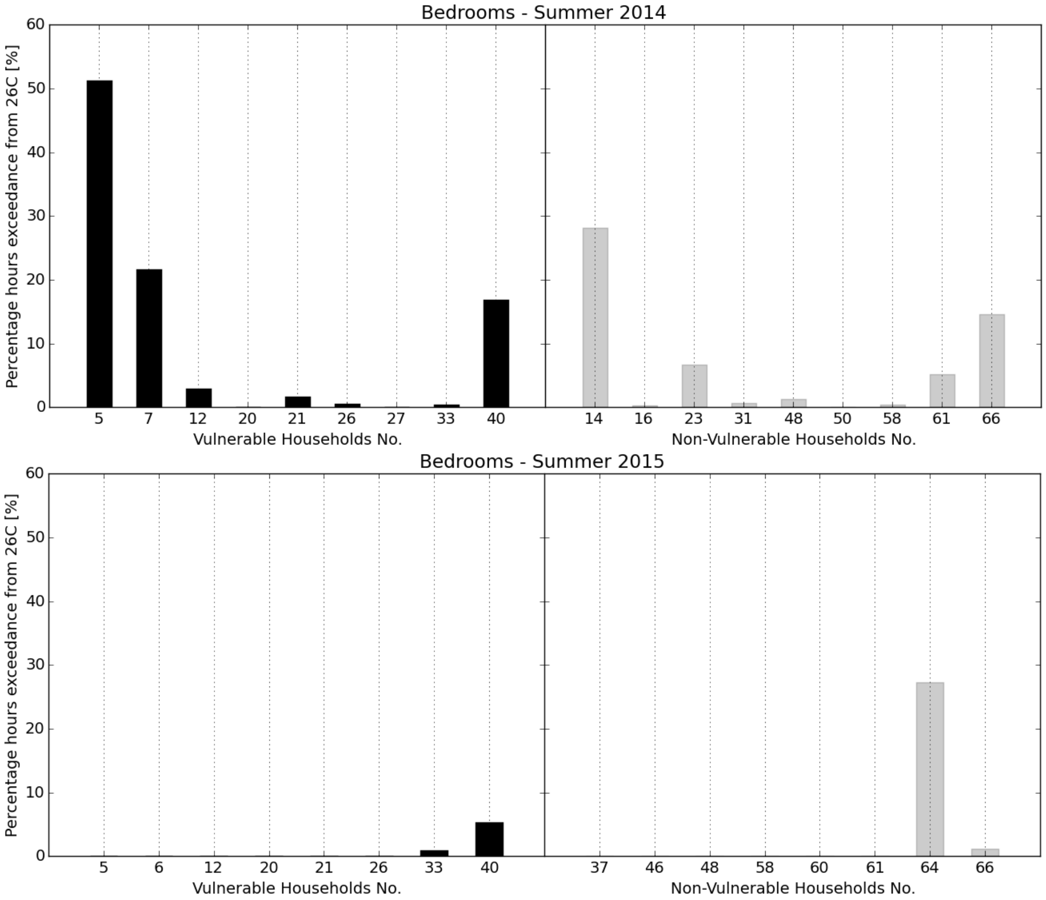


Figure *10*. Kitchens were more exposed to the risk of overheating than living rooms. This is in agreement with the higher mean temperatures found in kitchens (see Table 6)which may have been due to the high internal heat gains associated with the cooking activities.

From the overheating assessment of bedrooms using the fixed CIBSE criteria of 26°C, 4 out of 16 bedrooms overheated during summer 2015, while 15 out of 18 rooms overheated during



the warmer summer of 2014, see Figure 11. The high temperatures of the bedrooms can be explained by the fact that they are mostly located under the roof (74% of the monitored bedrooms are roof-exposed).

Overall 38% of the monitored vulnerable rooms overheated during the summer of 2014, while 18% of the non-vulnerable rooms suffered overheating according to the CIBSE fixed criterion (for bedrooms) and the adaptive criteria (for living rooms and kitchens).

By looking at the radiator temperatures, more vulnerable homes than non-vulnerable homes tended to keep their heating system on during summer. For summer 2014, 77% of the vulnerable homes (10 out of 13) kept their radiators on, while only 33% of the non-vulnerable homes had their radiators on (8 out of 24). For summer 2015 the situation is similar: 54% of the vulnerable homes (7 out of 13) kept the heater on, while only 21% of the non-vulnerable homes had the radiators on (5 out of 23). These differences provide an important insight into the reasons for overheating in summer, especially for the vulnerable homes.

7.2. Ventilation and indoor air quality

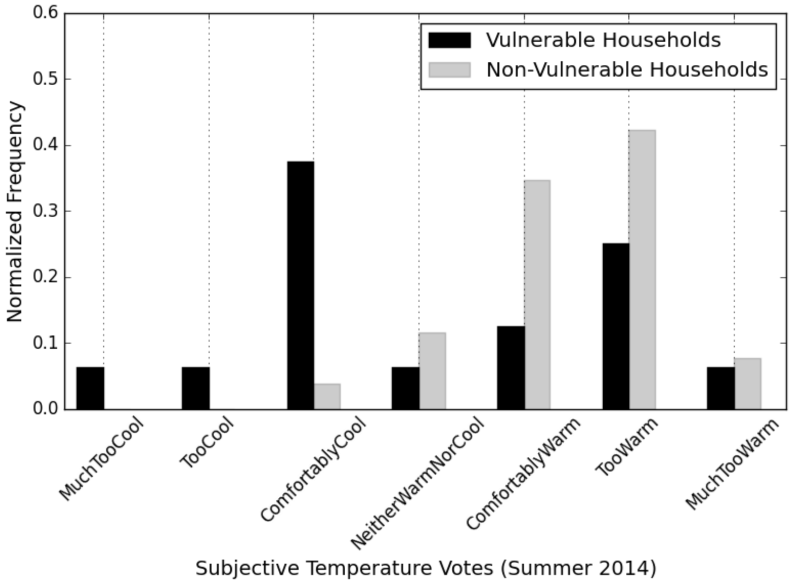
From the ventilation survey a statistically significant difference between the average ventilation frequency vote of vulnerable and non-vulnerable households was found (see Table 6) with vulnerable occupants having a tendency to open windows less often. Also, by looking at the CO_2 levels recorded in 21 living rooms (10 Vulnerable and 11 Non-Vulnerable households) during June, July and August 2015, a statistically significant higher mean CO_2 concentration was found in vulnerable living rooms compared to non-vulnerable ones. This provides a physical confirmation of the survey results, and discounts the possibility that they are opening the windows less often, but wider. In Figure 13 it can be seen that in non-vulnerable homes the recommended limit of 1000 ppm (ASTM, 2012) for the indoor CO_2 concentration was exceeded only 4% of the monitored hours which indicates good indoor conditions. However, the situation is quite different in vulnerable homes where the limit of 1000 ppm is exceeded in 20% of the monitored hours. This is worrying given that occupants are less likely to open windows during winter and, therefore, CO_2 levels can be expected to be even higher and indoor air quality to be worse.

These findings of significantly different window opening patterns for vulnerable occupants, and a corresponding reduction in air quality represents an important new insight since occupants' age was not found to be a significant driver of windows opening behaviours in previous works (Fabi et al., 2012).

The higher temperatures recorded in vulnerable and overcrowded living rooms may have been due to high internal gains (in overcrowded homes) and poor ventilation and radiators on (in vulnerable homes).

7.3. Thermal comfort

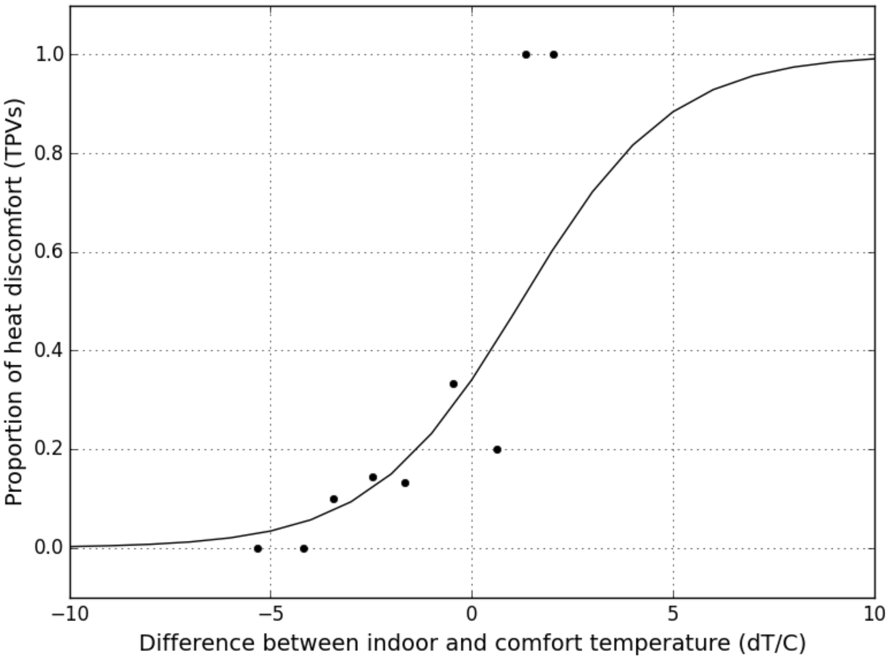
The analysis of the thermal comfort responses for summer 2014 (paper questionnaire in Table 2) indicates that vulnerable occupants had the tendency to feel cooler when compared to non-vulnerable occupants (see Figure 14 and Table 6). This is probably why vulnerable occupants decided to keep their radiators on, as noted earlier (Section 7.1). This is dangerous since it could potentially make them less ready to undertake behavioural actions for heat protection.



