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Temperature in housing: stratification and contextual factors.

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Key words: *buildings, structures & design , field testing and monitoring, thermal effects*

Introduction

Overheating in housing poses a serious health risk now and in the future (DCLG, 2012; Quinn *et al.*, 2014). The latest findings on potential overheating in UK housing (Tillson *et al.*, 2013) show that 99% of housing will be at medium to high risk if average summer temperatures rise by 1.4°C. There are numerous studies on climate change adaptation for UK housing (DCLG, 2012; Gupta and Gregg, 2013; McLeod *et al.*, 2013; NHBC Foundation, 2012; Porritt *et al.*, 2012) which suggest various positive interventions to address this risk, including guidance on glazing ratios and solar shading alongside good insulation levels. Equally there is a variety of thermal comfort (Hwang *et al.*, 2009; Lomas and Kane, 2013, Spataru and Gillott, 2010; Soebarto and Bennetts, 2014) and heating practice studies (Gram-Hanssen, 2010, Heubner *et al.*, 2013) which focus on the user, but there is relatively little literature which refers to the stratification of temperatures in housing as part of these overheating scenarios and comfort practices. Most literature on temperature stratification in buildings rests at the level of the experimental design of ventilation systems within a single space (Vaskova *et al.*, 2013, Wang *et al.*, 2014).

The stratification on a whole building scale and its impact on performance of individual dwellings has been included in some recent overheating risk models. One study concludes that *'Bungalows, semi-detached dwellings and top floor flats were most vulnerable to outside temperature while cloud cover acted to reduce the indoor temperature levels in flats more than detached or semi-detached dwellings.'* (Mavrogianni *et al.*, 2014). Modelling and limited field measurements taken in a passive house study (Rhodin *et al.*, 2014) also found a 1°C temperature difference between ground and first floor and reported cold floor complaints from the occupants more frequently in passive houses than in conventional buildings. This finding is then explained by lack of radiators in passive houses and decreased radiant heat contribution, thereby increased risk of low floor surface temperatures. Neither of these studies covers heating practices in relation to stratification, which can help to further inform design and specification decisions for low carbon housing. This study, based on one year long field measurements and in-depth understanding of home use practices in two case study residential developments, encompasses both winter and summer conditions. It examines the effects of temperature difference related to a dwelling's location within a building. It also examines a varied external context (Steemers *et al*., 1998), heating energy consumption, inhabitants' perceptions and home use practices across a significant variety of dwellings.

Methods: This study adopts a case study approach (Yin, 2013) , using mixed methods in order to derive rich contextual data which can provide meaningful interpretations and evidence to explain numerical monitoring data related to temperature, humidity and energy use. This involved a prolonged data collection period over a one year period April 2013 - August 2014 and repeated home visits every 7-8 weeks on top of two quantitative surveys and an interview combined with a home tour with each of the 20 households in each of the two case studies. The rich data allowed cross –correlation of a wide variety of different user-centred factors against the physical factors to explore in depth key findings relating to energy use and comfort levels. These factors include heating consumption and comfort expectations based on previous accommodation patterns (this is known as the Prebound effect as identified by Sunnika Blank and Galvin (2012)), cost-incentives to save energy, tariff switching, and usability - all of which can play a major role in how well energy systems perform.

The BUS survey is an established technique for building performance evaluation (Leaman *et al.*, 2010) to understand how well users' needs are satisfied. It was carried out within 4 consecutive days in mid-February 2014 and aimed to capture views of the whole population of both case studies. All the other study elements were limited to a 10% sample of the larger case study (20 apartments out of 200) and 100% in the smaller one (20 dwellings out of 20). The BUS survey was extended with custom questions developed by the researchers to capture the patterns in use of the heating and ventilation systems provided. The survey covered all the apartments in the larger case study (Case B) building which had been occupied for more than two seasons – the response rate was 44% with 95 surveys returned. 100% of the surveys for the smaller case study (Case A) were returned. These reflect a high level of interest in the study by residents.

