The Role of Air Motion for Providing Thermal Comfort in Residential / Mixed Mode Buildings: a Multi-partner Global Innovation Initiative (GII) Project

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Abstract

As the climate changes, global use of air-conditioning will proliferate as solutions are sought for maintaining thermal comfort in buildings. This rises alongside increased purchasing power as economies grow, harbouring the potential to unleash an unprecedented growth in energy demand. Encouraging higher levels of air movement at warmer temperatures to maintain thermal comfort may offset the risk of increased air-conditioning use. Whilst laboratory studies have quantified air motion effects on the human body, it remains unclear as to how best to incorporate higher air motion in the design and operation of residential / mixed mode buildings to offset air-conditioning use.

The project reported is developing a better understanding of thermal comfort in residential /mixed mode buildings and is identifying the potential for higher air movement for providing energy-efficient comfort. Co-ordinated field surveys in British and Indian residences of thermal conditions, sensations and air motion practices have been conducted. The data generated will contribute to a worldwide database, and will inform validation of a coupled thermal comfort / airflow model for designing comfortable, energy-efficient indoor environments that exploit higher air motion. This paper describes the overall project, and presents preliminary findings from the British residential field survey.

Keywords

Thermal Comfort, Residential/mixed mode, Field Studies, air motion, database

1. Introduction and Background

A growing body of evidence has established links between climate change and the carbon dioxide (CO_2) emissions that arise from energy production and consumption. In 2010, annual CO_2 emissions from the building sector were 9500 Mt, equating to one-third of the world's total CO_2 emissions (IEA, 2011). Amongst the top 10 emitting countries in 2010, the US was second, India was third and the UK was tenth.

The energy used for space cooling and heating accounts for the majority of CO_2 emissions from buildings; up to 43% in the US (Levine et al 2012), 50% in India (Kapoor et al, 2011) and 60% in the UK (Palmer and Cooper, 2011). Demand for this energy is driven by the basic human need for thermal comfort and good indoor air quality (IAQ), supplied via a suitable ventilation strategy to maintain the health and wellbeing of occupants. The evidence is clear that it is critically important to address buildings if we are going to make a difference in global energy use and its subsequent effect on climate change and the environment.

With people typically spending 90% of their time indoors, the qualities of the indoor environment, such as thermal comfort and IAQ, can have a significant impact on people's health and well-being. With a changing global climate, current energy-intensive paradigms for conditioning indoor environments have the potential to unleash an unprecedented growth in energy demand in the next few years. The challenges and potential solutions are somewhat different in the residential and commercial building sectors, but both are critically important for affecting society at large. The combination of global warming and increase in purchasing power by growing economies bring forward a serious threat that air-conditioning will proliferate throughout the global residential sector, with potentially disastrous consequences for further energy demand and climate change. The global electricity consumption for home cooling is predicted to rise eightfold by 2050 (Isaac and Van Vuuren, 2009). Within India alone, a 20% annual growth rate in air-conditioning for the past decade has been reported, and it is estimated that by 2030 nearly 200 million air-conditioning units will be in service – an increase of almost 40 times the current number. Part of the solution for minimizing residential air-conditioning is likely to include encouraging higher levels of air movement at warmer temperatures, but although there are enough laboratory studies to quantify its effect on the body, it is still not clear how to best incorporate it in the design and operation of residential buildings in order to reduce air-conditioning use. An important reason for this lack of understanding is the inherently dynamic qualities of indoor air motion and the human response to it, which have been difficult to quantify.

To date, global understanding of thermal comfort and IAQ is well developed for commercial buildings that use air-conditioning (the most energy-intensive method of providing indoor comfort). Since the 1950s, such buildings have predominantly had sealed envelopes and require continuous mechanical conditioning. Natural ventilation, in which operable windows allow one to harness the forces of wind and temperature difference to provide comfortable indoor conditions, can deliver significant energy savings for many types of buildings when operated in conjunction with properly controlled air-conditioning. This arrangement is known as mixed-mode. However, the building industry lacks information on how to design these buildings in a contemporary context so that they perform well.

Existing building standards are very limiting in their guidance towards this approach. The current Adaptive Comfort Model in ASHRAE Std. 55 (ASHRAE 2013) incorporates findings that occupants perceive warmer and cooler indoor air temperatures as comfortable when the building allows them to adapt to outdoor weather conditions, and defines an expanded comfort zone for naturally ventilated buildings. However,

this standard does not apply to mixed-mode, severely limiting our industry's ability to use this energy-conserving strategy in building design. The evidence is clear that people are accepting of wider temperatures in naturally ventilated buildings, and the analysis to date suggests that this is only partially due to higher air movement and more adaptive clothing patterns. The other part is likely due to shifting thermal expectations and preferences resulting from having a degree of control over one's thermal environment, and having a more variable thermal history that is more closely connected to the natural swings of the outdoor climate. However, compared to naturally ventilated buildings, there has been relatively little comparable data collected in mixed-mode buildings that combine both operable windows and mechanical cooling. Without this information, it is difficult for standards to provide adaptive design guidelines for mixed-mode buildings.

Hence, the aim of our GII project is to develop a better understanding of human thermal comfort in buildings across the globe, and to identify and exploit opportunities for natural ventilation, mixed-mode strategies and other low-energy techniques that provide air movement, such as evaporative cooling, to reduce energy demand.

Field work is vitally important for capturing 'real world' behaviour that in turn supports modelling at the individual building and wider scale. It is the combination of field monitoring plus simulation that will finally enable us to better understand the unique transient and dynamic conditions in these low energy buildings that may very well be at the heart of how we can simultaneously achieve reduced energy consumption with enhanced thermal comfort. These two goals must be achieved in concert if we are going to have a real impact on mitigating climate change without sacrificing occupant well-being. These are the principal research approaches being adopted in this project, for the purpose of reducing global energy demand and carbon impact.

2. Aims and Objectives

To date, literature on thermal comfort field-based investigations in residential settings is relatively limited compared to the significant volume currently available for non-residential buildings (Attia and Carlucci, 2015). This is to some extent understandable, given the challenges of trying to work in such private and personal environments as people's homes (Limbachiya et al, 2012). Nevertheless, such work is vital given the significant energy consumption of the residential stocks in many countries. The comprehensive review by Rupp et al (2015) discussed thermal comfort field studies in residential buildings in a number of countries, highlighting differences between reported thermal sensations and those predicted by the PMV approach, and the role played by adaptive behaviours. The paper also reports work by Zhang et al (2011) that proposes wider ranges of indoor temperature in HVAC (mixed mode) buildings achievable through the use of ceiling and personal fans. Peeters et al (2009) suggest that a wider range of conditions than those of the adaptive model might be considered acceptable in residential environments. With regard to the use of air motion, Huang et al (2013) report survey and chamber work in China. Whilst no residential field work was conducted, it suggests that thermal neutrality could be achieved in residential buildings at temperatures up to 32C.

