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Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation

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ABSTRACT

Upgrading the thermal insulation of UK houses to improve wintertime energy efficiency raises concerns about potential summertime overheating risk. To address these concerns, experiments were conducted in a pair of thermally matched, solid walled houses, located in the UK. One of the pair was retrofitted with internal wall insulation, while the other remained uninsulated; both houses were monitored for four weeks during the summer of 2015. Operative temperatures in the living room and main bedroom were observed to be higher in the internally insulated house in comparison to the uninsulated house. The houses were again monitored for a further three weeks with a simple overheating mitigation strategy applied consisting of night ventilation and shading using internal blinds. The data were normalised for variations in external weather conditions using a linear regression model, with the exponentially-weighted outdoor running mean air temperature as the predictor variable of indoor operative temperature. The results showed that the mitigation strategy was effective at reducing the internal temperature in the internally insulated house to a level similar to that observed in the uninsulated house. The marginal increase in overheating risk should not be considered a barrier to the uptake of IWI in this type of house and location, at this time. Shading devices and secure noise attenuating vents for existing dwellings may be needed as part of a package of refurbishment in the future. It could become a requirement within the Building Regulations [1] to reduce overheating risk when retrofitting existing homes.

1. Introduction

This paper contributes new evidence on the impact of internal wall insulation on summertime overheating risk in UK solid walled houses. The work presented is based on measurements taken in a unique test facility comprised of a matched pair of semi-detached solid wall[1] houses, and employs an innovative method for comparing short term test results carried out under different weather conditions. It is the first time, to the authors' knowledge, that tests and analyses of this nature have been undertaken.

31% (8.5 million) of the 27.7 million dwellings in Great Britain are of solid wall construction, and only 8% of these buildings (approximately 718,000) have insulated external walls [2]. These, predominantly older, solid wall properties are not generally known to exhibit overheating problems, except in the most extreme weather conditions. The Energy Follow-Up Survey (EFUS), which is based upon the earlier 2010/11 English Housing Survey (EHS), reports that occupants of pre-1919 dwellings are the least likely to report a problem with overheating, while more energy efficient dwellings are more likely to experience overheating than less efficient dwellings [3]. A large monitoring study of 207 dwellings conducted across England recorded bedroom and living room temperatures during the cool summer of 2007, finding that the lowest bedroom temperatures occurred in pre-1919 properties [4]. Another large scale monitoring study of 282 dwellings in Leicester, UK, during the summer of 2009, found that the risk of overheating was lowest in solid wall properties [5]. This could change with the addition of insulation.

Solid walls (average U-value of 1.77 W/m^2K [6]) have a much higher heat loss in winter than the walls of homes built to modern standards (U-values of 0.3 W/m^2K [7]). The fifth UK carbon budget [8] calls for a further 2 million solid walls to be insulated to meet the carbon reduction targets set out in the 2008 Climate Change Act [9]. The rate of heat loss can be reduced by the addition of either external or internal wall insulation. External wall insulation (EWI) is a common technique that involves applying a layer of insulation material to the external wall surfaces of a building, the insulation is then covered by a protective coating of render or brick slips. EWI has the benefit of minimal disruption to the occupants during installation and avoids the

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[1] 'Solid wall' is the term used to describe external walls that have no cavity.

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need for internal redecoration. However, it is costly, alters the external appearance of the building, and may not be permitted in some locations [10]. Planning permission for EWI is required for a house in a conservation area and consent would be needed to retrofit EWI onto a listed building [11]. The high cost of installation, combined with the removal of many grants and subsidies, has resulted in a limited uptake of EWI. The latest available figures [12] show that although 27% of solid wall dwellings in the social rented sector have had solid wall insulation applied, only 7% of the private sector has solid wall insulation.

In contrast, the potential for installing internal wall insulation (IWI) may be high. There are approximately 500,000 listed buildings in England, though not all of them are dwellings, and 97% of these were built before 1900 and will therefore have solid walls [13]. There are also 1.1 million dwellings in conservation areas [14]; many of these are likely to be of solid wall construction due to their historic nature. Internal wall insulation (IWI) has the advantage of maintaining the external appearance of a building, but suffers the disadvantage that it can cause disruption to the occupants during installation and can result in a loss of internal space as well as a requirement for redecoration. However, IWI can be installed at a cost lower than that of EWI [10] and may be installed on a room-by-room basis, or in single flats in a block, making it more flexible and affordable.

Recent reports by the Zero Carbon Hub [15] and the Building Research Establishment [16] as well as numerous research projects [17] have highlighted summertime overheating as a growing problem in modern, well insulated and airtight dwellings. Overheating can pose a significant threat to the health and wellbeing of UK citizens [18]. Nighttime comfort is a particular concern as people need to sleep and recover during hot weather if they are to be productive [15]. There are concerns that making older dwellings more energy efficient using IWI could have unintended consequences, that include summertime overheating.

Much of the evidence underpinning these concerns is based on simulation studies using dynamic thermal modelling. Porritt et al. [19] used modelling to quantify the effect of retrofit interventions on overheating and found that IWI could increase overheating for west facing rooms in solid wall end terrace houses, whilst EWI reduced overheating for all cases. Gupta and Gregg [20] found through modelling that IWI in most cases lead to increased overheating, whilst EWI could reduce overheating compared to an uninsulated house. Ji and Webster [21] carried out comparative modelling of IWI and EWI on a pre-1919 house using a calibrated model and found that IWI resulted in significantly greater overheating than EWI. Mavrogianni et al. [22] modelled the effect of IWI as a retrofit measure and reported an increase in maximum daytime temperatures during a sample of five consecutive hot days. A further study by Mavrogianni et al. [23] modelled internally insulated solid wall dwellings, with and without mitigation strategies to reduce overheating, and found that overheating could not be fully mitigated through the use of night ventilation window opening combined with daytime shading using blinds. The SNACC project surveyed residents and found that they were willing to adapt their behaviour by closing window coverings in the day and opening windows at night [24]. Whilst thermal modelling studies may shed light on the relative overheating risk associated with different types of insulation, the prediction of the absolute number of overheating hours is highly uncertain, with predictions from different models differing by 50–100% [25].

Measurements conducted in real buildings can produce even more compelling evidence for overheating risk, but there has been little measurement-based evidence from real houses to understand the relationship between IWI and overheating. The Retrofit for the Future programme measured summer temperatures in 20 dwellings, pre and post retrofit, and found that overheating was only reported in one case, although the type of wall insulation applied was not stated [26]. In another retrofit study, measurements taken in 18 living rooms and bedrooms of flats retrofitted with EWI demonstrated widespread overheating [27]. Several measurement studies in modern, well insulated and airtight dwellings have reported overheating [28–31]. Improving traditional solid walls to modern building regulation standards could also cause these dwellings to overheat. It has been identified that dynamic thermal models are not the most effective at predicting overheating and that models derived from measurements may have a valuable role to play [17].

A Department for Communities and Local Government investigation into overheating in dwellings has highlighted the gaps in knowledge that exist around energy efficiency upgrades and their potential impact on overheating. They note the inherent uncertainty in modelling and call for more data from real buildings to validate the estimates produced from modelling [32]. This paper provides data of the kind required.

If the installation of IWI in houses was to lead to increased overheating, which in turn resulted in the uptake of air conditioning to meet indoor comfort expectations, then the required reductions in energy demand and carbon emissions are unlikely to be achieved. However, if it can be demonstrated through the use of passive cooling strategies that IWI can meet energy saving and carbon reduction targets, whilst at the same time providing a comfortable indoor environment for occupants during the summer, then IWI could be a viable option for reducing carbon emissions. This paper provides measurement-based evidence to demonstrate that IWI is a viable option.

2. Data collection

In order to quantify the risk of summertime overheating, a pair of solid wall houses was monitored throughout the summer of 2015. Synthetic occupancy was used to represent the heat gains from the presence of occupants and their use of lights and electrical appliances. One of the houses had IWI installed and experiments were carried out to compare the internal environment of the houses in three different test configurations.