For the analysis of the thermal comfort responses collected during the telephone interviews (Table 3), the mean temperature recorded in the hour preceding the phone call for the room where the occupants indicated that they spent most of the time was used. If the environmental sensor was not reporting in this room then the temperature of another room in the home was used when available. The difference dT between that temperature T_{room} and the comfort temperature T_{comf} defined by the European adaptive equation (Nicol and Humphreys, 2010) was then calculated.

$$dT = T_{room} - T_{comf} \text{ where } T_{comf} = 0.33 * T_{rm} + 18.8$$

Finally, a logistic regression was fitted using thermal preference (TPV), thermal sensation (TSV) and thermal acceptability votes (TAV) and the calculated dT.



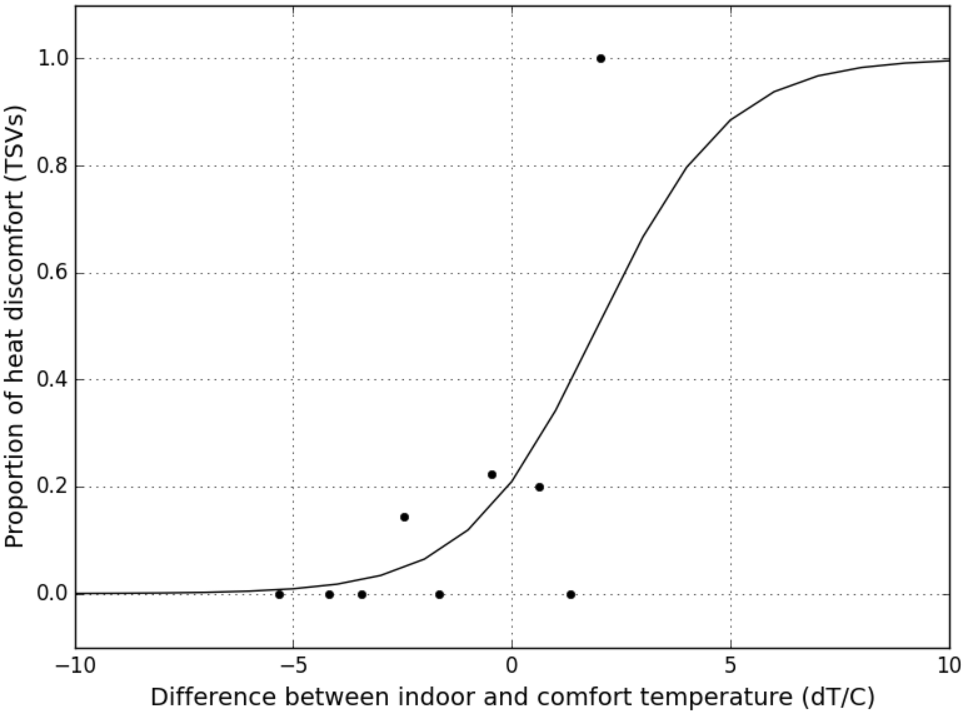
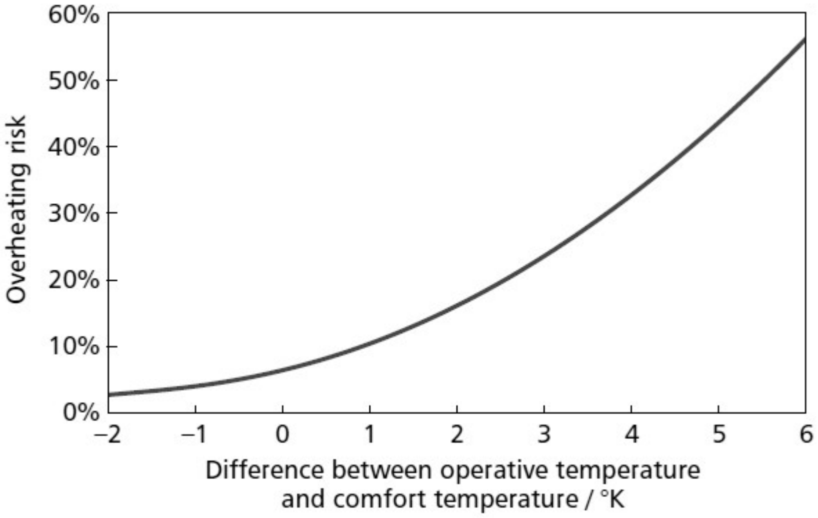


Figure 16,

Figure 17 and Figure 18 show the fitted logistic models together with the data binned for 1°C of dT. Logistic regression for TPV and TSV are statistically significant (p equal to 0.026 and 0.03 respectively), while the logistic regression for TAV does not reach statistical significance (p equal to 0.124) and it is therefore not considered further in the analysis.

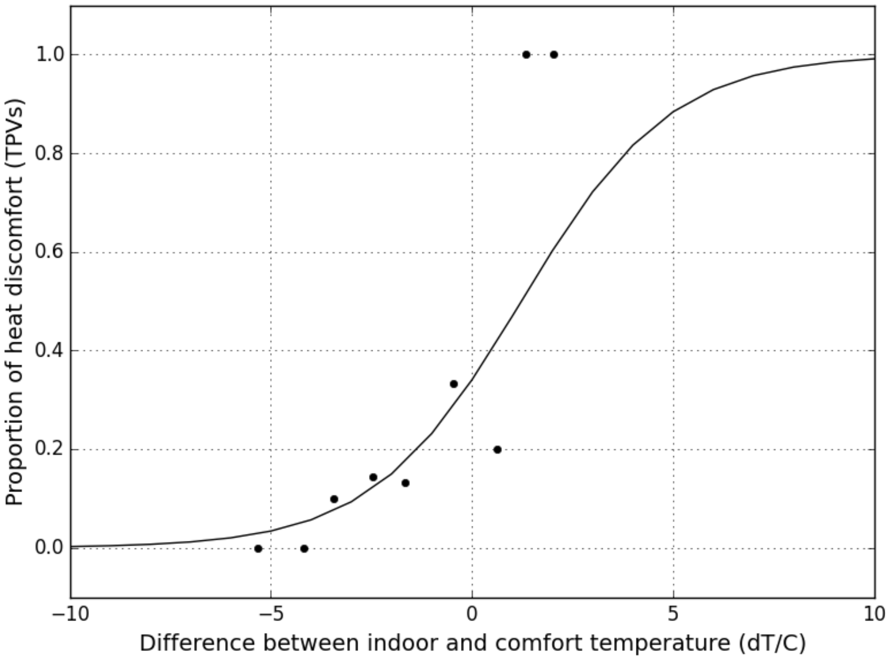
Based on the results from the SCATs surveys from 26 European office buildings (Nicol and Humphreys, 2007) at the base of the European adaptive equation, the proportion P of subjects voting 'Warm' or 'Hot' on the ASHRAE comfort scale is given by the following logistic model (see also Figure 15):



$$P = \frac{e^{(0.4734 * dT - 2.607)}}{1 + e^{(0.4734 * dT - 2.607)}}$$

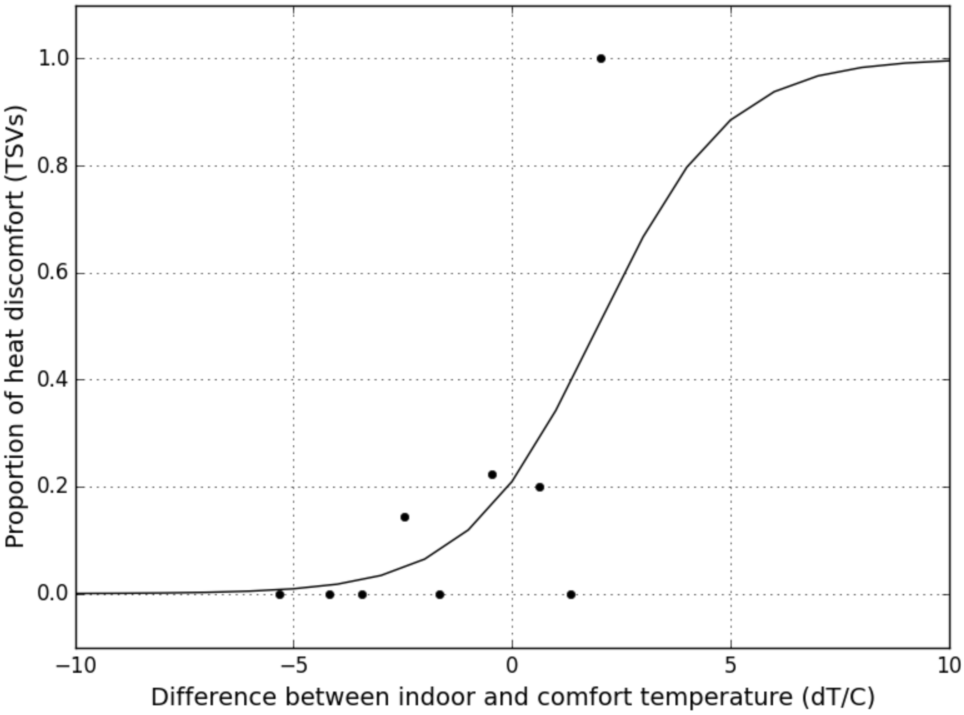
European adaptive model predictions have been compared against observed discomfort votes given by the fitted logistic regressions which suggest that at dT =0:

1. 35% of the occupants prefer 'Much cooler' or 'A bit cooler' (



2. Figure 16).

3. 20% of the occupants voted 'Warm' or 'Hot', instead of the 10% predicted by the SCATS logistic model (



4. Figure 17).
5. If dT is calculated using the maximum allowable operative temperature for vulnerable occupants, i.e. $T_{max\ (Cat\ I)}$ (see Section 4), the proportion of the occupants voting 'Just unacceptable' or 'Clearly unacceptable' is equal to 35% which is 15% more than the 20% predicted by the adaptive comfort model.