However, Wang et al (2010) report survey work involving air movement sensation and preferences with families in naturally-ventilated residential buildings in Harbin, China, showing that air motion has a positive effect on thermal sensation. Indraganti (2010) also describes use of air movement and diverse adaptation mechanisms for providing comfort in Indian apartment buildings. As far as the authors are aware, no studies to date have specifically investigated air motion practices in UK residences, in relation to thermal comfort.

Given the preceding background, funding was secured from the British Council for a research project of 30-months duration (April 2014 – September 2016) bringing together an international partnership to investigate thermal comfort, and the potential for higher air motion, in residential / mixed mode buildings within an international comparative context.

The overall aim of the project is to develop a better understanding of human thermal comfort in residential buildings in an international comparative context, identifying and exploiting opportunities for higher air motion (natural ventilation, mixed-mode and other approaches) to reduce energy demand.

The specific objectives of the project are as follows:

- To gather data for understanding thermal conditions, thermal comfort and occupant responses in residential/mixed mode environments internationally, for contributing to a world-wide field study database to be made public for use by other researchers and students.

- To conduct field surveys in residential buildings in India and the UK, and utilise an existing coupled thermal comfort/air flow model alongside dynamic thermal simulation to assess the ability of a range of low energy techniques that employ higher air motion to deliver comfort and energy savings.

- Using the outcomes from the preceding objectives, to develop new insights and data for an international database that can lead to approaches and guidelines for such environments on conditions for thermal comfort so as to promote lower energy approaches for heating, cooling and ventilation, minimising unnecessary use of air conditioning.

In terms of partnership roles, residential field studies are being conducted by CEPT, De Montfort and Loughborough Universities, the latter two partners also responsible for coupled thermal comfort / airflow model development and dissemination. Database compilation and analysis is being conducted by UC Berkeley, with overall project management by Loughborough.

3. Methodology

Field studies were designed to gather data about thermal sensations, environmental conditions and air motion practices, in order to understand availability of, and occupant utilisation of, opportunities for use of air motion within buildings. The additional purpose was to supply data for the UC Berkeley database. The field studies were conducted in two countries, India and the UK, allowing coverage of both natural and mixed-mode ventilation strategies within a residential context. At the same time the arrangement afforded the opportunity to compare behaviours

and responses in two different climates and in an international context. The approach adopted combined detailed subjective data gathering alongside objective monitoring of indoor and outdoor thermal conditions in people's homes.

3.1 Recruitment of Participants & Residences

Participants were recruited initially for a six-month study (with the possibility of extension), via the use of leaflets and 'word of mouth'. Family members comprised of adults and children across the age range 7-75 years, with consent from adults and assent from children being gained in line with full ethical requirements. An information leaflet, and a screening survey to obtain preliminary information about the homes and occupants, were designed and helped support sample selection. For the UK, the sample of residences for the study were located in the East Midlands within a fifteen-mile radius of the town of Loughborough, with two additional households located in Yorkshire. Climatic conditions experienced are 'temperate oceanic' as described in the Koppen Climate Classification (Wikipedia 2016). For India, the sample of residences were located in the city of Ahmedabad, Gujarat, a 'hot semi-arid climate region' (Wikipedia 2016)

3.2Residences Description

Twenty residences were recruited for the India part of the study, comprising sixteen apartments (mainly 2-3 bedrooms) and four independent houses (two-storey, with three or more rooms per floor). These represent the typical housing typology prevalent in most cities in India. As preferred in most Indian residences, the approach for ventilation is mixed-mode, involving natural ventilation and the availability of air-conditioning (split units) to manage summer peak outdoor conditions. The UK study was made up of fifteen residences composed of a mixed sample of housing types giving a reasonable reflection of the national stock composition, though with some under-representation of terraced housing when compared to recent UK Government stock profile figures (DCLG 2013). However, this was not considered to unduly affect the study. More importantly for this study, in UK homes natural ventilation via windows and doors is the dominant mode, though there is some growth of mechanical ventilation with heat recovery (MVHR) and occasional instances of whole house or localised room air conditioning. The UK sample has attempted to capture this range of air motion capabilities. Table 1 summarises details of the residences and participants.

Table 1: Residences and participants summary, India and UK field studies

Country	India	UK
Total residences surveyed	20	15
Residence type and storeys, floor locations	4 houses (2-storey) 16 apartments (9 on ground to 3rd floor; 4 on 4th and 5th floors; 3 on or above 6th floor)	1 terrace - (3-storey) 6 semi-detached - (5 are 2-storey and 1 is 3-storey) 6 detached - (5 are 2-storey and 1 is 3-storey) 1 flat

		(non-ground floor) 1 bungalow (ground floor)
Modes of ventilation	Mixed: natural via windows, doors, ceiling and pedestal fans, supplemented as required by evaporative air coolers and split-unit air conditioning	Natural: via windows, doors, worktop and pedestal fans. Instances of: MVHR (whole-house); air conditioning (whole house or conservatory-only); mechanical ventilation (no heat recovery)
Numbers of participants	42	31
Age ranges	16-74 years	7-75 ears

3.3 Data Gathering

Central to this was the design, trialling and evaluation of an advanced questionnaire and associated delivery / response mechanism. The questionnaire, titled the 'Home Thermal Comfort and Air Motion Survey' differed from those of previous field studies in four important respects: i) by asking about activities and behaviours immediately prior to, as well as at the time of, completion; this allowed estimation of closeness to thermal steady state at any given time, and related to activity, clothing and location within or outside the home; ii) by gathering details about availability and usage of air motion devices, and proximity (distance and direction) of the participant to those devices (includes windows, doors and equipment); iii) by gathering details about the presence or absence of any solar radiation incidence upon parts of the participant's body; iv) by remotely delivering and then collecting participant responses using digital media, important for minimising disruption for people in their own homes (though paper-based versions can be used where acceptable). In other respects, the questionnaire was similar to standard field study approaches (seeking participant responses on features that included thermal sensation, acceptability, preference, air movement and local discomfort).

It is essential to strike a balance between the level of detail that one might like from such a survey, and the level of inconvenience that this might impose upon participants, especially given the challenging nature of the environment in question – the participant's own home. We therefore devised a method for remote delivery, completion and collection of the survey using on-line techniques via home computer, 'tablet' and smartphone. This balance was achieved following rigorous pilot trials with volunteers (not study participants) aged 8-80 years, who provided feedback that enabled the survey tool to be finalised and rendered capable of completion in less than 10 minutes, thus encouraging retention of participants throughout the study. The survey can also be completed in paper format, if appropriate technology is not available.

Following an initial home visit by members of the research team, participants thereafter completed the survey on a (generally) weekly basis over a period of up to 9 months, commencing April 2015 and ending January 2016, capturing late spring, summer, autumn and early winter periods in the UK, and late summer, monsoon

(rainy season), autumn and winter periods in India. At the time of writing, UK data gathering has been completed and the homes de-commissioned of sensors, with the Indian homes still engaged in the field study. All discussion and results that follow relate to the UK field survey.