2.1. The pair of houses

The research was carried out in a pair of semi-detached solid wall houses, built around 1910 and located in a rural village in Leicestershire, UK (Fig. 1). Each house has a living room, dining room and kitchen on the ground floor, with a main bedroom, second bedroom and bathroom on the first floor (Fig. 2). The houses were unoccupied and there were no furnishings other than the equipment used for monitoring and for synthetic occupancy. The houses are referred to as the 'left house' and 'right house' when looking at the front, south-southeast facing, elevation.

The external walls are of a traditional UK solid wall brick construction (for construction U-values see Table 1). The houses are ideal candidates for the installation of IWI as they are semi-detached and therefore have three external walls through which heat loss can be reduced. This is not typical of the majority of solid wall homes; 21% are semi-detached, 41% are terraced, 26% are flats and 8% are detached [33]. However, semi-detached houses are also a reasonable proxy for end-terraced houses. The basic construction of the houses is typical of many houses of the period, including the brick type and plaster; pitched slate roof construction; and the floor construction. The ground floors in the living rooms consist of uninsulated suspended timber with a 0.3 m cavity below, whilst the floors of the dining rooms and kitchens are of solid concrete construction. The glazed facades of the living rooms and main bedrooms are oriented south-southeast, and have large bay windows that provide direct solar gains in the summer. The houses were identically refurbished before the tests commenced, with the installation of PVCu double glazed low-emissivity windows and doors and 300 mm of fibreglass loft insulation. This is fairly typical of the refurbished state of many houses in England, where 47% of homes have loft insulation over 150 mm in thickness and 74% of homes have double-glazed windows [14]. Each house has a floor area of 82 m^2, around the average for English solid wall dwellings [33].

Fig. 1. The S-SE facade of the pair of Test Houses. Internal wall insulation was installed in the left house.

As was standard practice at their time of construction, each house had a fireplace and chimney breast. For this study, the chimney breasts in both houses were sealed, but were fitted with a plastic fixed louvre vent in the living rooms and dining rooms. There were air-bricks close to the ceiling of the kitchen of both houses and bathroom of the left house, these were covered with a plastic fixed louvre vent inside; these

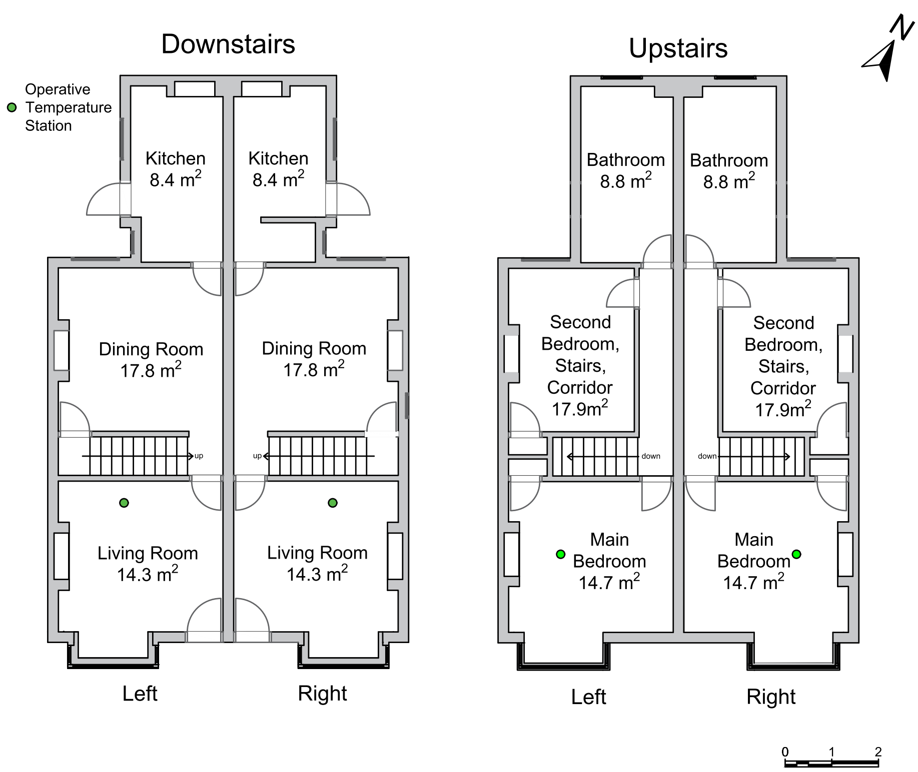

Fig. 2. Floor plans of the pair of Test Houses with location of sensors.

Table 1
Construction characteristics of the pair of Test Houses.

Element	Details	Assumed[a] U-Value (W/m^{2}K)
External walls (as built)	Solid brick with internal plaster, thickness 0.23 m	1.7
External walls (with IWI)	As above plus air gap, 0.065 m phenolic boards faced with plasterboard	0.30
Roofs	Pitched with slates and joist level fibreglass insulation, thickness 0.3 m	0.13
Ground floor (front)	Suspended timber (uninsulated)	0.84
Ground floor (rear)	Solid concrete (uninsulated)	1.25
First floor	Timber joists with a lath and plaster ceiling	–
Windows	Double glazed, low-e, white PVC-u frames	1.2
Doors	PVC-u	1.2

[a] Values taken from The Government's Standard Assessment Procedure for Energy Rating of Dwellings, RdSAP vs. 9.93 [34] and manufacturers data for windows.

ventilated directly to the outside and had a free area of roughly 35000 mm^2. The windows were installed with trickle vents that were open for all of the tests. Nylon carpet with a bonded underlay was fitted in all rooms apart from the kitchen, which had a tiled floor, and the bathroom, which had a vinyl floor covering.

Characterisation tests were undertaken after the installation of the loft insulation and replacement doors and windows, but before the IWI was installed in the left house, to confirm the extent to which the properties could be considered a thermally matched pair. These tests consisted of co-heating (after [35]) to measure the whole house heat transfer coefficient, and air permeability tests to measure the airtightness of each house. The co-heating tests produced almost identical heat transfer coefficient values of 238 W/K for the left house and 240 W/K for the right house. The experimental uncertainty in these values is expected to be lower than the value of ± 10% reported by Jack et al. [36] for the co-heating test because the houses were tested at the same time and therefore experienced the same boundary conditions. The blower door tests (after ATTMA [37]) showed that the left house (Q_{50} = 8.0 ± 0.8 m^3/h.m^2 @50Pa) was 9% less airtight than the right house (Q_{50} = 7.3 ± 0.7 m^3/h.m^2@50Pa). This difference may be due to the additional bathroom vent, but the results are within the uncertainty of ± 10% associated with a blower door test when carried out in calm conditions [38].

2.2. Monitoring equipment

Each house was equipped with two DataTaker DT85 data loggers [39], one upstairs and one downstairs (four in total), recording the following variables, each at 5 min intervals:

- Outdoor air temperature using a shielded U-type thermistor [40] (uncertainty ± 0.2 °C).
- Indoor air temperature at three heights, 0.1 m, 0.6 m and 1.1 m above the floor, using U-type thermistors [40] (uncertainty ± 0.2 °C) shielded with aluminium foil.
- Surface temperatures of the walls, floor and ceiling in the living rooms and main bedrooms using T-type thermocouples (uncertainty ± 1 °C).
- Black globe temperature at 0.6 m height in the living rooms and main bedrooms using Swema 05 globe thermometers with pt100 sensors [41] (uncertainty ± 0.1 °C).
- Air velocity at 0.6 m height in the living rooms and main bedrooms using Dantec 54T21 omnidirectional transducer anemometers [42] (uncertainty ± 0.05 ms^{-1}).
- Relative humidity at 0.6 m height in the living rooms and main bedrooms using Rotronic HC2-S hygrometers [43] (uncertainty ± 0.8% RH at 23 °C).

In the living room the air temperature at three heights correspond to the locations of the ankles (0.1 m), torso (0.6 m) and head (1.1 m) of a seated person. In the main bedroom the height of 0.6 m corresponds to the location of a person lying on a bed. All sensors were calibrated prior to deployment.

The air temperature, black globe temperature, air velocity and relative humidity sensors were placed in the living room and main bedroom at the centre point of the likely location of a sofa and bed respectively (thermal comfort stations, see Figs. 2 and 3) so as to capture the conditions that would be experienced by occupants. Four surface temperature sensors were affixed on each of the four walls, the floor and the ceiling of the living rooms and main bedrooms. In each case the sensors were evenly distributed across the surface. Outdoor air temperature was measured next to the north-northwest facade, away from the houses and shaded by a solar radiation screen.