These results provide new insight on the validity of the European adaptive relation in Europe suggesting that the adaptive model slightly underestimates occupants' thermal discomfort in Exeter, UK. This is not wholly unexpected given that the work on the European adaptive model suggested that people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones. However, in reality, the model is used in a climate agnostic manner. That is, the model predicts that at a mean outdoor air temperature of 25°C, 80% of occupants will find it thermally acceptable until 29°C – whether in Northern England or Southern Italy. This, and the fact that the underlying data for the model derives primarily from offices, creates difficulties in the application of the model.

8. Limitations

This study has the following limitations:

- The distinctions between vulnerable and non-vulnerable households, in terms of either the temperatures within their homes, or the ventilation patterns they choose is based on a relatively small sample of homes. CO_2 levels were recorded during summer 2015 in only 21 living rooms - 10 Vulnerable and 11 Non-Vulnerable households. During summer 2014 temperatures were monitored in 76 rooms, 38 from Non-Vulnerable homes and 38 from Vulnerable and Non-Vulnerable Overcrowded homes. While during summer 2015 temperatures were monitored in 72 rooms, 40

from Non-Vulnerable homes and 32 from Vulnerable and Non-Vulnerable Overcrowded homes.
- The CIBSE adaptive overheating criteria are based on the monitored occupied hours; the fact that occupancy could not be detected implies that overheating predictions based on the model might not be accurate.
- Finally, the differences found between vulnerable and non-vulnerable households might have been exacerbated by the monitored sample being social housing. Another study on the same lines but applied to a different social context in UK could help demonstrating if any such differences are still present.

9. Conclusions

This study aimed to investigate overheating, ventilation, thermal comfort and indoor air quality in social dwellings occupied by vulnerable and non-vulnerable households.

Air and radiator temperatures, relative humidity and CO_2 were recorded over two summers in 55 homes, and surveys were concurrently administered to the occupants. The homes were carefully selected to be medium weight, not over-glazed, low-rise, within a maritime climate with little risk of being affected by an urban heat island. The only uncontrolled variable, the weather, did not create extreme or atypical conditions that would increase overheating risk.

Despite this, it was observed that:

1 Overheating occurred even though the study period contained no heat waves as defined by the MET Office.
2 There was a clear difference in the measured frequency of overheating between vulnerable and non-vulnerable households.
3 There was a statistically significant difference in the survey-reported attitudes to window use between vulnerable and non-vulnerable households and this conclusion was supported by CO_2 measurements in the homes.
4 The CO_2 measurements pointed to poor summertime air quality in vulnerable households.
5 The European adaptive model predictions were found to slightly underestimate occupants' thermal discomfort.

These results are both worrying and comforting. With 14,000 elderly people dying in Paris during a single heat wave, the confirmed existence of overheating during two typical summers in homes occupied by the vulnerable is a great cause for concern. The experiment was deliberately designed through choice of its location and type of building to make overheating unlikely, yet it was found in 38% of the vulnerable homes.

However, the discovery that reduced levels of ventilation in vulnerable homes is a major contributor to this overheating is good news, as it points to a possible strategy. Because the experiment contained a control group (the non-vulnerable households) living in near-identical homes the experiment also shows that these increased ventilation rates can be achieved without alterations to the homes, but through behavioural change, and are therefore, essentially, zero-cost.

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11. Appendix

Table 7 and

Home	Summer 2014				Summer 2015				
No.	Lr	Br	K	R	Lr	Br	CO_2	K	R
1		x	x						
2	x								
3			x		x	x		x	
4	o		o						
5		o		o	o	o		o	o
6	o		o	o	o	o	o	o	o
7	o	o		o	x	x	o	x	o
8	x	x	x	x	x	x	o	o	o
9	o	x		o					
10	o			o					
11	o		x	x	x		x	x	x
12	o	o	x		x	o	x	x	
13	o			o	o		o		o
14	o	o	x	o	o	x	o	x	o
15	o		x	o					
16	o	o	o	x	x	x	x	o	x
17	x		x	o	o			x	o
18	o		x	o					
19	o		o		x		x	o	
20	x	o	o	o	x	o	o	o	x
21	x	o	o	o	o	o		x	o
22	x	x	x	x					
23	x	o	o		o	x		o	
24	o		x	x	o		o	o	o
25	o		o	o	x		o	x	x
26	o	o	o	x	o	o	o	o	o
27	o	o	x	o	o	x	o	x	o
28	o			o	o		o		o
29	x			o	o		x	o	o
30	o	x	o	o	o	x		x	o
31	o	o	x	o	x	x			x
32	x		x	o					
33	o	o		o	o	o	o	o	o
34					x		x	x	x
35	x			o	o		x		x
36	o			o					
37	x		x	o	x	o		x	x
38	o	x	x	x	o	x	o	o	o

39	x		x	x				x	x
40	○	○		○	○	○	x	○	○
41	○		x	○	○		x	x	○
42	○	x	○	○	○	x		x	○
43	x	x		x					
44	○		x	x	x	x	○	x	○
45	x				x		x	x	○
46	○	x	x	○	○	○		x	○
47	○		x		○		○	x	○
48	○	○		○	x	○	○	○	○
49	○	x	○	○	○			○	x
50	x	○		○	x	x	x		x
51					x		○	○	○
52	x	x	x	x	x	x		x	x
53	○			○	○		x	x	○
54	○		○	○	○			○	○
55	○				○		○	○	○
56	○		○		○		x	○	
57	x	x		x					
58	x	○	x	x	x	○	○	x	○
59	x	x	x	x	x			○	○
60			x		x	○	x	○	○
61	○	○	○	○	○	○		○	○
62	x		x						
63	○		○	○	○		○	○	○
64	○	x	x	○	○	○	○	x	○
65	x	x		x	x	x	x	x	x
66	○	○	x	○	○	○		○	○
67	○	x	○	○	○	x	x	x	○
68	○	x	x	○	x	x		○	○

Lr: Living room, Br: Bedroom, K: Kitchen, R: Radiator, CO_2: Living room CO_2

Table 8 are to be included in the Appendix.

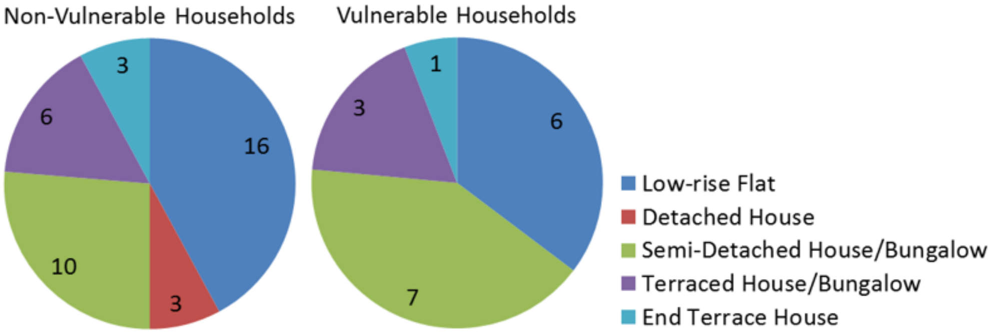

Figure 1 Distribution by built type of the 55 monitored dwellings for non-vulnerable and vulnerable households.

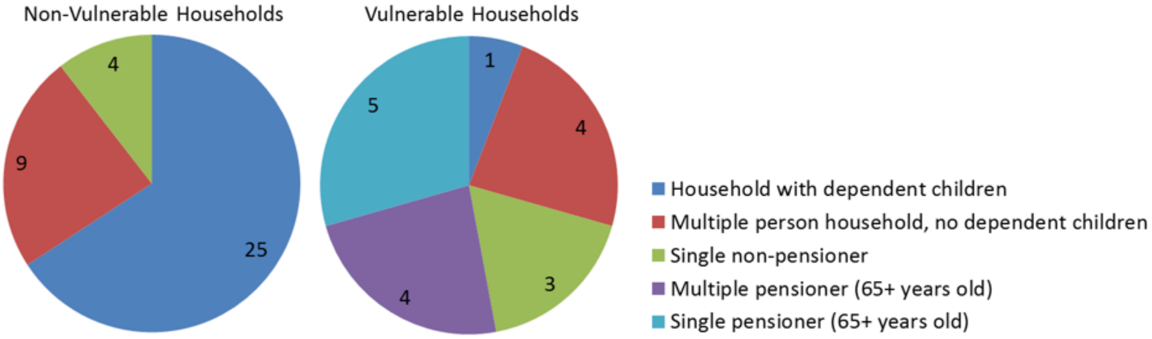

Figure 2 Overview of the demographic of the 55 monitored non-vulnerable and vulnerable households.