The visit allowed for a full thermal comfort survey to be conducted using a Dantec Dynamics 'ComfortSense system (compliant with EN 13182, ISO 7726 and 7730, and ASHRAE Standards 55 and 113). Calibrated sensors (HOBO U10 and Pendant 64K) were positioned and left in households for the duration of the study, to record air temperatures and relative humidities in living rooms, bedrooms and conservatory (where applicable). Specific measurements with the Dantec system confirmed similarity of air and mean radiant temperatures, and very low values for airspeed indoors in each home. At the end of the field study period, researchers again visited the homes, and carried out a 30-minute interview with the participants to ascertain the representativeness of their on-line responses over the study period to their residential living behaviour in general.

4. Preliminary Results & Discussion

The majority of the UK participants completed the Home Thermal Comfort and Air Motion Survey online, with only two participants preferring to use paper versions. In India, reliable access to the internet or mobile technology could not be guaranteed for all participants, and so all completions were paper-based. Consequently, Indian survey data are still being processed and reported on later, and so results presented here are the preliminary findings from the UK field study only, with analysis continuing of the 'cleaned' data gathered.

The online method for delivery, completion and collection proved to be very successful, with all 31 UK participants in 15 homes, resulting in 509 individual responses between April and December 2015. Of the 509 responses, 47% were completed by females, with 53% completed by males. In terms of ages of respondents, 100 completions (approx. 20%) were from participants in age range 7-16 years, and 409 completions (approx. 80%) from participants in age range 18-75 years. Table 2 shows house type, household make-up and ventilation category against identification number allocated.

Table 2: UK households participant composition, house type and ventilation category

House number	House type	Participants	Ventilation
1	Detached	2 adults (1m, 1f) 1 child (f)	Natural, plus air-conditioning of whole house
2	Semi-detached	2 adults (1m, 1f) 1 child (m)	Natural, plus air-conditioning in conservatory
3	Detached	4 adults (2m, 2f) 1 child (m)	Natural
4	Semi-detached	2 adults (1m, 1f)	Natural
5	Detached	2 adults (1m, 1f) 2 children (2f)	Natural
6	Detached	1 adult (m)	Natural
7	Semi-detached	2 adults (1m, 1f)	Natural
8	Semi-detached	2 adults (1m, 1f)	Natural
9	Flat	1 adult (f)	Natural
10	Detached	2 adults (1m, 1f) 1 child (m)	Natural
11	Semi detached	2 adults (1m, 1f)	Natural
12	Terraced	1 adult (m)	Natural and MVHR
13	Detached bungalow	1 adult (f)	Natural and MVHR
14	Semi detached	1 adult (m)	Natural and MV
15	Detached	1 adult (m)	Natural and MVHR

At the time of writing, it must be emphasised that the field data campaign in the UK ended only in the last few weeks (with India still continuing). This has generated a large, longitudinal, rich dataset gathered over a 9-month period, and comprised of reported thermal sensations and related factors. Analysis is in its early stages, but here we present a descriptive statistical overview of several key facets from the total of 509 responses to the survey. Thus, for the UK sample of 31 participants, for the period April-December 2015, at the instant of completion, findings to date are as follows.

4.1 Participant behaviours
In the majority of cases, survey completions took place in the living room and in the evening. Figure 1a and 1b show that the main and other activities taking place during the 15-minute period prior to survey completion were largely of a sedentary nature, the remainder illustrating a wide range of other residential activities. With respect to clothing, very little change (addition or removal) of items of clothing was reported during the 15 minute-period prior to survey completion (94% of the 409 adult responses showing no change). Clothing ensembles data gathered are extensive, but selecting one item from this (footwear), Figures 2a and 2b illustrate a predominant lack of any footwear in the home (slippers, shoes or socks) during the summer period, with an increase in socks-only during the autumn / winter period.
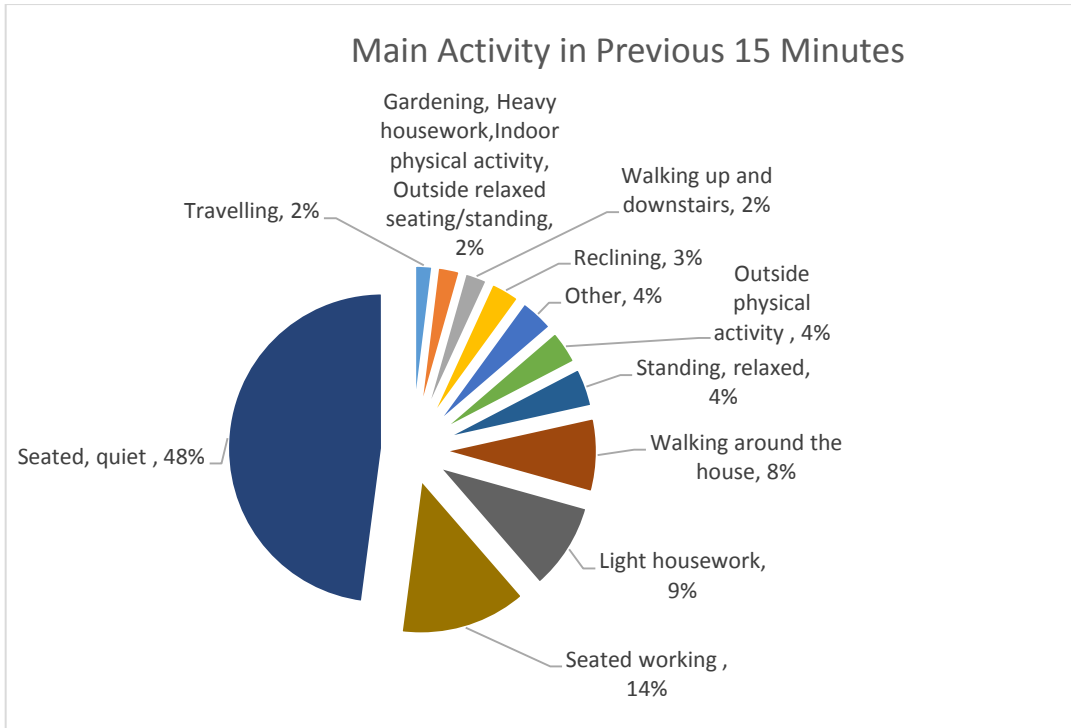
Main Activity in Previous 15 Minutes

Gardening, Heavy housework,Indoor physical activity, Outside relaxed seating/standing, 2%