2.3. Synthetic occupancy

Synthetic occupancy was used to create realistic test conditions that were identical in each house. Heat sources were installed in each house that reproduced typical heat gains due to occupants and appliances (Fig. 3). Heat gains from people were generated using incandescent and compact fluorescent light bulbs fitted into custom-made ventilated matt black metal cylinders, each 1.2 m tall, 0.3 m diameter; similarly constructed matt black metal boxes were used to replicate heat gains from televisions and entertainment devices; cooking gains were reproduced using oil filled radiators in the kitchens. The heat sources were switched on and off according to the occupancy schedule in Table 2 using a smart home controller (Vera 3) and wireless (Z-Wave) plug sockets. Motorised, cream-coloured roller-blinds were fitted to all of the front south-southeast facing windows and controlled using plug-in timer switches.

The occupancy and gains profiles described in Table 2 were designed to represent those of an elderly couple who were deemed to be at home during the day and the night. The profile was based on that developed by Porritt et al. [19], but adjusted for use in test houses by removing duplicate gains found in different rooms for one person. The elderly couple profile was chosen because the occupants would be at home during the hottest parts of the day and therefore be exposed to the greatest risk from overheating. Gains from lights, cooking and appliances were based on tables published by the American Society of Heating Refrigerating and Air conditioning Engineers [44]. The lighting gains were reduced to 20 W per room, to take account of the proliferation of low energy lighting in UK dwellings.

2.4. The IWI system

The installed IWI system was a commercially available product and comprised of 0.05 m thick phenolic insulation boards laminated with 0.0125 m of plasterboard, screwed onto a metal frame (Fig. 4). The installation was slightly atypical to enable the system to be removed following testing: the air gap between the boards was wider in places to extend over skirting boards at floor level and coving at the ceiling, and the joints between the boards and at their edges were taped, but the final thin plaster 'skim' coat was not applied. The plasterboard had the same reflectivity, emissivity and albedo as a finished wall and the lack

Fig. 3. Synthetic occupancy and monitoring equipment in the living room of the right Test House. The image shows at the back of the room the shielded temperature sensors at three heights and the black globe thermometer. On the left and right of the image there are the custom-made ventilated matt black metal cylinders and boxes used as synthetic occupancy, providing gains for two 'occupants', electrical appliances and lights.

of plaster was estimated to have a negligible effect on the total thermal resistance of the wall with IWI system; the plaster skim would have represented only 0.3% of the total resistance. The resulting total thickness of the system was approximately 0.14 m, on average.

Thinner insulation boards of 0.0325 m thickness (0.02 m of insulation plus 0.0125 m of plasterboard) were adhered directly to the wall in the window and door reveals. Short returns of 0.4 m width were adhered directly to the party wall and on the internal partition walls, where they met external walls, to reduce thermal bridging. The existing ventilation ducts on fireplaces and in the kitchens and bathroom were extended through the insulation layer to avoid ventilating the air gap behind the insulation.

2.5. Test configurations

There were three different test configurations. Each test was subject to a conditioning period, where the synthetic occupancy equipment and the blinds and windows were operated according to the schedules for that test, for a period of seven days, prior to the commencement of data collection. The tests are presented in their logical order, but were undertaken in a different chronological sequence during the summer of 2015 (Table 3). The synthetic occupancy gains from people and appliances remained the same for all three configurations.

In the 'Matched Pair Test', both houses were in their uninsulated state in order to determine to what extent they were thermally matched. In the 'Left House Insulated Test', the left house was fitted with IWI while the right house remained uninsulated. In the 'Mitigation

Table 2
Occupancy and gains schedules for each room of the pair of Test Houses.

Room	Time of day	Gains source (W)	Calculated Gains[a] (W)	Actual Gains[a] (W)
Living Room	08.30–17.30	Adult seated: 108*2 Television: 150 Lighting: 20	386	382
	17.30–18.30	Adult seated: 108 Television: 150 Lighting: 20	278	270
	19.30–23.00	Adult seated: 108*2 Television: 150 Lighting: 20	386	382
Dining Room	8.00–8.30	Adult seated: 108*2 Lighting: 20	236	240
	18.30–19.30	Adult seated: 108*2 Lighting: 20	236	240
Kitchen	7.30–8.00	Adult cooking: 189 Cooking: 160 Lighting: 20 Fridge: 60	429	400
	17.30–18.30	Adult cooking: 189 Cooking: 1600 Lighting: 20 Fridge: 60	1869	1900
	8.00–17.30 18.30–7.30	Fridge: 60	60	60
Main bedroom	23.00–7.00	Adult sleeping: 72*2	144	140
	7.00–7.30	Adult Sleeping: 72	72	70
Bedroom Two	–	–	0	0
Bathroom	7.00–8.00	Adult standing: 126 Lighting: 20	146	140

[a] Calculated gains are the exact gains that were wanted, calculated from the gains sources. Actual Gains were those provided by the equipment.

Fig. 4. The IWI system installed in the left house showing original plaster wall, air gap, steel framing and insulation panels. All joints between panels were sealed before testing.

Test', the left house remained insulated and a mitigation strategy was employed in both houses, to measure the impact of using blinds for solar shading together with night ventilation by opening bedroom windows to purge warm air and replace it with cooler ambient.

The use of blinds for solar shading and opening of windows for ventilation were chosen for the mitigation strategy because both of these options would be available in most homes and could offer a simple, low cost method of reducing overheating for most people. In the 'Mitigation Test', the blinds in the south-southeast oriented living rooms and main bedrooms remained closed throughout the day and night. To provide additional night ventilation the small top light windows on the first floors of the houses (Fig. 1) were opened to 45° at 17:30 each evening and closed again at 08:00 the following morning. The measured free area provided by these openings for both houses was 0.51 m^2 in the main bedroom, 0.29 m^2 in the second bedroom and 0.24 m^2 in the bathroom. The windows in the bathroom and small bedroom were on the opposite façade to the main bedroom windows, which provided cross ventilation and internal doors remained open. The downstairs windows remained closed due to security concerns, which is likely to be the case in many occupied dwellings.

3. Data analysis

Operative temperature, the equal combination of air and mean radiant temperatures at velocities under 0.1 ms^{-1} [45,46], was used to compare the various results from the tests as it represents the thermal experience of occupants. The operative temperatures inside the left and right houses were compared in the Matched Pair Test, to determine the extent to which the two houses behaved as a matched pair. Suitable overheating criteria were then defined, and a simple statistical model was used to enable direct comparison of the houses with and without the mitigation strategy, for the weather today and in the future.

3.1. Comparing the houses in the Matched Pair Test

Statistics were calculated to describe the operative temperatures of the living room and main bedroom in each house for each test for the assumed 'occupied' hours, which were set as 08:30 to 23:00 in the living rooms and 23:00 to 07:30 in the main bedrooms. This was deemed important, because outside of these hours there would be no one present to experience the temperatures and thus it would not matter if unoccupied rooms overheated. Outdoor air temperature was also averaged over the two occupied periods, whilst solar radiation data are presented as daily average values.

The indoor operative temperatures of the same rooms in the two houses were then compared directly for the duration of each test using the Mean Absolute Difference as defined in Equation (1).

$$Mean\ Absolute\ Difference = \frac{\sum_{t=1}^{n} |T_{o,l} - T_{o,r}|}{n} \qquad (1)$$

Where:

$T_{o,l}$ is the indoor operative temperature of the left house at time t, °C.
$T_{o,r}$ is the indoor operative temperature of the right house at time t, °C.
n is the number of time steps.

3.2. Defining the overheating criteria

The CIBSE TM52 adaptive criteria for defining overheating in free-running buildings [46] was used to assess whether overheating occurred during occupied hours in the living rooms. CIBSE [47] cautions against the use of the adaptive criteria for assessing overheating in bedrooms because occupants have limited adaptive opportunity while in bed. Instead, CIBSE recommends that a fixed operative temperature threshold of 26 °C should not be exceeded, unless there is a means for creating air movement [47]. To remain consistent with the adaptive criteria used for the living rooms, a limit of 3% of occupied hours over the fixed bedroom overheating threshold of 26 °C was used.