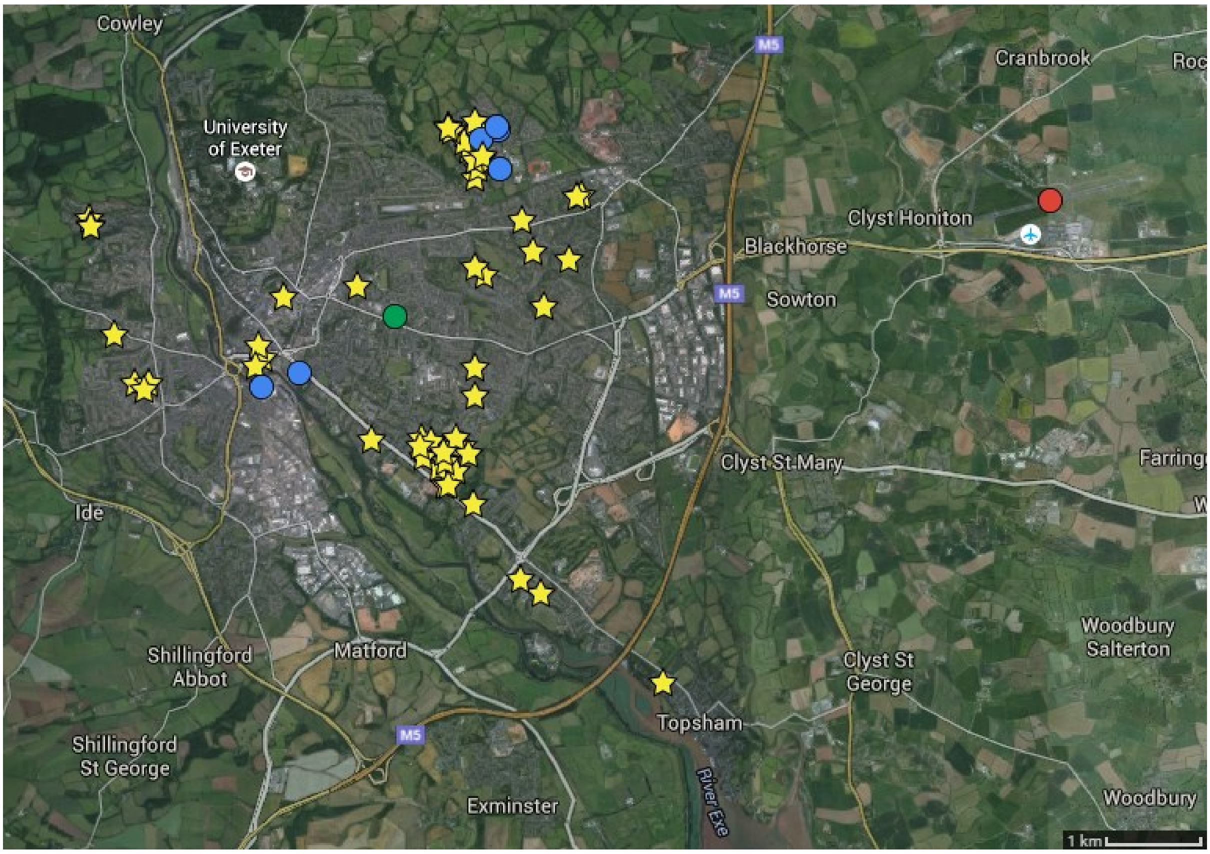

Figure 3 Location of the monitored dwellings (yellow stars) and weather stations (blue, red and green dots) in the city of Exeter in South West England (Source: Google Maps ©).

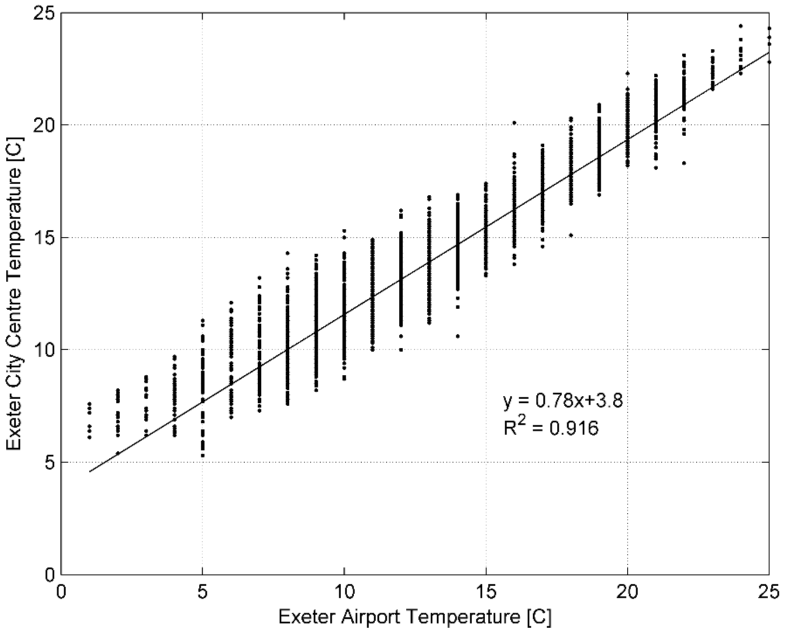

Figure 4 Regression line fitted between Exeter city centre and Exeter airport temperatures.

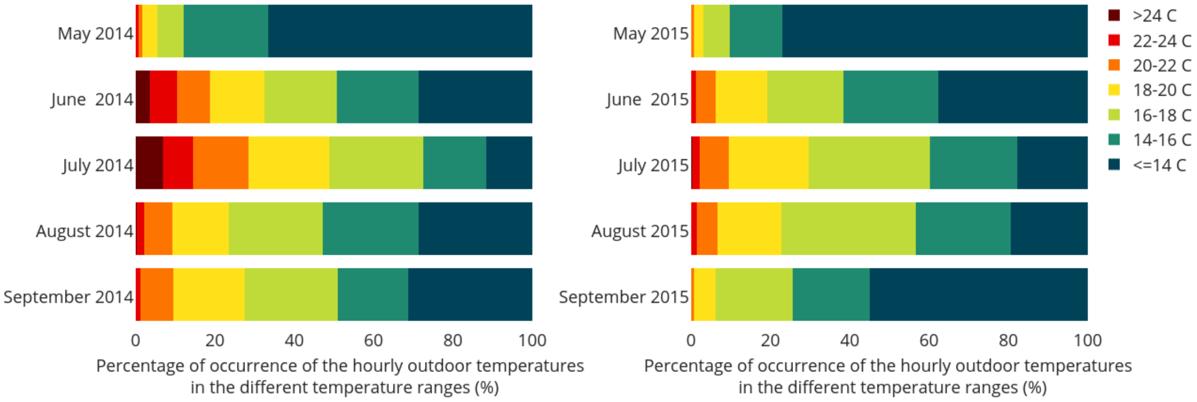

Figure 5 Percentage of occurrence of the hourly outdoor temperatures in the different temperature ranges (%).

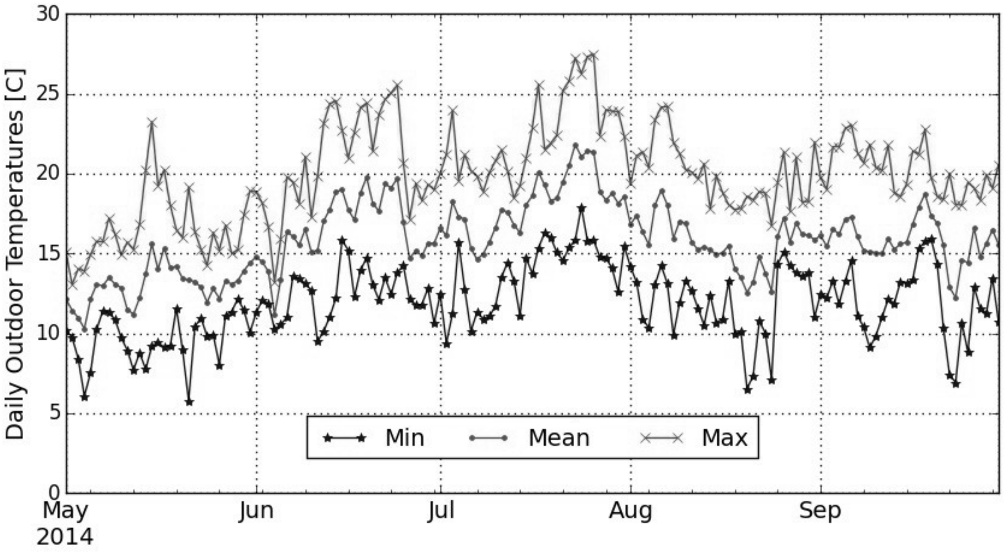

Figure 6 Daily minimum, mean and maximum outdoor temperatures during the period May-September 2014.