Travelling, 2%

Walking up and downstairs, 2%

Reclining, 3%

Other, 4%

Outside physical activity , 4%

Standing, relaxed, 4%

Walking around the house, 8%

Seated, quiet , 48%

Light housework, 9%

Seated working , 14%

Figure 1a Main activity during 15 minutes prior to online survey completion based on the total of 409 adult responses) ('other' ranged from bathing to eating/drinking to DIY / car washing to opening windows)
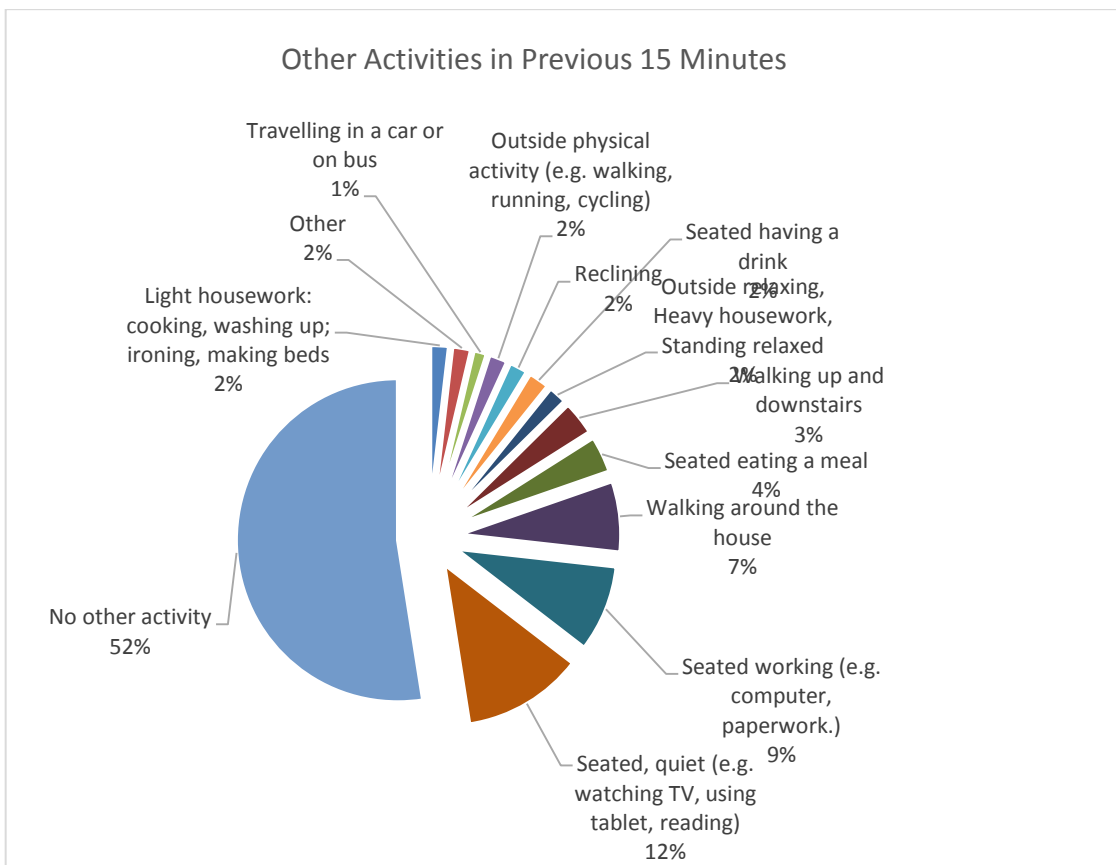
Other Activities in Previous 15 Minutes

Travelling in a car or on bus 1%

Outside physical activity (e.g. walking, running, cycling) 2%

Other 2%

Reclining 2%

Seated having a drink relaxing, 2%

Outside Heavy housework, 2%

Light housework: cooking, washing up; ironing, making beds 2%

Standing relaxed 2% Walking up and downstairs 3%

Seated eating a meal 4%

Walking around the house 7%

No other activity 52%

Seated working (e.g. computer, paperwork.) 9%

Seated, quiet (e.g. watching TV, using tablet, reading) 12%

Figure 1b: Other activities during 15 minutes prior to online survey completion based on the total of 409 adult responses.
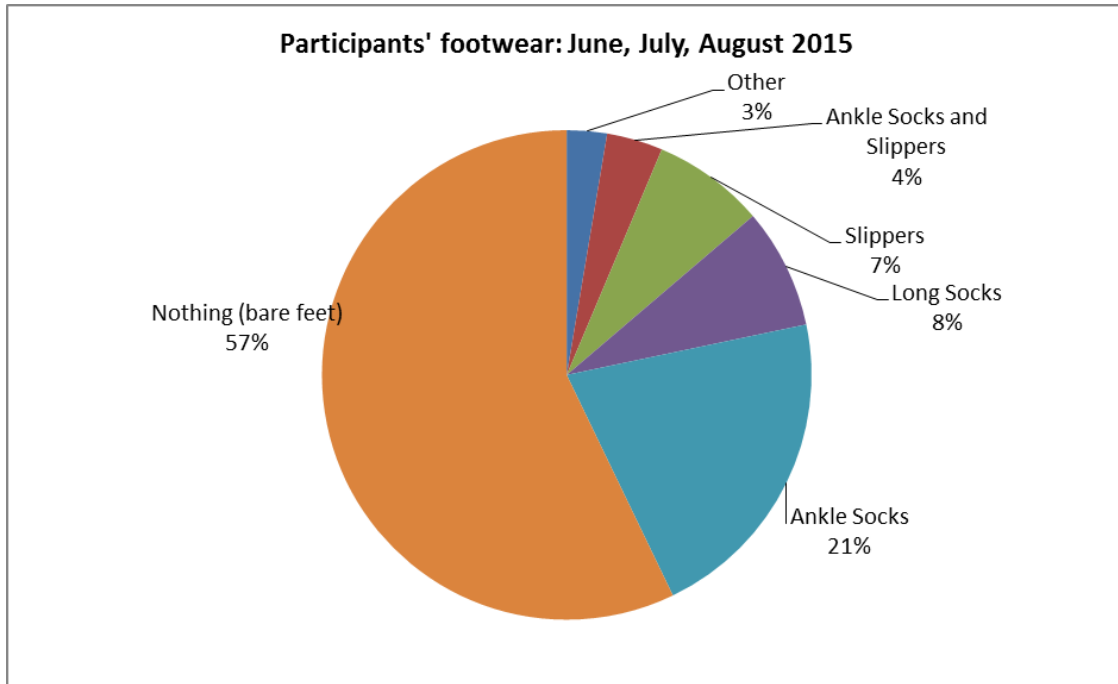
Participants' footwear: June, July, August 2015

Other 3%
Ankle Socks and Slippers 4%
Slippers 7%
Long Socks 8%
Nothing (bare feet) 57%
Ankle Socks 21%

Figure 2a: Participants' footwear at home, during summer period (June-August)