Table 3
Summary of the three tests carried out in the pair of Test Houses.

Test Name	Start Date	End Date	Length of tests (days)	Left house internally insulated?	Mitigation Strategy Applied?	
					Windows open 17.30 to 08.00	Blinds Closed 24 h
Matched Pair Test	19th August 2015	8th September 2015	21	×	×	×
Left House Insulated Test	5th June 2015	3rd July 2015	29	✓	×	×
Mitigation Test	11th July 2015	31st July 2015	21	✓	✓	✓

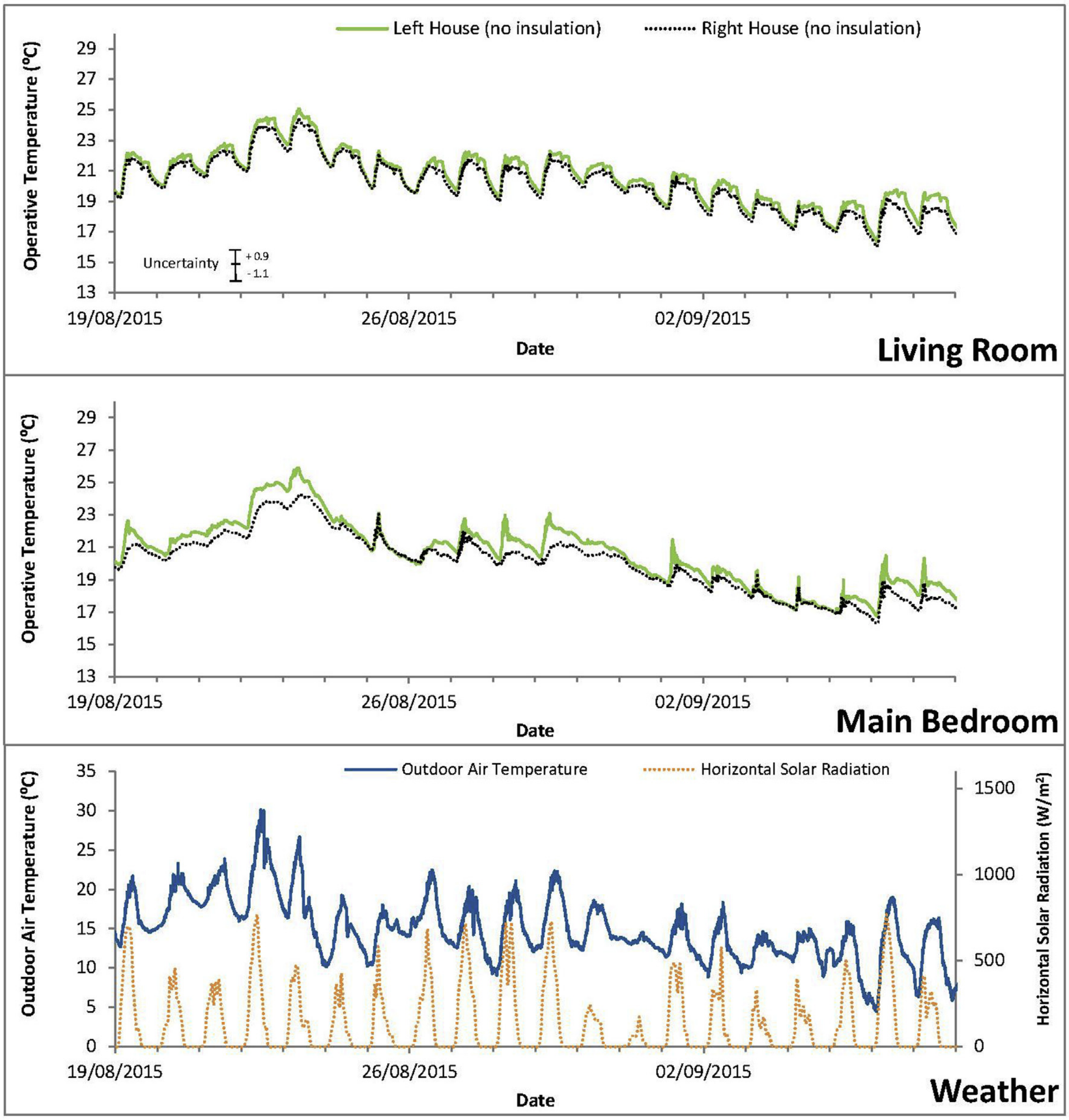

Fig. 5. Matched Pair Test - Indoor operative temperature in living room and bedroom, outdoor air temperature and horizontal solar radiation measured at 5-min intervals.

3.3. Creating a statistical model

The indoor temperatures that were measured cannot be directly compared across different test periods because they occurred under different weather conditions. Therefore, an innovative method using linear regression models was used to make this comparison. The daily mean operative temperature was regressed against the exponentially-weighted outdoor running mean temperature, which has been shown by Oraiopoulos et al. [48] to have an excellent linear relationship to indoor daily mean temperatures.

The exponentially-weighted outdoor running mean temperature, calculated for every day over the summer period using Equation (2), is a measure of the outdoor air temperature today, but it also takes into account the outdoor air temperatures of past days. This is similar to T_{rm} from CIBSE TM52 [46] but T_{WO} uses the current day's temperature and those before it, whereas T_{rm} uses yesterday's temperature and those before it, and is an established method of time series analysis [49]. This approach is particularly useful for buildings because it takes into account the effect of thermal mass, where a change in outdoor temperature has a lagged effect on indoor temperature. The initial value of T_{WO} is calculated using Equation (3).

$$T_{WO} = (1 - \alpha)T_t + \alpha T_{WO-1} \tag{2}$$

Where:

T_{WO} is the exponentially-weighted running mean daily outdoor temperature of day t, °C.
T_t is the mean outdoor air temperature on day t, °C.
α is a constant specific to the characteristics of the particular house being studied.
$T_{WO\text{-}1}$ is the value of T_{WO} calculated for the previous day

$$T_{WO} = (1 - \alpha)(T_t + \alpha T_{t-1} + \alpha^2 T_{t-2} + \alpha^3 T_{t-3} + \alpha^4 T_{t-4} + \alpha^5 T_{t-5} + \alpha^6 T_{t-6}) \tag{3}$$

The value of α will depend on the physical characteristics and use of the building, such as its thermal mass, thermal insulation and window opening schedule. A building with little thermal mass, no insulation and with its windows open would result in a lower value of α that puts a higher weighting upon the current day. The relationship between exponentially-weighted outdoor running mean temperature and indoor temperature was first tested using a sample of 230 homes in Leicester [50] where it was found that using an alpha of 0.6 best represented the characteristics of homes in summer. In order to compare the test results in this study, an alpha value of 0.6 was used in all cases as this offered a good correlation.

Mean UK temperatures during the testing in the summer of 2015 were slightly below the 1981 to 2010 average, whilst the month of June experienced higher than average sunshine [51]. In order to explore what the operative temperatures might be under future warmer summers, hourly temperature data from the UKCP09 weather generator 'medium emissions' scenario were produced for the location of the test houses during two thirty-year periods: 2036–2065 and 2066–2095. The weather generator returns 100 probabilities of air temperature that could occur in the future and the average of these is the most likely to occur. These data were used to produce exponentially-weighted outdoor running mean temperatures for each day of the 30 years and the 100 probabilities that are given. The median was then calculated across the 100 probabilities, giving a single T_{WO} value for each day of summer, May to September, for 30 years. Box plots were used to compare the predicted weather of the future to that during the summer in which this investigation took place.

4. Results

4.1. Matched Pair Test

The results from this test demonstrated that the thermal behaviours of the two uninsulated houses were similar. Similar operative temperatures occurred throughout the day and night in the living rooms of both houses, with more variability evident between the main bedrooms (Fig. 5). The larger differences, observed during days with higher solar gains, were considered to be most likely due to the differing orientation of the side walls. The side wall of the right house faced 57° from North and was mostly shaded by an adjacent house, whereas the side wall of the left house faced 237° from North, and was only partially shaded at living room level (Fig. 1). Despite the difference in indoor temperature, presumably caused by orientation, there is little difference in the time of peaks (Fig. 5).