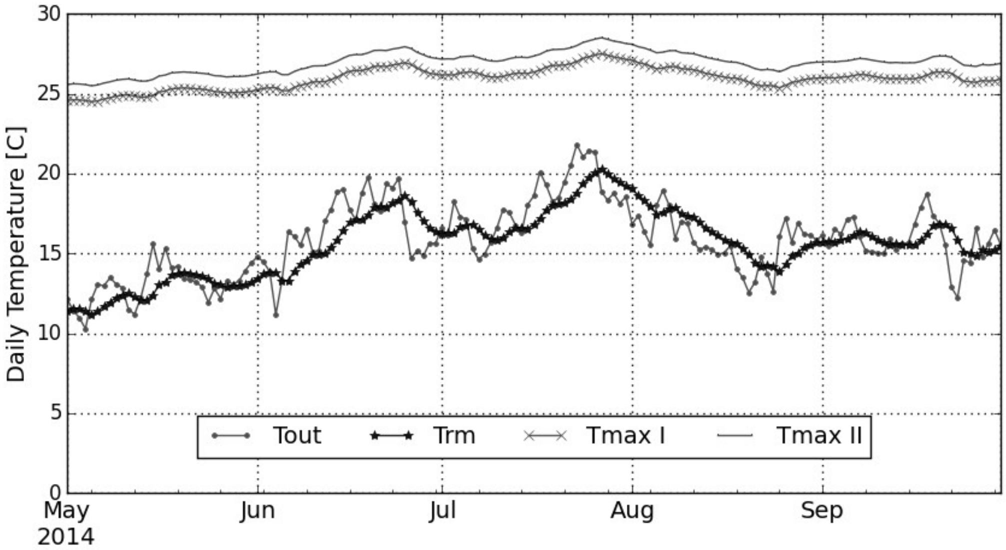

Figure 7 Daily mean outdoor temperatures (Tout), exponentially weighted running mean of Tout (Trm), maximum allowable temperatures (Tmax) for Category I and II during the period May-September 2014.

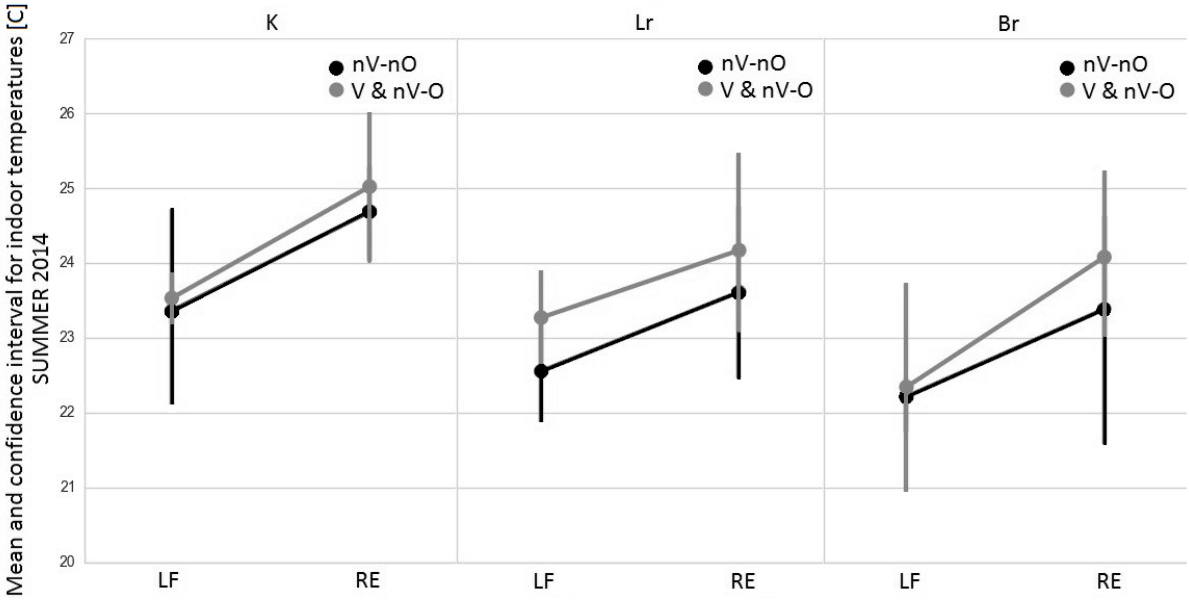

Figure 8 Results of the ANOVA analysis for summer 2014.

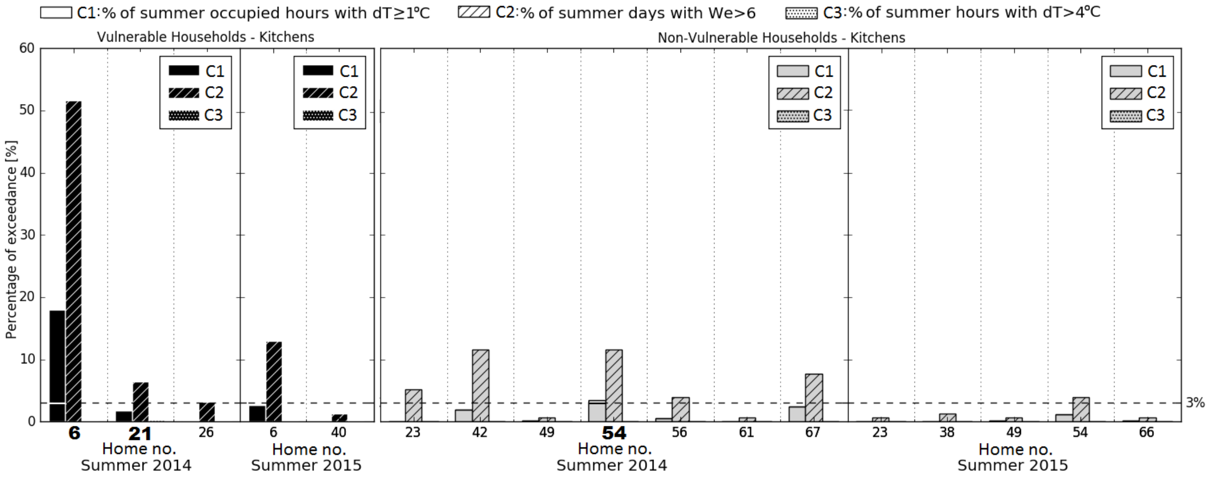

Figure 9 Percentage of exceedance for the 3 criteria (C1, C2 and C3) for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored kitchens for 2014 and 2015. Only rooms failing at least one criterion are shown in the plot. The vulnerable kitchens represent 60% and 25% of the monitored sample, in 2014 and 2015 respectively. The non-vulnerable kitchens represent 60% and 30% of the monitored sample, in 2014 and 2015 respectively. Overheating rooms are indicated in bold.

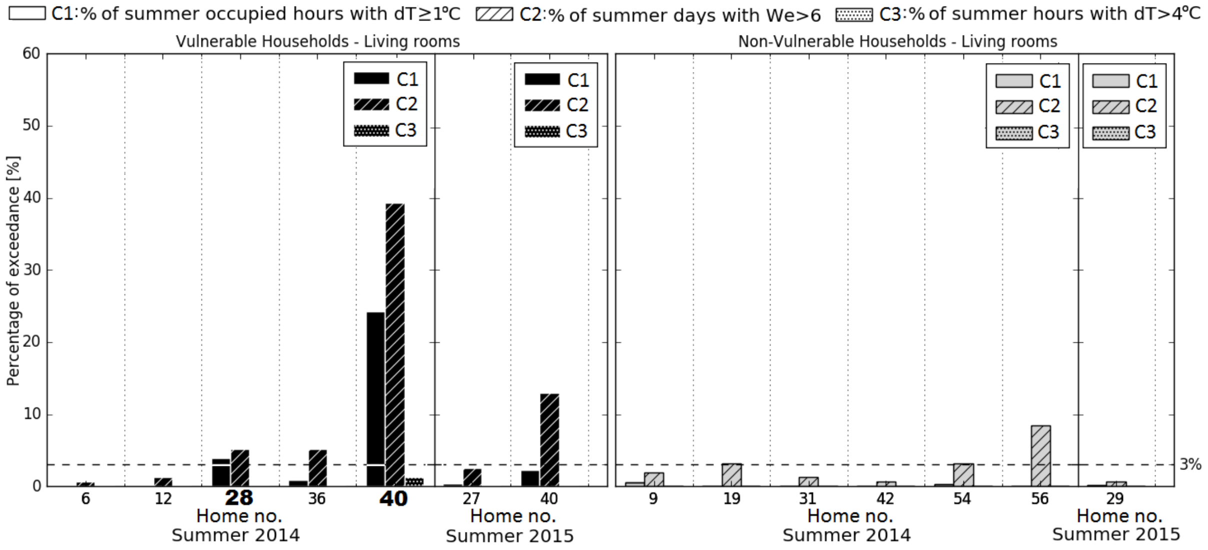

Figure 10 Percentage of exceedance for the 3 criteria (C1, C2 and C3) for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored living rooms for 2014 and 2015. Only rooms failing at least one criterion are shown in the plot. The vulnerable living rooms represent 38% and 20% of the monitored sample, in 2014 and 2015 respectively. The non-vulnerable living rooms represent 21% and 5% of the monitored sample, in 2014 and 2015 respectively. Overheating rooms are indicated in bold.