Participants' footwear: October, November, December 2015

Other 6%
Nothing (bare feet) 21%
Ankle Socks and Slippers 16%
Slippers 14%
Long Socks 16%
Ankle Socks 27%
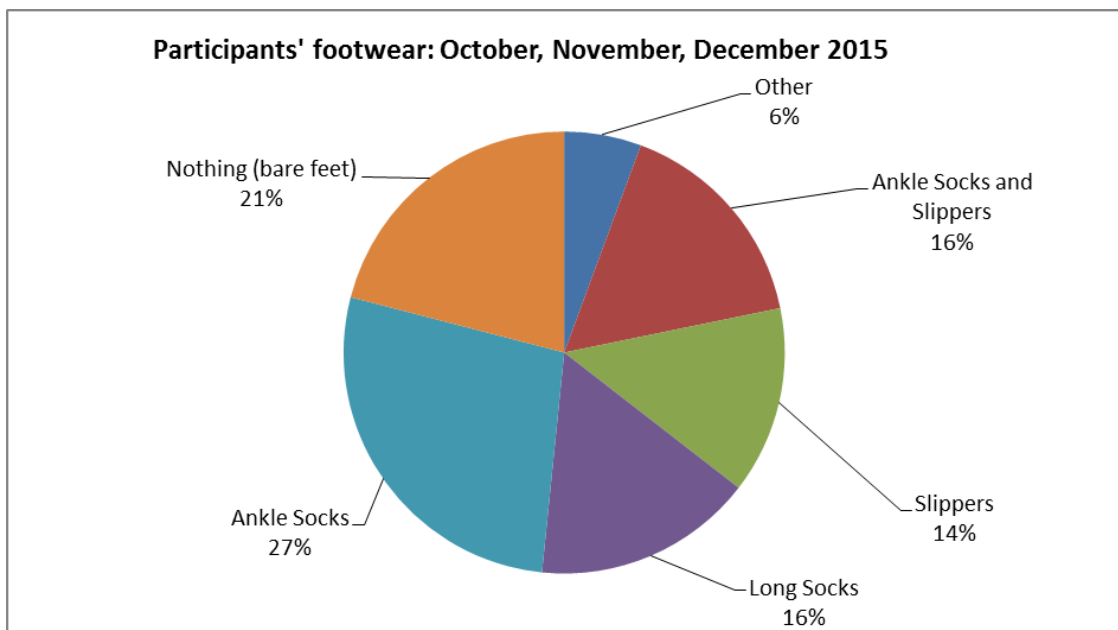
Figure 2b: Participants footwear at home during autumn / winter period (October-December)

4.2 Air motion practices

For responses from adults, Figures 3a and 3b present the reported usage of windows (as percentage of responses) in the room being occupied by the participant at the time of online completion for the summer period (June-August) and autumn/winter period (October-December) respectively.. Figures 4a and 4b present the reported usage of external doors (as percentage of responses) in the room being occupied by the participant at the time of online completion for the summer period (June-August) and autumn/winter period (October-December) respectively In the autumn/winter months Little or no use of fans was reported. Where devices (includes air-

conditioning as well as those that promote higher air motion) are reported, Figure 5 gives the percentage distribution of usage of these devices. It is clear that there has been little reported usage of means to promote higher air motion in the sample of homes during this period. It should be noted that the UK summer period of 2015 had relatively mild steady temperatures, with the only hot spells in late June / early July and in mid-August (see section 4.3 for further details). This might have inhibited air motion use for maintaining comfort, and further data is required.

Within the scope of this GII project, it was not possible to gather quantified airspeed data on a continual basis local to the participant. However, it was possible to determine details regarding the location of a participant in relation to the principal air motion device(s). This will be important for subsequent detailed airflow and sensation investigation currently in progress and scheduled to continue beyond the GII project funding period.
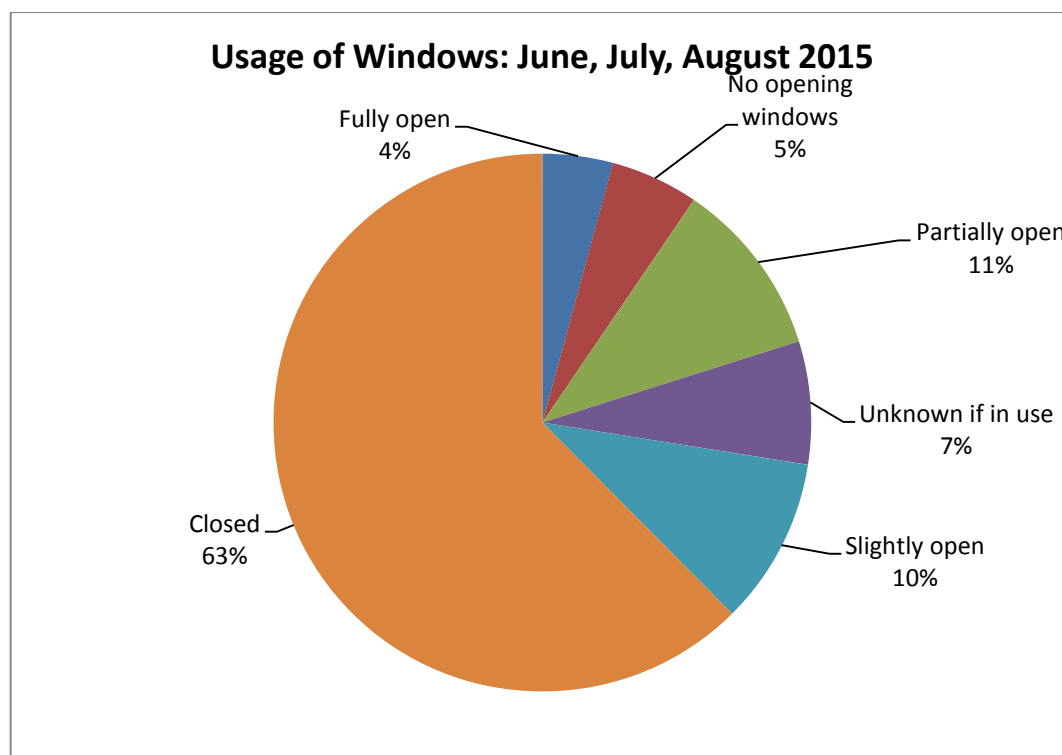

Figure 3a: Reported usage of air motion devices (windows) at time of online survey completion during summer period (June-August)
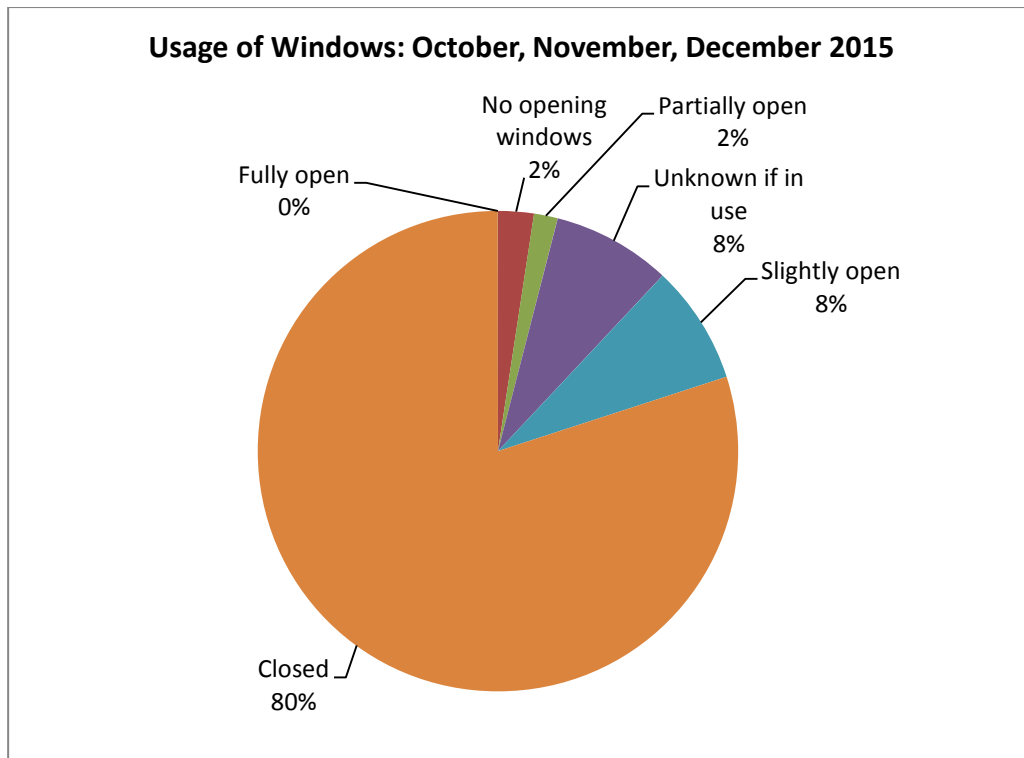
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Usage of Windows: October, November, December 2015