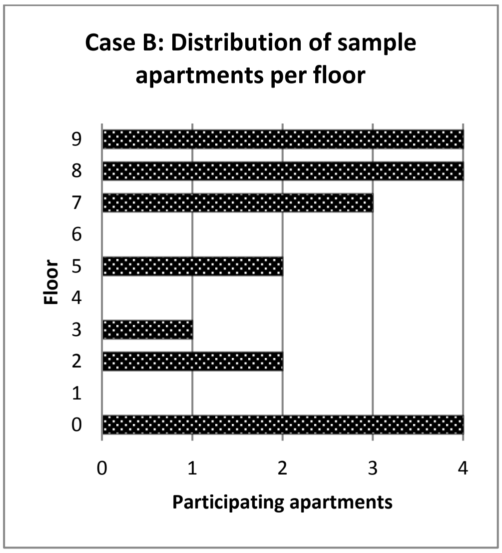


Figure 1. Distribution of participants per floor in Case B development.

The sample of 20 participants in Case B covers all major typologies (1 and 2 bedroom apartments) and demographics. The distribution of participants per floor is shown in Figure 1. On-site observations focused on home use practices and informal discussions with the residents during home visits repeated every ca. 7 weeks. Semi-structured interviews and home tours were carried out in summer (end of July-beginning of August 2014). Photographic survey and notes from home visits together with the interviews and 2 surveys provided rich information about adaptation measures taken by the residents, both 'behavioural' and 'technological' as defined by Fountain *et al.* (1996). Alongside the information relating to the residents themselves, physical housing performance evaluation methods were used including thermographic and photographic surveys. Thermographic survey was performed using a Flir E40bx camera in the recommended weather conditions for checking insulation. All the participating apartments were for one year equipped with three wireless i-Button sensors DS1923 logging readings of temperature and relative humidity (RH) in the living room, bedroom and bathroom (Fig. 2) every half an hour. The sensors were placed at a height 80-100cm from the floor and away from direct sunlight. In addition, two sensors were placed in the Case B staircase core at 1st floor and 10th floor level, and one sensor per development outside in spots sheltered from direct sunlight in proximity to monitored buildings. In order to extend the period between visits to download data the sensors were set for a low resolution allowing accuracy better than ±0.5°C within a temperature range of -10°C to +65°C according to manufacturer's data sheet (Maxim, 2015). Temperature results error analysis indicates 0.1% of faulty readings. These readings (always equal -41°C) were removed for further calculations.

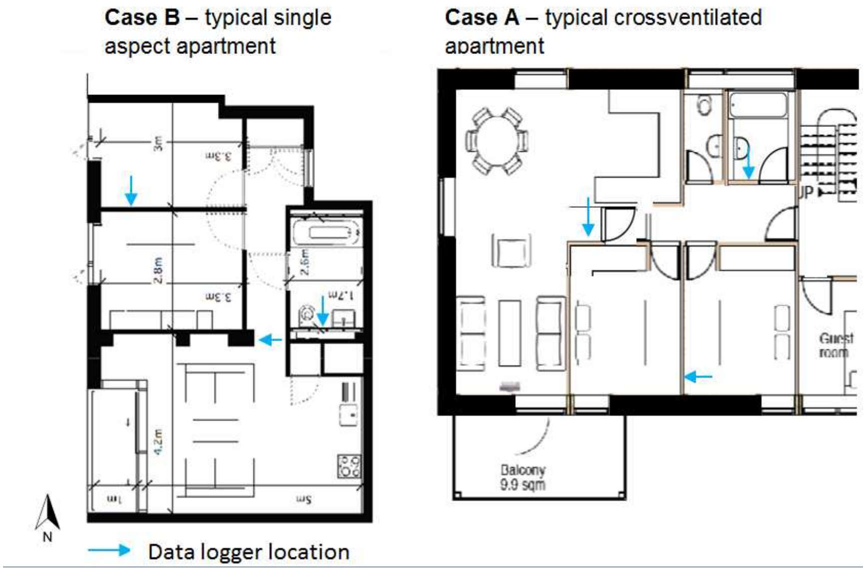


Figure 2. Sensor locations in typical apartments in Case A and Case B.