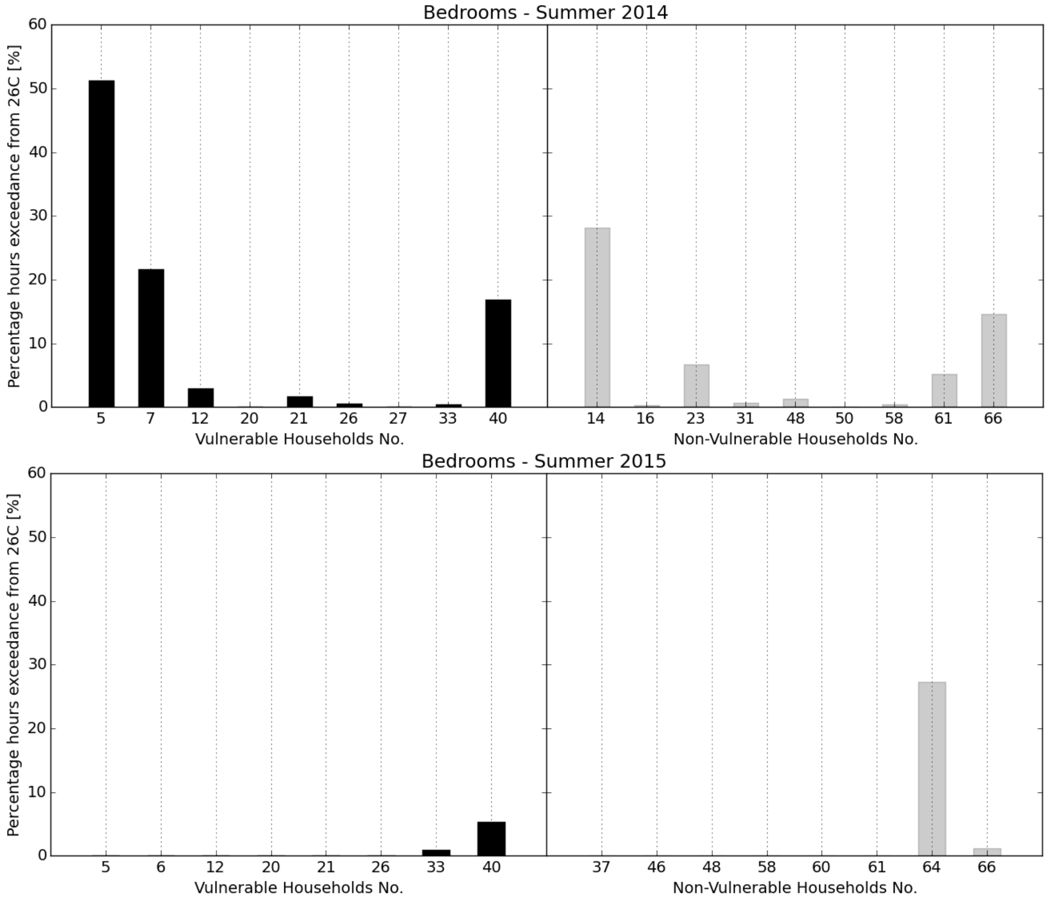

Figure 11 Percentage of exceedance from 26°C for both Vulnerable and Non-Vulnerable Households in the monitored bedrooms for 2014 (above) and 2015 (below).

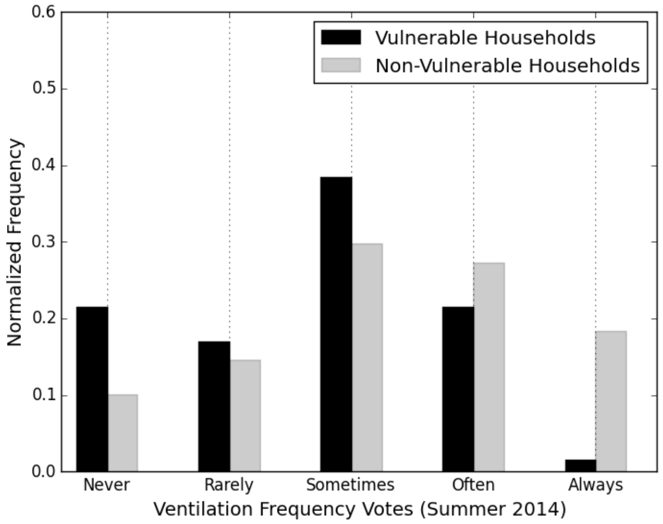

Figure 12 Ventilation frequency votes for Vulnerable and Non-Vulnerable Households (summer 2014).

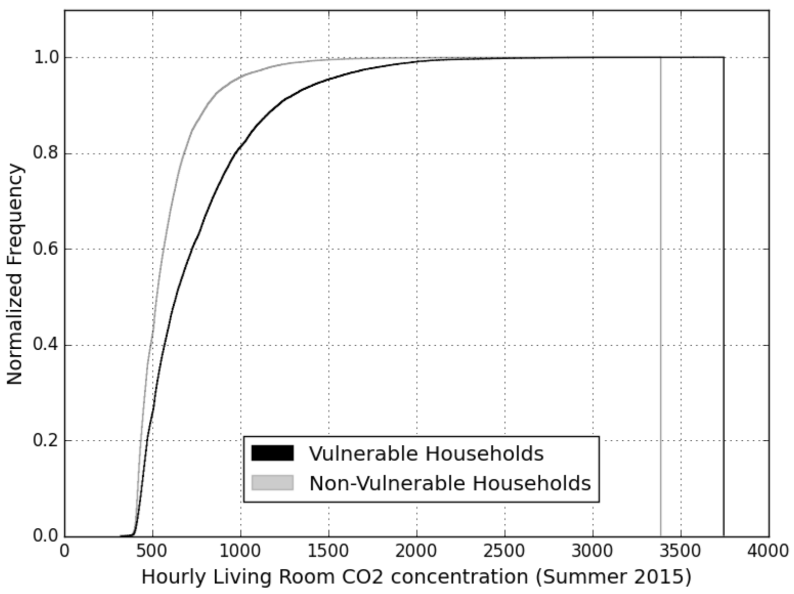

Figure 13 Cumulative histogram of hourly monitored CO_2 concentration for Vulnerable and Non-Vulnerable Households (summer 2015).

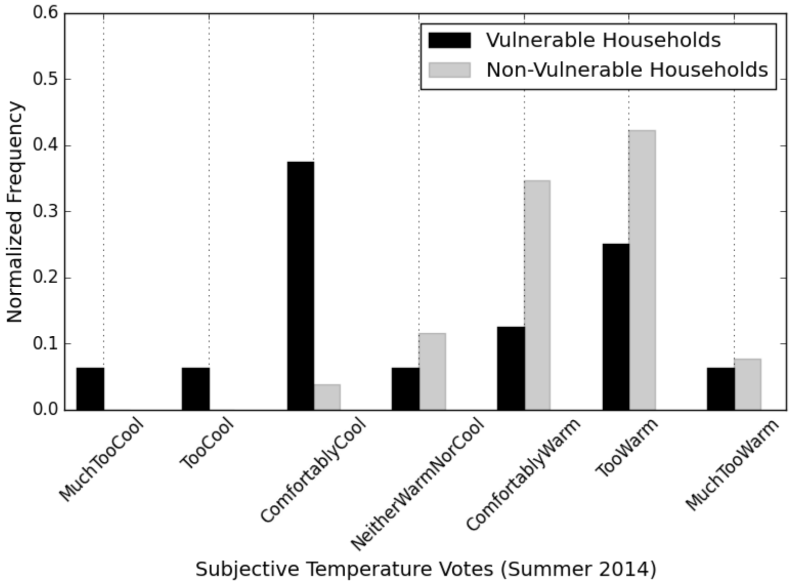

Figure 14 Subjective temperature votes for Vulnerable and Non-Vulnerable Households (summer 2014).

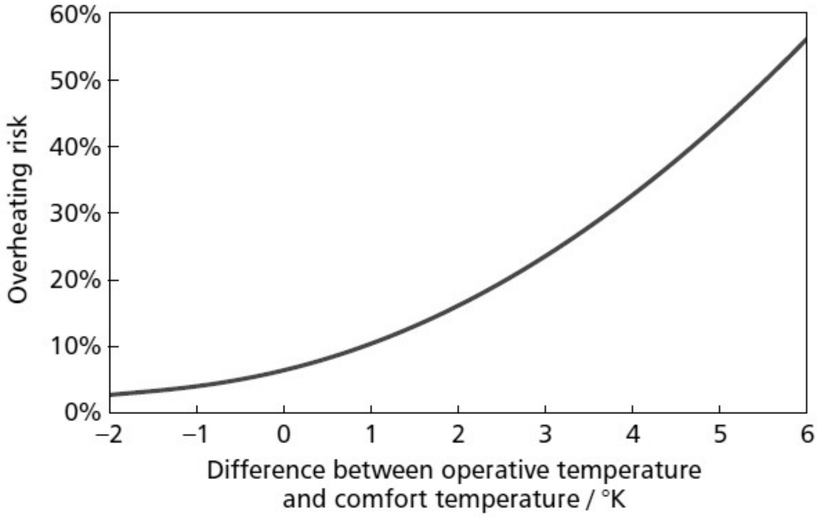

Figure 15 Proportion of subjects voting 'Warm' or 'Hot' on the ASHRAE scale (overheating risk) as a function of the difference dT between indoor operative temperature and comfort temperature (Nicol and Humphreys, 2007).