No opening windows 2%
Partially open 2%
Fully open 0%
Unknown if in use 8%
Slightly open 8%
Closed 80%

Figure 3b: Reported usage of air motion devices (windows) at time of online survey completion during autumn / winter period (October-December)
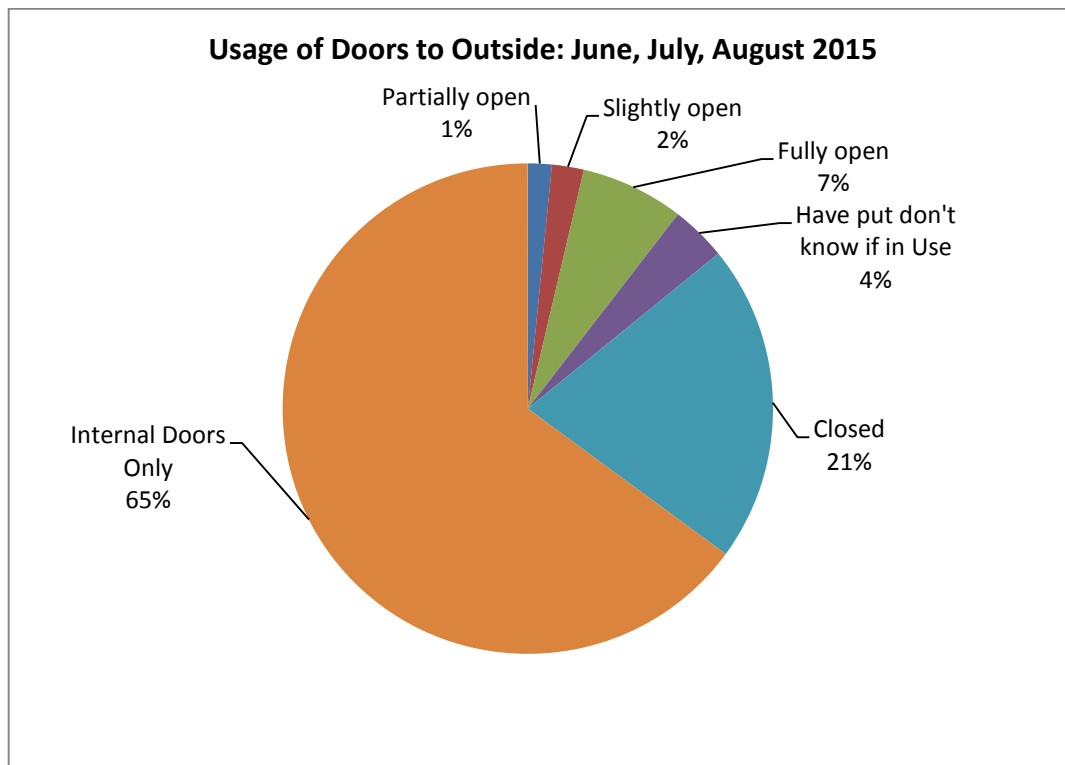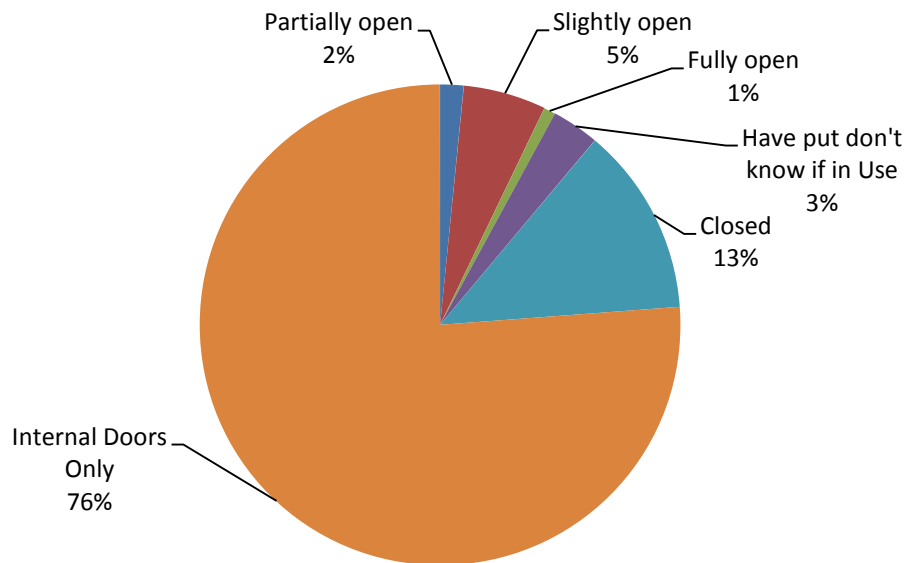
Usage of Doors to Outside: June, July, August 2015

Partially open 1%
Slightly open 2%
Fully open 7%
Have put don't know if in Use 4%
Closed 21%
Internal Doors Only 65%

Figure 4a: Reported usage of air motion devices (Doors) at time of online survey completion during summer period (June-August)