Over the 21-day test period, the mean and minimum operative temperatures of the living rooms and bedrooms were within 0.5 °C of each other during the occupied periods (Table 4 and Fig. 6, left column of plots). Larger difference between the maximum operative temperatures occurred: 0.6 °C for the living rooms and 1.2 °C for the bedrooms.

The Mean Absolute Difference in operative temperature for the entire period was 0.5 °C between both the living rooms and the main bedrooms. No overheating occurred during this period, according to the criteria described in section 3.2.

4.2. Left House Insulated Test

This test showed that installing IWI in the left house resulted in consistently higher operative temperatures during the 29-day test when compared to the uninsulated right house (Fig. 7).

Descriptive statistics demonstrate that the temperatures were notably higher in the left house both in the living room and in the main bedroom (Table 4, Fig. 6). The Mean Absolute Difference in operative temperatures was 2.2 °C and 1.5 °C between the living rooms and the main bedrooms, respectively. Although the left house was slightly warmer than the right before the insulation was installed, the insulation substantially increased the difference.

The living room of the insulated house was deemed to have overheated according to CIBSE TM52 Cat I overheating criteria. It failed on both criterion 1 and 2: the operative temperature in the living room exceeded T_{max} Cat I for 4.7% of occupied hours, and it failed the weighted exceedance, in criterion 2, on the 1st of July. The living room in the uninsulated house passed the TM52 overheating criteria, not exceeding T_{max} Cat I at any point during testing.

The main bedrooms in both houses overheated due to exceeding the threshold of 3% of total occupied hours above 26 °C. The main bedroom of the insulated house exceeded the threshold for 12.3% of total occupied hours, while the main bedroom of the uninsulated house exceeded the threshold for only 4.6% of total occupied hours.

4.3. Mitigation Test

This test showed that the difference in the magnitude of overheating between the insulated and uninsulated houses could be minimised by applying an overheating risk mitigation strategy, consisting of solar shading and night ventilation to both houses (see section 2.5). With the mitigation strategy employed, the left insulated house living room was warmer than that of the right uninsulated house, but the two houses had similar operative temperatures in the bedrooms at night when they were occupied (Fig. 8).

During occupied hours the living room in the left, insulated house experienced higher operative temperatures than the living room in the right, uninsulated house, the differences in peak temperatures are particularly notable (Fig. 6, Table 4). However, during night-time occupied hours, the operative temperatures in the main bedrooms of the insulated and uninsulated houses are almost the same, with a mean absolute difference of 0.5 °C, but a difference in means of 0.1 °C (Table 4): each house was warmer at different times (Fig. 8). The similarity in indoor operative temperature at night was due to the increased rate of ventilation due to the opening of windows.

None of the rooms overheated during this 21-day test, although it should be noted that this test was carried out under cooler weather conditions than the 'Left House Insulated Test'.

4.4. Statistical models

By normalising for external temperature, the linear regression models showed that the mitigation strategy was effective at reducing indoor operative temperature in the house with IWI (Fig. 9). The living room temperatures during occupied hours were considerably reduced by mitigation. With mitigation employed, the bedrooms of the two houses perform almost identically, demonstrating that a thermally comfortable sleeping environment can be achieved in an internally-insulated house that is similar to that of an uninsulated house.

In the main bedrooms the mitigation strategy was always effective at reducing indoor operative temperature in both the insulated and uninsulated houses, demonstrated by the lack of intersection of the lines of best fit in Fig. 9. In the living room of the uninsulated house the mitigation strategy was no longer effective at an exponentially-weighted outdoor running mean temperature higher than 19.9 °C, i.e. above this running mean temperature the room would be cooler without the mitigation. Comparatively, in the internally insulated house, the mitigation strategy was no longer effective at an exponentially-weighted outdoor running mean temperature above 21.6 °C, as the room would be cooler without mitigation above this running mean temperature.

Through analysis of outdoor air temperatures of the 10 summers prior to this study, i.e. the years 2006–2015 (Fig. 9), it was found that there have been only 35 days (2.3% of summer days) where the exponentially-weighted outdoor running mean temperature exceeded 19.9 °C and only 8 days (0.5% of summer days) where the exponentially-weighted outdoor running mean temperature exceeded 21.6 °C. These are considered as rare events in the years 2006–2015 and mitigation would have been effective at reducing internal temperatures most days in both houses.

The tests took place in 2015, which was slightly cooler than the thirty-year average of summers, but with a heatwave consisting of 2-

Table 4
Mean Average, minimum, maximum, range and standard deviation of indoor operative temperature, outdoor air temperature and solar radiation in occupied periods.

Test	Occupancy Period	Measurement/location		Mean	Standard Deviation	Minimum	Maximum	Range	Mean Absolute Difference[a]
Matched Pair Test	Daytime 8.30: 23.00	Living Room Operative	Left	20.9	1.7	17.1	25.1	8.0	0.5
No insulation		Temperature (°C)	Right	20.5	1.7	16.6	24.5	7.8	
No mitigation		Outdoor Air Temperature (°C)		16.4	3.7	7.2	30.1	22.9	
(19/08/2015-08/09/2015)	Night-time 23.00: 07.00	Main Bedroom Operative	Left	20.2	2.1	16.8	25.0	8.2	0.5
		Temperature (°C)	Right	19.7	2.0	16.3	23.8	7.6	
		Outdoor Air Temperature (°C)		12.3	3.2	4.5	21.9	17.4	–
	All hours	Horizontal Solar Radiation (W/m^{2}K)		134	208	0	1164	1164	–
Left House Insulated Test	Daytime 8.30: 23.00	Living Room Operative	Left	22.8	1.9	18.7	28.0	9.3	2.2
Left insulated		Temperature (°C)	Right	20.6	2.1	16.8	26.2	9.5	
No mitigation		Outdoor Air Temperature (°C)		17.8	4.6	7.7	35.0	27.3	–
(05/06/2015-03/07/2015)	Night-time 23.00: 07.00	Main Bedroom Operative	Left	22.2	2.4	18.5	28.8	10.3	1.5
		Temperature (°C)	Right	20.7	2.5	17.3	27.8	10.4	
		Outdoor Air Temperature (°C)		12.0	3.5	4.2	25.4	21.2	–
	All hours	Horizontal Solar Radiation (W/m^{2}K)		222	292	0	1393	1393	–
Mitigation Test	Daytime 8.30: 23:00	Living Room Operative	Left	21.3	1.6	16.7	23.9	7.2	1.1
Left insulated		Temperature (°C)	Right	20.2	1.5	16.3	22.8	6.6	
Mitigation applied		Outdoor Air Temperature (°C)		17.6	2.9	10.5	24.6	14.1	–
(11/07/2015- 31/07/2015)	Night-time 23:00: 07:00	Main Bedroom Operative	Left	18.4	1.9	14.2	21.6	7.4	0.5
		Temperature (°C)	Right	18.3	1.8	14.1	21.4	7.3	
		Outdoor Air Temperature (°C)		12.6	2.4	5.3	17.4	12.0	–
	All hours	Horizontal Solar Radiation (W/m^{2}K)		179	248	0	1238	1238	–

[a] See Equation (2).

days over 30 °C from 1st - 3rd July; the 1st July had a peak outdoor air temperature of 35 °C. The exponentially-weighted outdoor running mean temperatures calculated for these 3 days (22 °C, 21 °C and 20 °C), were above the 90th percentile for the years 2006–2015, though potentially slightly more frequent in the future weather scenario predictions for 2036–2065 (see the box-whisker plots in Fig. 9). The predictions for 2066–2095, however, are much warmer, with an increase in the median temperature of 3 °C compared to the period 2006–2015 (see the box-whisker plots in Fig. 9). Without a mitigation strategy, the house with IWI would likely overheat more often in the future. The mitigation strategy of reducing solar gains by closing blinds and providing night ventilation through opening upstairs windows becomes less effective in the living room in hotter weather; this is evident where the lines of best fit converge and eventually cross. From 2066 onwards, the mitigation strategy would no longer be effective in the living room for 9% of summer days, averaging at 14 days every summer.