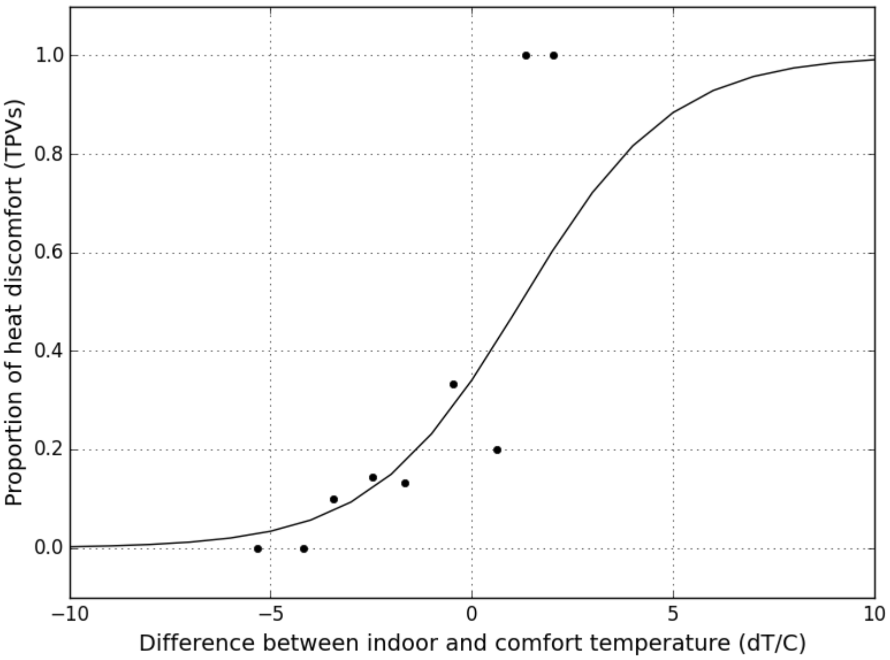

Figure 16 Proportion of subjects voting 'Much cooler' or 'A bit cooler' as a function of the difference dT between indoor temperature and comfort temperature.

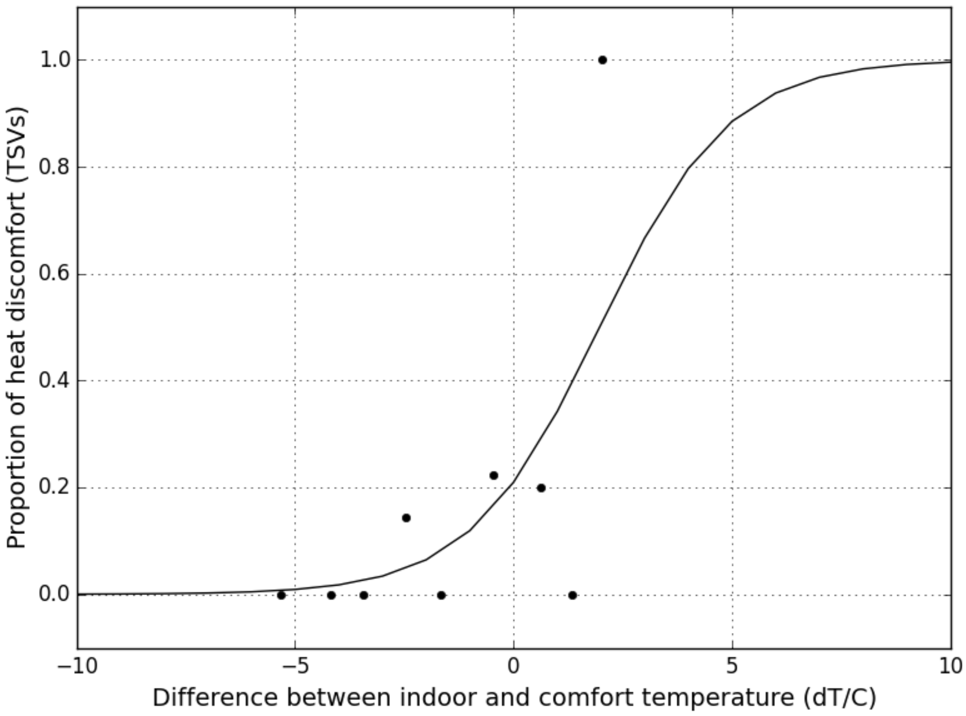

Figure 17 Proportion of subjects voting 'Warm' or 'Hot' as a function of the difference dT between indoor temperature and comfort temperature.

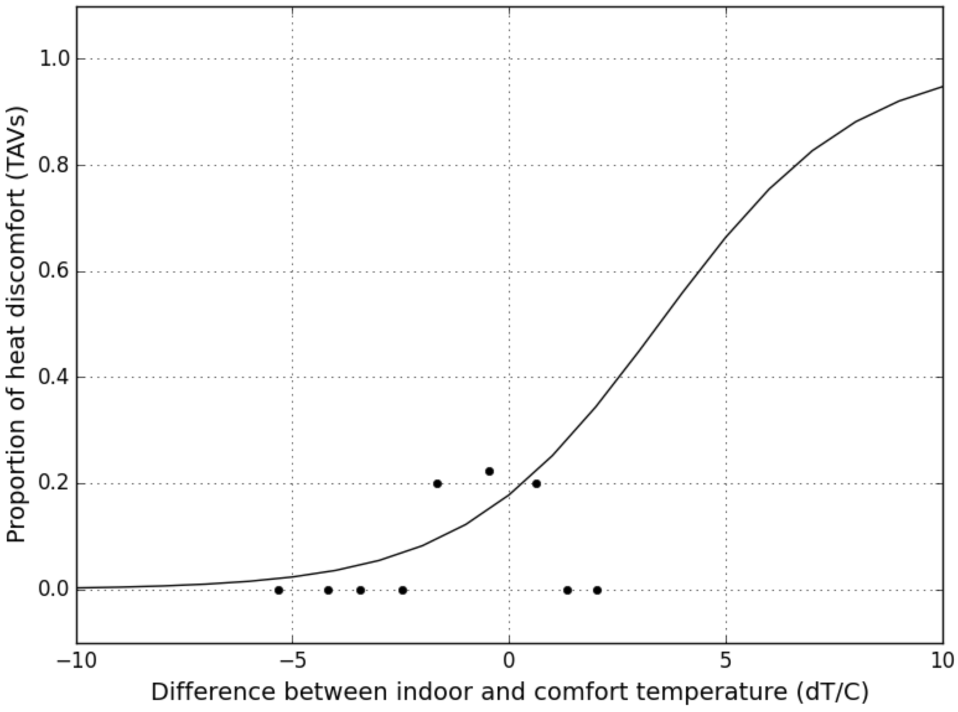

Figure 18 Proportion of subjects voting 'Just unacceptable' or 'Clearly unacceptable' as a function of the difference dT between indoor temperature and comfort temperature.

Table 1 Sensors.

Parameter	**Range**	**Accuracy**
DS18B20 temperature sensor (used for both air and radiator surface temperature measurements)	-10 – +85°C	±0.5°C
RHT03 humidity sensor	0 – 100%	±2%
K30 Senseair CO_2 sensor	0 – 5000	±30ppm
HC-SR501 PIR Infrared Motion Sensor	120°, 0 - 7m	n.a.

Table 2 Paper questionnaire.

This summer, when the weather was warm, how did you find the temperature in your home?	
1 = Much too cool, 2 = Too cool, 3 = Comfortably cool, 4 = Neither warm nor cool, 5 = Comfortably warm, 6 = Too warm, 7 = Much too warm	
When you open the windows in your home, how often is it for the following reasons?	
To cool your home down	1, 2, 3, 4, 5
To get rid of smells or smoke	1, 2, 3, 4, 5
To get rid of moisture	1, 2, 3, 4, 5
When a room is too stuffy	1, 2, 3, 4, 5
Because you are drying clothes	1, 2, 3, 4, 5
1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Always	
How often do you (or someone else in your household) open windows on opposite sides of the building to get a draught flowing through your home?	
1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Every day	

Table 3 Telephone questionnaire.

Current clothing	Could you generally describe what are you currently wearing?
Activity level	In the last 30 minutes before we started this conversation, how would you describe what you were doing?
Occupied room	In the last 30 minutes before we started this conversation, which room of your home were you in for most of that time?
Thermal sensation vote (TSV)	How are you feeling right now? Measured on the ASHRAE seven-point Likert scale.
Thermal preference vote (TPV)	If you could change the current temperature in your home, what would you prefer it to be? Reported on Nicol's scale: -1 (much cooler), -0.5 (a bit cooler), 0 (no change), 0.5 (a bit warmer), 1 (much warmer).
Thermal acceptability vote (TAV)	What do you think about the temperature of your home right now? Reported in the scale: 1 (clearly acceptable), 2 (just acceptable), 3 (just unacceptable), 4 (clearly unacceptable).
Perceived temperature control	How well do you feel that you can control the temperature in your home right now? Reported in the scale: 1 (no control), 2 (light control), 3 (medium control), 4 (high control), 5 (total control).
Sleep quality	At night-time, do you find that it is difficult to sleep because the temperature in your bedroom is too high? Reported in the scale: 1 (not difficult at all), 2 (slightly difficult), 3 (very difficult).

Table 4 Historic average meteorological temperatures.

Month	Averages for 1981-2010			2014	2015
	Max (°C)	Min (°C)	Mean (°C)	Mean (°C)	Mean (°C)
May	16.8	7.6	12.2	13	12.4
June	19.8	10.5	15.15	16.5	15.1
July	21.7	12.4	17.05	18.1	16.5
August	21.5	12.3	16.9	15.7	16.2
September	19.2	10.3	14.75	15.8	13.8

Table 5 Results of the four-way ANOVA and descriptive statistics for the two summers.