Usage of Doors to Outside: October, November, December 2015

Partially open
2%

Slightly open
5%

Fully open
1%

Have put don't
know if in Use
3%

Closed
13%

Internal Doors
Only
76%

Figure 4b: Reported usage of air motion devices (Doors) at time of online survey completion during autumn / winter period (October-December)
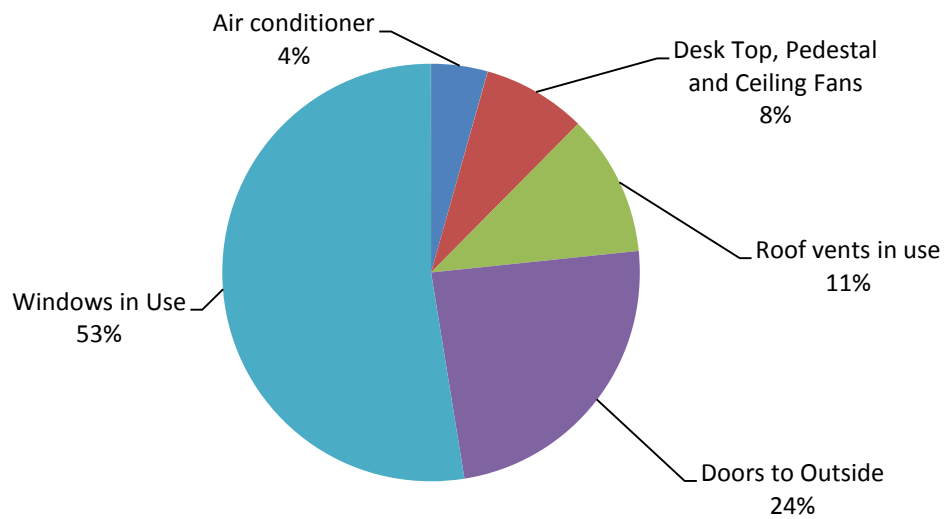
Methods of 'Cooling'

Air conditioner
4%

Desk Top, Pedestal
and Ceiling Fans
8%

Roof vents in use
11%

Windows in Use
53%

Doors to Outside
24%

Figure 5: Where devices are reported as being used for 'cooling' (includes air motion and air-conditioning), percentage distribution of usage of devices

4.3 Actual thermal sensations

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Figure 6 presents actual mean votes (AMV) of all participants aged 18-75 years reported over the entire period April-December 2015, expressed as a time series. Figure 7 shows a similar time series of the AMVs of participants aged 7-16 years, while Figure 8 presents a histogram of average adult household AMV for each house (as identified by its allocated number - refer to Table 2) for the 'warmer' (June, July and August) and the 'cooler' (October, November and December) periods. Preliminary inspection suggests that the majority of responses lie within a range +1 to -1 AMV, and outside this range there are more 'warmer' than 'cooler' responses. The range in the outdoor temperatures measured hourly in Loughborough for the period April-December 2015 was approximately 5-20C, with an average around 12C, a period popularly noted that year for its fairly consistent 'mildness', except for a 'hot' spells in late June to early July, and around mid-August (measured peak temperatures of 33.6C on 1 July, and 28.1C on 22 August).

Monitored data from the sensors placed in rooms in the 15 UK houses is currently being collated with the subjective data gathered for analysis. A similar process is underway for the data gathered in the Indian field survey. These will be supplied to the UCB database for overall analysis alongside other field studies. A significant dataset has been generated from the UK and India residential field studies, and this will be analysed in detail over coming months and beyond the GII project.
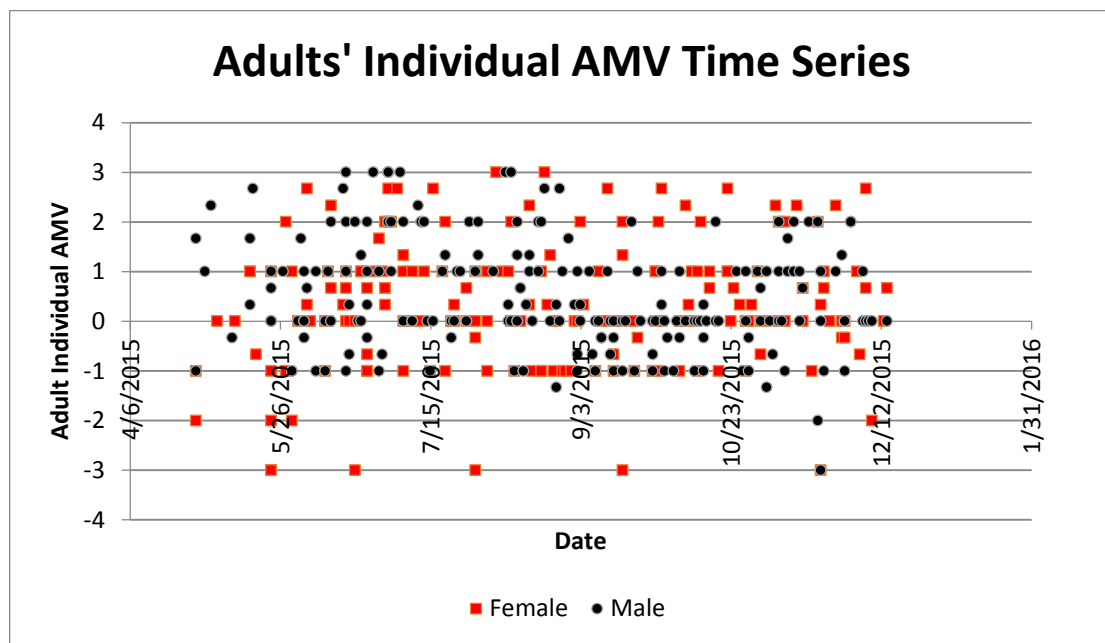