5. Discussion

This research developed a unique test facility comprised of two almost identical adjoining solid wall houses and employed them to evaluate overheating risk arising from installation of IWI in one of the houses. This is the first time, to the authors' knowledge, that an empirical comparison of overheating risk has been carried out in this manner. The method has the advantage of direct side-by-side comparison. The results were used to show that longitudinal comparisons are also possible by employing an empirical linear regression model to compare conditions with and without an overheating mitigation strategy. It is anticipated that these methods will be valuable for future measurement studies of overheating.

While it is possible to carefully control the synthetic occupants in these tests, the results are dependent on the weather that occurs during the test period. The summer of 2015 was slightly cooler than normal, with mean temperatures in June, July and August 0.2 °C–0.7 °C lower than the 1981–2010 average [51]. The linear regression model presented in this paper provides a relatively simple method to extrapolate the results for warmer conditions, though this does not provide any indication of how many hours a certain threshold will be exceeded and more work is required to develop this technique.

A further consideration is that the work is based on only one type of solid wall dwelling, with one type of occupants and in one location. Analysis of the 2015 English Housing Survey data reveals that 21% of solid wall dwellings in England are semi-detached [33] as these houses were. The results may also be representative of end terrace properties, which constitute 11% of solid wall dwellings [33]. The houses tested in our study were south facing and it may be that west facing homes are at a greater risk of overheating due to high solar gains from low evening sun. Note also that the floor area of each test house is 82 m^2, this is close to the median of floor areas of solid wall dwellings in the 2015 English Housing Survey data [33]. Further work is therefore required to understand how other types of houses would perform, in particular mid-terrace houses with solid walls (which constitute 30% of solid wall dwellings in England) and flats with solid walls (which constitute 26% of solid wall dwellings in England) [33].

The finding that IWI increases indoor operative temperature is in agreement with previous research in this field. However, it has been found here that overheating would be a rare occurrence in the current climate and up to the year 2065.

With the sensible use of internal blinds to reduce solar gains combined with ventilation to cool the house overnight, indoor operative temperatures can be reduced, and overheating rendered unlikely for houses with IWI, even under continuous occupation. Importantly, night-time thermal conditions in the bedroom would not be adversely affected by the installation of IWI as long as mitigation strategies were employed. It could be imagined that opening windows in the living room, while it was occupied during the day and the air temperature cooler outside, might further reduce the additional overheating risk that was found to occur in the living room. Based on this study, the marginal increase in overheating risk should not be considered a barrier to the uptake of IWI in this type of house and location.

There are some limitations to the finding that IWI only caused a marginal increase in overheating risk. Occupants may not want to keep their blinds or curtains closed during the daytime when they are at home due to a loss of natural light and view. Occupants may also not be able or willing to cross ventilate their bedrooms each night due to: noise outside, insects or pollen, air pollution, desire to close internal doors and security concerns. The study showed that increased risk of overheating at night can be mitigated through the use of the upstairs top

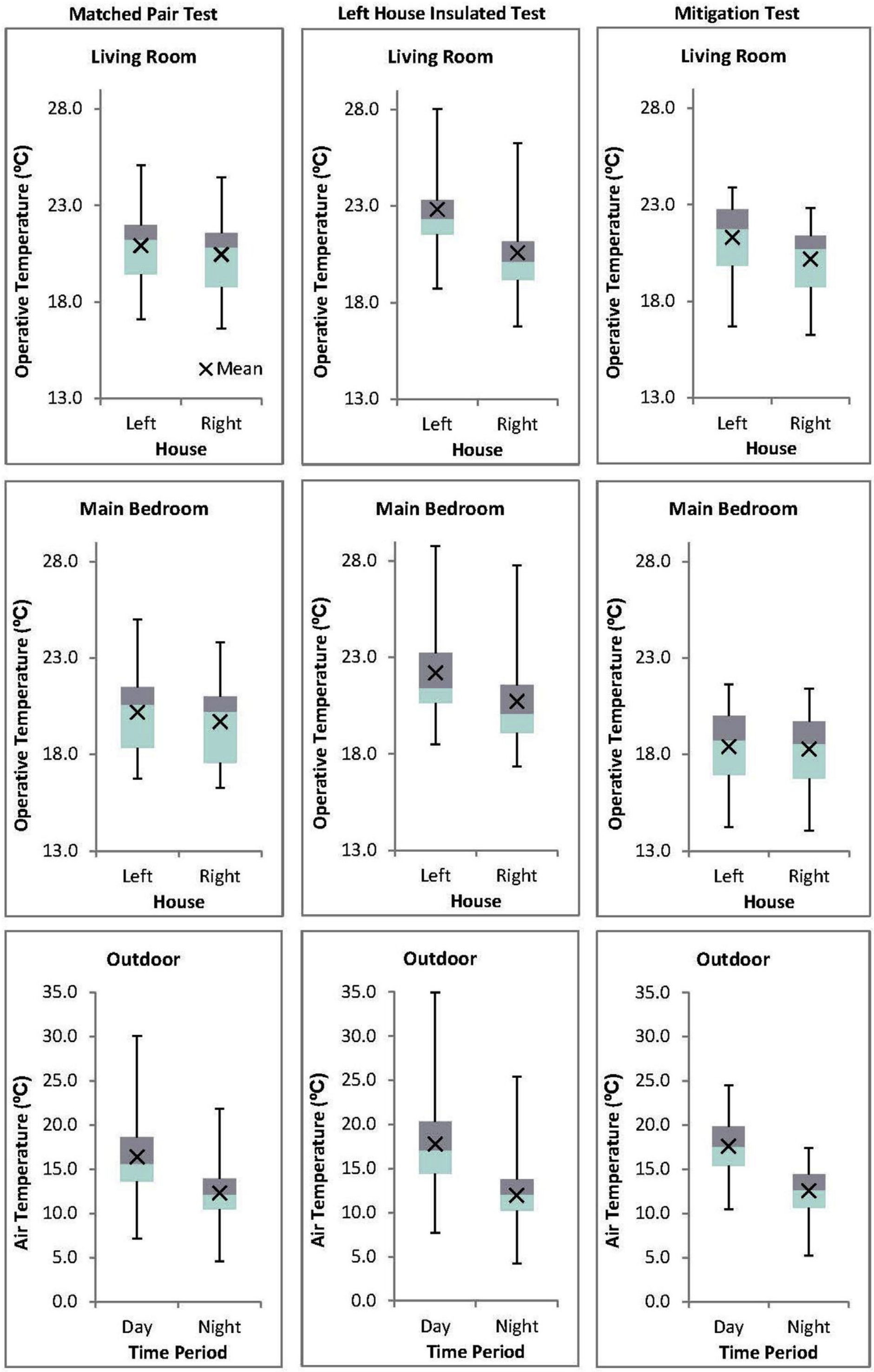

Fig. 6. Box and whisker plots[2] of living room and main bedroom operative temperature and outdoor air temperature for all three tests.

light windows alone, which may alleviate concerns about security and would reduce the ingress of pollutants. It should be noted however that under a future warming climate it is likely that there will be a smaller diurnal swing in temperature; as night time temperatures increase night cooling becomes less effective.

In terms of future UK refurbishment strategies, a more holistic view of house retrofit is needed to mitigate high internal temperatures in homes and to provide comfortable and secure living environments. Used widely throughout mainland Europe, though currently rarely used in the UK, brise soleil could offer reduced solar gains in the summer while still allowing diffuse natural light into rooms. Screen windows could be used to filter air containing contaminants or pollen and to stop insects entering. Closable vents or window side panels with baffling

[2] These box plots are a graphical representation of the operative temperatures during each Test. From the bottom of each, the crossbar of the downwards extending line indicates the minimum, the bottom of the box indicates the 25th percentile, the line across the box indicates the median, the top of the box indicates the 75th percentile, the crossbar of the upwards extending line indicates the maximum value and the cross indicates the mean.