Group1 vs. Group2 vs. Group3	Summer	No. Rooms Group1	No. Rooms Group2	No. Rooms Group3	Mean±Std Group1 (°C)	Mean±Std Group2 (°C)	Mean±Std Group3 (°C)	Significance of difference	Stat. Test	P Value
S vs. N	2014	39	37		23.3±1.5	23.5±1.5		No	Four-way ANOVA	0.4
RE vs. LF		29	47		24.1±1.5	22.9±1.4		Strong		0.009
V-O vs. nV-nO		38	38		23.7±1.4	23.1±1.5		Weak		0.076
K vs. Lr vs. Br		17	41	18	23.9±1.3	23.1±1.5	23.4±1.7	Weak		0.078
S vs. N	2015	35	37		22.6±1.1	22.5±1.4		No	Four-way ANOVA	0.5
RE vs. LF		33	39		22.7±1.2	22.5±1.3		No		0.42
V-O vs. nV-nO		40	32		22.6±1.1	22.5±1.3		No		0.93
K vs. Lr vs. Br		25	31	16	23±1	22.2±1.2	22.5±1.4	Strong		0.049

S: Rooms with at least 1 window façade facing south, between 90 and 270°, N: The remaining rooms facing north.
RE: Roof-exposed rooms, LF: The remaining rooms in the lower floors. V-O: Rooms in vulnerable or overcrowded households, nV-nO: Rooms in non-vulnerable and non-overcrowded households. Lr: Living rooms, Br: Bedrooms, K: Kitchens.

Table 6 Results of statistical tests for ventilation frequency votes, subjective temperature votes and CO$_2$ concentration.

Groups	Items	Mean±Std Group 1	Mean±Std Group 2	Significance of difference	Statistical Test	P Value
V vs. nV	Ventilation frequency votes	2.6±1.1	3.3±1.2	Strong	*Mann-Whitney test*	1.9E-04
V vs. nV	Cross ventilation frequency votes	2.5±1.3	2.2±1.8	No	*Mann-Whitney test*	0.3
V vs. nV	Subjective temperature votes	4.1±1.7	5.4±0.9	Strong	*Mann-Whitney test*	0.01
V vs. nV	CO$_2$ concentration	751±173 ppm	589±94 ppm	Strong	*Mann-Whitney test*	0.007

V: Vulnerable Households, nV: Non-Vulnerable Households.

Table 7 Usable (○) and unusable (x) sensors for each dwelling during the two summers.

Home No.	Summer 2014				Summer 2015				
	Lr	Br	K	R	Lr	Br	CO_2	K	R
1		x	x						
2	x								
3			x		x	x		x	
4	○		○						
5		○		○	○	○		○	○
6	○		○	○	○	○	○	○	○
7	○	○		○	x	x	○	x	○
8	x	x	x	x	x	x	○	○	○
9	○	x		○					
10	○			○					
11	○		x	x	x		x	x	x
12	○	○	x		x	○	x	x	
13	○			○	○		○		○
14	○	○	x	○	○	x	○	x	○
15	○		x	○					
16	○	○	○	x	x	x	x	○	x
17	x		x	○	○			x	○
18	○		x	○					
19	○		○		x		x	○	
20	x	○	○	○	x	○	○	○	x
21	x	○	○	○	○	○		x	○
22	x	x	x	x					
23	x	○	○		○	x		○	
24	○		x	x	○		○	○	○
25	○		○	○	x		○	x	x
26	○	○	○	x	○	○	○	○	○
27	○	○	x	○	○	x	○	x	○
28	○			○	○		○		○
29	x			○	○		x	○	○
30	○	x	○	○	○	x		x	○
31	○	○	x	○	x	x			x
32	x		x	○					
33	○	○		○	○	○	○	○	○
34					x		x	x	x
35	x			○	○		x		x
36	○			○					
37	x		x	○	x	○		x	x
38	○	x	x	x	○	x	○	○	○
39	x		x	x				x	x
40	○	○		○	○	○	x	○	○
41	○		x	○	○		x	x	○
42	○	x	○	○	○	x		x	○
43	x	x		x					
44	○		x	x	x	x	○	x	○
45	x				x		x	x	○
46	○	x	x	○	○	○		x	○
47	○		x		○		○	x	○
48	○	○		○	x	○	○	○	○
49	○	x	○	○	○			○	x
50	x	○		○	x	x	x		x
51					x		○	○	○
52	x	x	x	x	x	x		x	x
53	○			○	○		x	x	○
54	○		○	○	○			○	○
55	○				○		○	○	○
56	○		○		○		x	○	
57	x	x		x					
58	x	○	x	x	x	○	○	x	○
59	x	x	x	x	x			○	○
60			x		x	○	x	○	○
61	○	○	○	○	○	○		○	○
62	x		x						
63	○		○	○	○		○	○	○
64	○	x	x	○	○	○	○	x	○
65	x	x		x	x	x	x	x	x

66	o	o	x	o	o	o		o	o
67	o	x	o	o	o	x	x	x	o
68	o	x	x	o	x	x		o	o

Lr: Living room, Br: Bedroom, K: Kitchen, R: Radiator, CO_2: Living room CO_2

Table 8 House and household characteristics. An empty space means that the information is not available.

Home No.	**Built Type**	**Construction Year**	**Insulated Loft**	**Floor Area [m^2]**	**Wall Type**	**Vulnerable Household**	**No. of Occupants**	**Participated 1st Survey**	**Participated 2nd Survey**	**Status Heating in 2014**	**Status Heating in 2015**
4	TH	1958	Y	99	CW	N	4	N	N		
5	LRF	1978	Y	53	CW	Y	1	Y	Y	ON	ON
6	SDB	1978	N	60		Y	1	Y	Y	ON	ON
7	TH	1962	Y	99	CW	Y	3	Y	Y	ON	OFF
8	LRF	1959		84	CW	N	4	Y	N		OFF
9	LRF	1962		70	CW	N	6	Y	N	OFF	
10	TH	1962	Y	99	CW	N	3	N	N	OFF	
11	SDH	1933		95	CW	N	3	N	Y		
12	LRF	1959		84	CW	Y	3	Y	Y		
13	SDH	1932		95	CW	N	4	N	Y	OFF	OFF
14	SDH	1929	Y	102	CW	N	6	N	N	ON	ON
15	LRF	1980		60	CW	N	5	Y	N	ON	
16	LRF	1980		60	CW	N	3	Y	N		
17	TH	1979		100	CW	N	3	N	N	OFF	OFF
18	ETH	1958	Y	99	CW	Y	2	Y	N	ON	
19	SDH	1932	Y	95	CW	N	6	N	N		
20	SDH	1959	Y	79	CW	Y	3	Y	N	ON	
21	SDH	1932	Y	73	CW	Y	1	N	N	OFF	ON
23	LRF	1960		84	CW	N		N	N		
24	SDH	1989	Y		CW	N	5	Y	N		OFF
25	DH	1989	Y		CW	N	3	Y	Y	OFF	
26	TB	1990	Y	75	CW	Y	1	Y	Y		OFF
27	LRF	1957		84	CW	Y	1	Y	Y	ON	ON
28	LRF	1952		50	CW	Y	1	Y	Y	ON	ON
29	ETH	1950	Y	112	CW	N	6	Y	N	OFF	OFF
30	LRF	1977		55	CW	N	1	Y	Y	OFF	OFF
31	LRF	1962	Y	70	CW	N	4	Y	N	ON	
33	TH	1933	Y	102	CW	Y	2	Y	Y	ON	OFF
35	SDH	1929		95	CW	N	2	Y	Y	ON	
36	SDH	1929	Y	95	CW	Y	2	Y	N	ON	
37	TH	1937	Y	102	CW	N	6	N	N	OFF	
38	TH	1935	Y	102	CW	N	5	N	Y		OFF
40	LRF	1967	Y	49	CW	Y	1	Y	Y	OFF	OFF
41	SDH	1933	Y	102	CW	Y	2	Y	Y	ON	ON
42	SDH	1937	Y	95	CW	N	3	Y	N	OFF	OFF
44	LRF	1975		70	CW	Y	3	N	N		OFF
46	ETH	1989	Y	74	CW	N	2	Y	N	OFF	OFF
47	LRF	1975		53	CW	N	2	Y	Y		ON
48	DH	1969	Y	95		N	4	Y	N	ON	OFF
49	LRF	1974	Y	70	CW	N	3	N	N	ON	
50	DH	1968	Y	77	CW	N	3	Y	N	OFF	
51	SDH	1929	Y	95	CW	Y	1	Y	N		OFF
53	LRF				CW	N	4	Y	Y	OFF	OFF
54	LRF	1939	Y	42	CW	N	1	Y	N	OFF	OFF
55	LRF	1937		61	CW	N	2	Y	Y		ON
56	LRF	1975	Y	70	CW	N	1	Y	N		
58	LRF	1971		83		N	2	Y	N		OFF
59	TH	1954		112	CW	N	3	Y	N		OFF
60	LRF	1959		84	CW	N	6	N	N		ON
61	ETH	1950	Y	112	CW	N	5	Y	N	OFF	OFF
63	SDH	1948	Y	97	CW	Y	2	Y	N	OFF	ON
64	LRF	1967		68	CW	N	1	Y	N	OFF	OFF
66	SDH	1936	Y	111	CW	N	3	Y	N	ON	ON
67	SDH	1936	Y	111	CW	N	3	Y	Y	ON	OFF

68	SDH	1935	Y	95	CW	N	4	N	N	OFF	OFF

TH: Terraced House, ETH: End Terrace House, LRF: Low-rise Flat, SDB: Semi-Detached Bungalow, SDH: Semi-Detached House, DH: Detached House, TB: Terraced Bungalow, CW: Cavity Wall