Figure 6: Actual mean vote (AMV) responses of all adult (18-75 years) participants (409 survey responses in total), expressed as a time series from April-December 2015. Sensation scale: -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot).
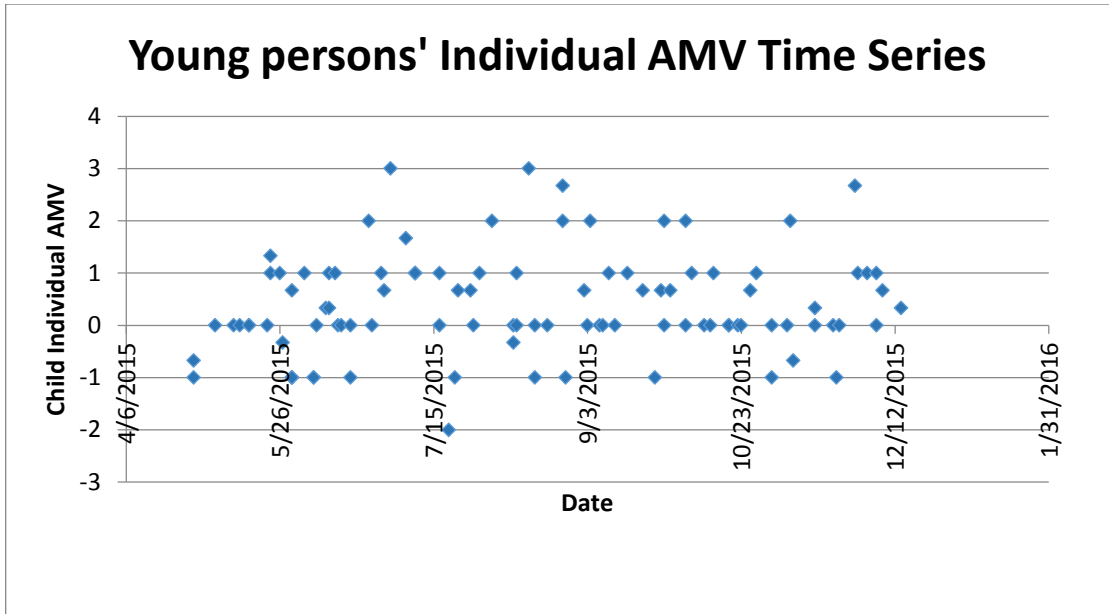
Figure 7: Actual mean vote (AMV) responses of all participants (100 survey responses in total) aged 7-16 years, expressed as a time series from April-December 2015. Sensation scale: -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot).
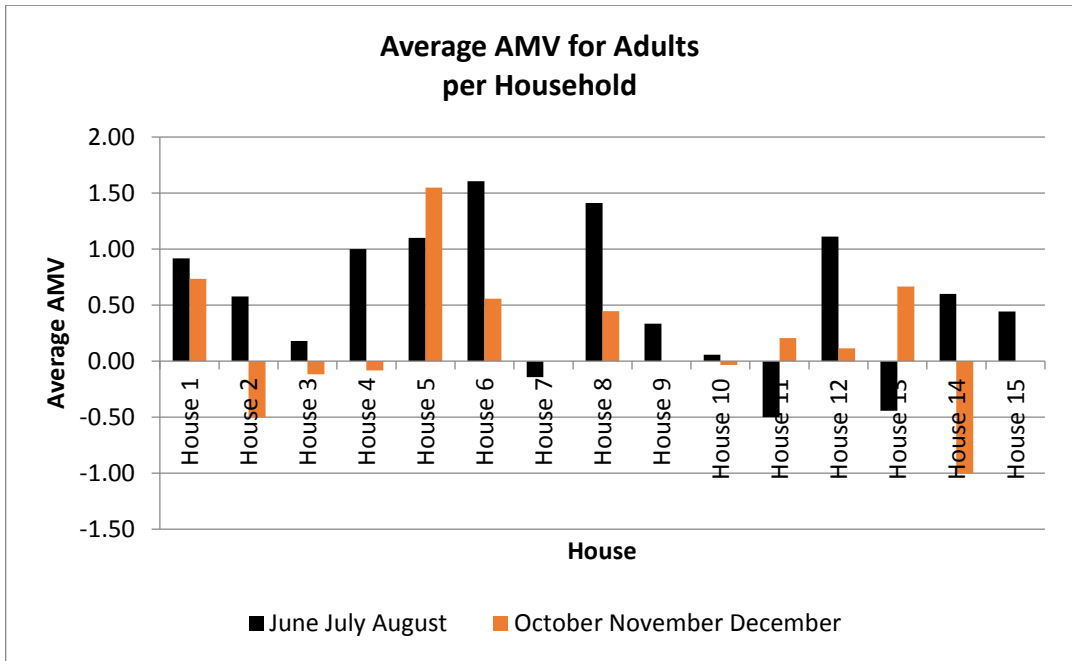

Figure 8: Average adult AMV per household for all houses, for 'summer' and 'autumn/winter' months. Sensation scale: -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot).

5. Next Steps for GII Project

5.1 Database Contribution

The field survey data gathered will be entered into a global database being developed at CBE. We have identified approximately 36 thermal comfort studies that

were conducted in mixed-mode and residential buildings, meet scientifically rigorous standards, and contain data usable for the GII project, and we are continuing to expand this search. To date, we have received positive replies from researchers willing to contribute their data from thermal comfort studies carried out in 13 different countries (Mexico, Finland, Estonia, Belgium, Italy, Slovakia, Portugal, Israel, Tunisia, China, Malaysia, India, Japan). Their data have already been received and we are currently working on data processing. We are simultaneously continuing with data gathering since more authors are being constantly invited to collaborate.

We are also working to expand and use two interactive visualization tools that allow users to look at all data, or subsets that are most interesting to them, based on building type (such as MM, NV, or HVAC), location, etc. The tools were described in Pigman et al (2014). The tools are built with the statistical package R, and the current user interface has dropdown menus, sliders, and input fields that allow users to filter the overall database based on the building location, cooling strategy, and program. Users can choose the metrics for the axes and for calculating satisfaction, the width of the bins, and the minimum number of votes that are required in a bin for it to be displayed. The screen then gives them immediate feedback, visualizing the results based on the input parameters and filters. In addition to the graph, there is a data table that indicates the sources of the data and the mean values of the basic physical and survey responses for each city that is included. This tool uses probit analysis to display the percentage of dissatisfied votes as a function of a variety of metrics - thermal sensation, PMV, or indoor temperature - and plots the corresponding probits. The four metrics for calculating satisfaction (or conversely, dissatisfaction) are acceptability, thermal sensation, comfort, and preference. The second tool, "Satisfaction mapping tool", provides a new way of analysing and representing data in these datasets that calculates satisfaction percentage directly, and visualizes the results directly in a form of the ASHRAE adaptive model.

5.2 Modelling
The UK and Indian field study findings about air motion practices are helping to inform experimental validation of a coupled thermal comfort / airflow model (Cropper et al, 2010). Knowledge transfer and training using the model is being arranged for all project partners, thereby building capacity at international level to tackle the problems posed by climate change. The model comprises a dynamically coupled model of human thermal comfort and physiology with computational fluid dynamics (CFD). The advantage of this modelling approach over existing thermal comfort prediction methods is its spatial resolution and two-way data transfer between the model of the human being and the CFD model of the occupied space. This enables accurate, time-dependent boundary conditions to be applied to each of the two models resulting in simulation of the evolution of occupant comfort as well as prediction of the steady state condition (where one exists). The types of scenarios being investigated involve localised air movement effects such as air flow through windows and those generated by fans. The model being used comprises 59 body segments which facilitates spatially-varying boundary conditions and so will enable such phenomena to be captured.

Once a set of viable ventilation/air movement scenarios has been identified, dynamic thermal simulation will be used to predict the likely energy consumption of each. These energy saving predictions of individual dwellings can be scaled up to building stock levels to give an overall prediction of the likely energy savings that could result from higher air motion in comparison with air-conditioning solutions.

6. Conclusions

The field studies in the UK (15 residences) and India (20 residences), whilst not being a particularly large sample, is nevertheless significant in two respects. Firstly, they have generated a large and very rich dataset, allowing a detailed picture of everyday family life as it might influence residential thermal comfort. Secondly, the work has successfully demonstrated a methodology that is suitable for residential application, can be replicated for subsequent national and international studies, and is capable of modification to suit particular circumstances and data requirements. Conclusions are as follows.

i) Residential dwellers will co-operate in surveys involving subjective and objective components if suitably approached and the surveys conducted carefully and sensitively. Online data gathering via mobile technology is an effective mechanism in this context.

ii) An advanced questionnaire, designed to align with the online approach, can be used to capture detail of air motion practices and configurations, together with information on other related factors.

iii) The method provides a rich and unique insight into residential practices that influence thermal comfort, and can be used in other such investigations elsewhere.

The data generated will be made available to the UCB database, and will be analysed in more detail in coming months. Remaining tasks of the GII Project will be completed, and will be reported on in due course.

7. Acknowledgements

8. References

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