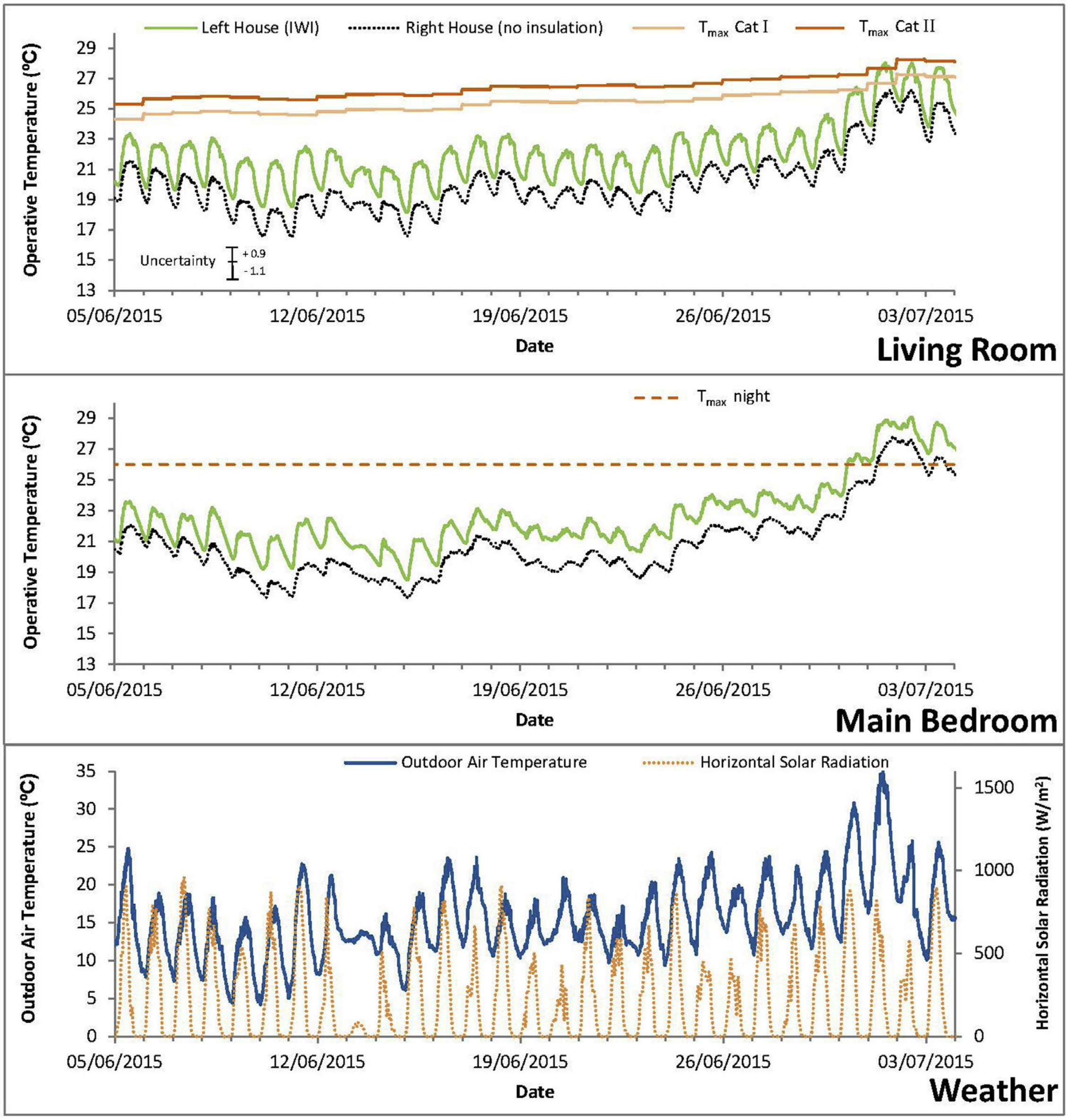

Fig. 7. Left House Insulated Test - Indoor operative temperature in living room and bedroom (with threshold temperatures), outdoor air temperature and horizontal solar radiation measured at 5-min intervals.

could be installed to allow air flow with reduced noise ingress. It is suggested therefore that the need for overheating mitigation measures are always considered as part of the planning and installation of energy efficiency measures in UK housing. Guidance could be given in Approved Document L1B [52], applicable when upgrading the thermal elements of existing buildings.

The Building Regulations 2010 [1] guidance for complying with the energy efficiency requirements in new dwellings, Approved Document L1A [7], recommends the use of SAP 2012 Appendix Part P [34] for assessing excess solar gains; these excess gains could lead to overheating. A study compared measured indoor temperatures to Appendix Part P assessments [30]; this showed that while 19 of 26 homes overheated for more than 10% of the year, SAP only predicted overheating in 2 homes. This indicates that this tool may not be appropriate for assessing excess gains and therefore controlling overheating under the Building Regulations in new or existing homes. Dynamic thermal simulation could be used instead; however this would likely be too burdensome for someone undertaking thermal retrofit of a single house. An alternative could be to use an overheating risk assessment method similar to that included within the Housing Health and Safety Rating System (HHSRS) [53]. This risk assessment could be used before upgrading a house to identify overheating risks. It could include a list of known overheating risk factors, weighted by severity of influence. For example, when it would be impractical for an occupant to open windows for reasons of security, noise or pollution. The assessment could offer design solutions that are location-specific, and simple to use for occupants. An overheating risk assessment for existing homes, as well as newly built ones, could be included in the national building regulations as we move towards a warmer future.

Whilst acknowledging the recent publication of CIBSE TM59 [54], the overheating criteria used in this study were designed using CIBSE TM52 to define temperature/time limits. These limits may not be suitable for short monitoring periods where unusual weather can bias the result, such as when overheating was seen to occur in the 'Left House Insulated Test' during the heatwave of 2-days over 30 °C. Empirical models are required to extrapolate meaningful results from measurements. The linear regression model presented here is limited to daily average operative temperature and further work is required to predict hourly values.

Collecting real measurements from homes with controlled and/or

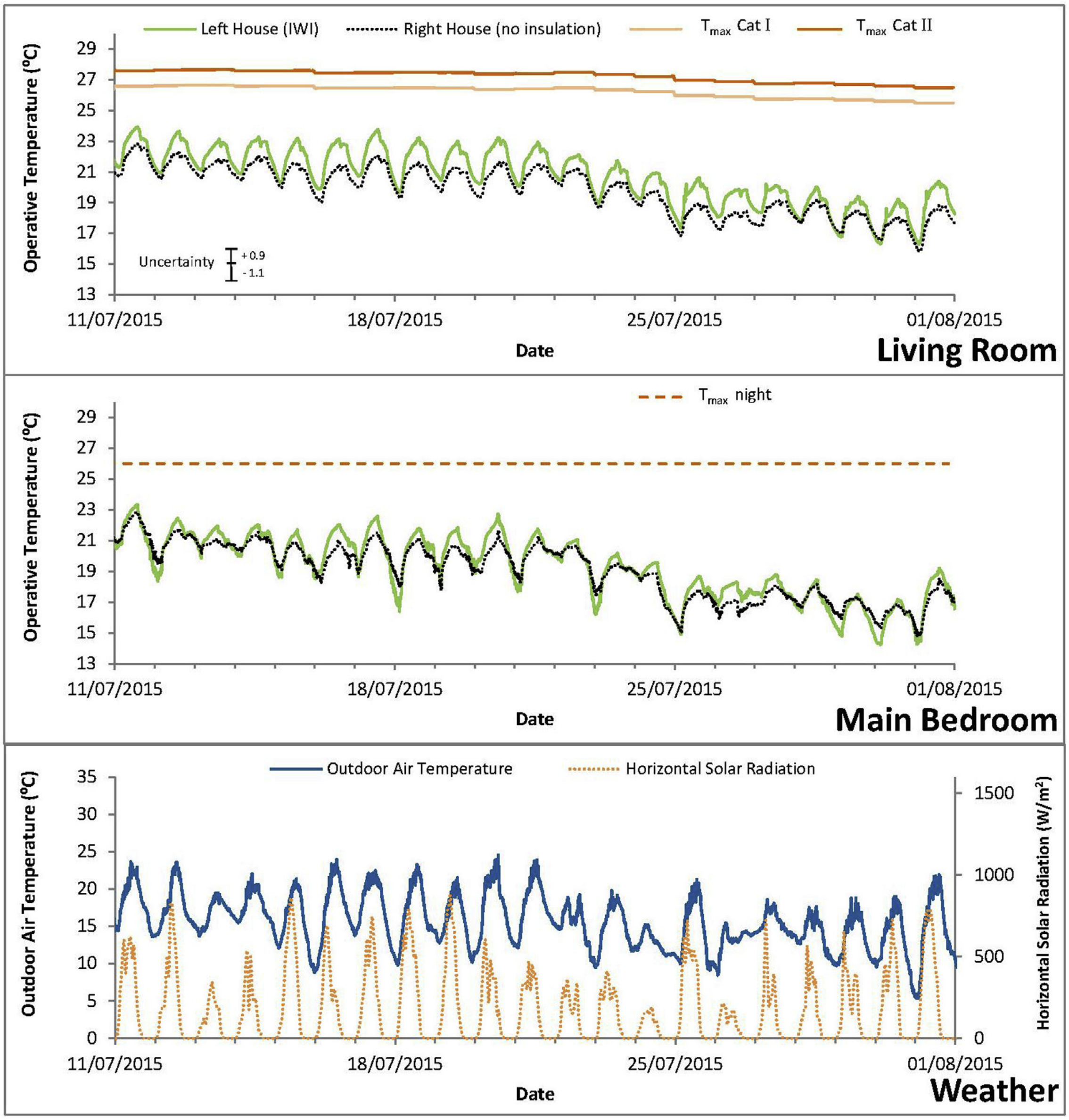

Fig. 8. Mitigation Test - Indoor operative temperature in living room and bedroom (with threshold temperatures), outdoor air temperature and horizontal solar radiation measured at 5-min intervals.

measured occupancy characteristics and measured thermal characteristics continues to be important. More work is needed to measure overheating in other house types, in different locations, and with various occupancy profiles. This would help the development of new empirical models, as well as to validate thermal simulations which require many inputs with uncertain values. Probabilistic modelling techniques would be useful to identify the inherent uncertainty of the predictions under a range of possible future weather scenarios.

6. Conclusions

A unique set of experiments in a thermally matched pair of solid wall houses, built around 1910, with synthetic occupancy schedules, were conducted to measure the effect of internal wall insulation (IWI) on summertime overheating risk. These are believed to be the first tests of this kind carried out in the UK. The following conclusions are drawn.

i) For the solid wall houses tested in this study, installing IWI in one house resulted in increased operative temperatures in living rooms and bedrooms compared with the uninsulated property; this led to overheating in both rooms during a heatwave of 2-days over 30 °C.
ii) A mitigation strategy consisting of closing blinds during the day, to reduce solar gains, and opening bedroom windows at night, to purge the warm air from the house, significantly reduced the overheating risk in the living room and returned night-time thermal conditions in the bedroom to the same level as in the uninsulated house.
iii) The houses used in these tests are semi-detached solid wall properties, and may also be representative of end-terrace properties of this nature. They are of near-average floor area, and their front facades are south-facing. Testing was conducted in summer 2015, which was slightly cooler than the 1981–2010 average, but included a heatwave of 2-days over 30 °C, where the peak temperature reached 35 °C. Whilst the above findings may be indicative of performances to be expected in other similar properties and situations, it is recommended that further work be conducted to understand how other house types may perform.
iv) An empirical model, regressing daily mean operative temperature

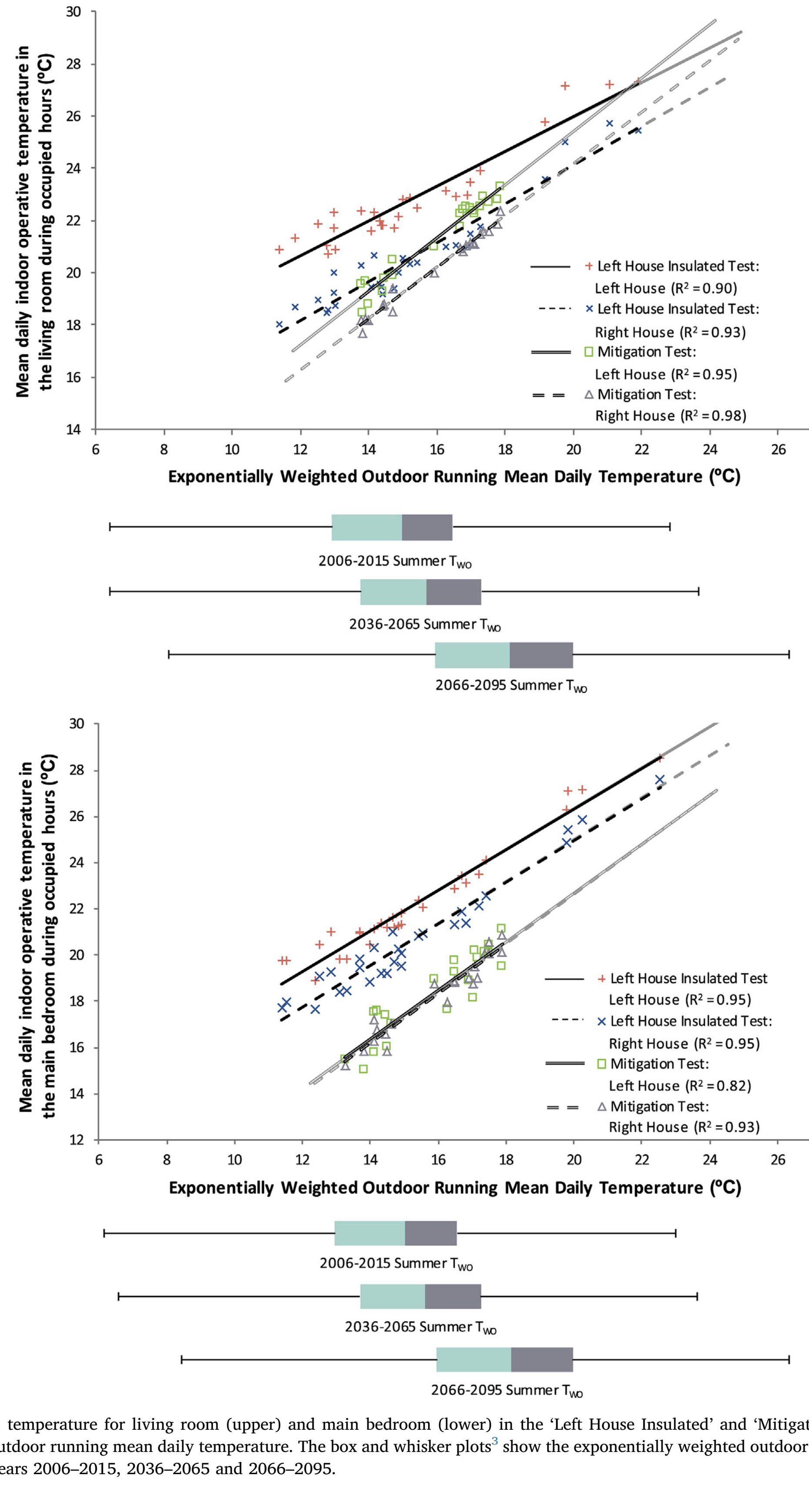

Fig. 9. Internal operative temperature for living room (upper) and main bedroom (lower) in the 'Left House Insulated' and 'Mitigation' Tests regressed against exponentially-weighted outdoor running mean daily temperature. The box and whisker plots[3] show the exponentially weighted outdoor running mean temperatures of summer days for the years 2006–2015, 2036–2065 and 2066–2095.

against the exponentially-weighted outdoor running mean temperature, was used to compare measurements made under different weather conditions and to make predictions about the performance of the house under future weather scenarios.

[3] These box and whisker plots show the minimum value on the left vertical line, the left of the box indicates the 25th percentile, the line across the box indicates the median, the right of the box indicates the 75th percentile, the right vertical line indicates the maximum value.

v) Results showed that warmer weather in the second half of the 21st century may require existing UK homes of the type tested to adopt further adaptation measures and it is suggested that this be considered in homes being built or refurbished today. In particular the use of shading devices and secure, noise attenuating vents should be considered. This could be a requirement in the Building Regulations Approved Document Part L1B: Conservation of fuel and power in existing dwellings [52].

vi) Based on this study, the marginal increase in overheating risk should not be considered a barrier to the uptake of IWI in this type of house and location.

vii) The data collected in this study will be suitable for the development of empirical models for overheating risk assessment as well as for the validation of the predictions from dynamic thermal simulation

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