Alongside monitoring, the design process and documents, including UK Standard Assessment Procedure (SAP) (DECC, 2012), were reviewed to understand modelled energy use (Leaman *et al.*, 2010). The predicted temperatures and SAP were used to identify the potential overheating risk. Nevertheless care had to be taken with using SAP given its limitations in relation to accuracy (Kelly *et al.*, 2012, Hughes *et al.*, 2013). Solar exposure and Direct Insolation data for Case B were calculated using Solar Analysis module in Bentley's Microstation V8i (Select Series 3) (Bentley, 2012). For the purpose of comparative evaluation of cases an averaged solar intensity of 1000 W/m^2 was used.

Case study buildings description

The two case studies represent different scales of residential developments: 2 storey houses and 3 storey apartment blocks in Case A and a 10 storey apartment block in Case B. The developments represent varied demographic factors and building typology but within same climate and culture of Leeds, UK. This allows for a greater degree of comparability (Table 1) (Flyvbjerg, 2006). The studies have also been chosen to reflect different housing energy standards operating in the UK in order to contribute to the performance discourse that goes beyond the carbon footprint focus. The temperature stratification is examined in relation to perceived thermal comfort of the inhabitants of developments built to Eco Homes 'very good' and Code for Sustainable Homes Level 4.

Case study	**Case A – low new built**	**Case B - high retrofit block of apartments**
Completion	2013	2011
Size + units	20 units: 8 houses (3&4 bedroom), 12 flats (1&2 bedroom) mutually owned	234 units: 1&2 bedroom owned/shared ownership/rented
Dwelling types	new build terrace, semi-detached houses, apartments	refurbishment 1950's apartment block: single aspect (east or west facing)
No. of floors	houses:2; apartment blocks:3	10
Fabric materials: U-values*	straw/timber panel system: U=0.20 W/m^{2}K flat straw insulated roof: U=0.155 W/m^{2}K suspended concrete floor: U=0.25 W/m^{2}K triple glazing: U=1.24 W/m^{2}K	external wall SIPS panels: U=0.20 W/m^{2}K stairwell wall: insulated masonry U=0.25 W/m^{2}K flat roof: U=0.2 W/m^{2}K double glazing (trickle vents on the ground floor): U=1.57^a W/m^{2}K (1.71 in SAP)

		concrete floor slab: U=0.17 W/m^{2}K
Air permeability	designed: q_{50}=4-5 m^3/hr.m^2 achieved: q_{50}=1.42-4.3 m^3/hr.m^2 (across all dwellings)	designed: q_{50}=7 m^3/hr.m^2 achieved: q_{50}=4.29 - 5.33m^3/hr.m^2 (from sample of 4 tests available)
Energy	gas and electricity + renewables on site	electricity
Heating, hot water and ventilation features	MVHR + natural cross ventilation possible gas central heating in each dwelling, electric oven, gas hob, PV panels Flats: combi-boilers Houses: solar thermal, gas boilers in each home, hot water storage tank	mechanical extract ventilation (MEV) – single aspect thermostatic programmed electric panel heaters, hot water cylinder
Energy standards	Code for Sustainable Homes Level 4	2006 UK Building Regulations for retrofit Eco Homes Very Good

*U-values taken form SAP worksheets or manufacturer's guidelines[a] – not verified on site.

Table 1: Case study characteristics.

Weather

During the monitoring period between the 24th July 2013 and 24th July 2014 the outdoor temperature ranged between: -2.3°C and 29.2°C. Slight frost repeated for a few nights in January and February however the maximum extreme was approached only once between 5-7pm on the 1st August. Otherwise, at the Met Office weather station nearest to the case studies, even in the hottest period of heatwave at the turn of July-August 2013 mean daily temperatures ranged between 17.8°C-22.8°C. The winter period was a mild one for this location in Leeds, North of England. Normalised energy consumption refers to standard UK annual degree days of 2462 K·day (to base 15.5°C). Local average degree-days to base temperature 15.5 °C for the monitoring period was 2393 K·day – close to the UK average, however over 12% less than local average degree days for the last 8 years based on data available for Bingley Met Office weather station located ca. 10 miles from Case A and 14.5 miles from Case B. (http://www.eci.ox.ac.uk/research/energy/degreedays.php#degreedays) (Figure 3). However this is part of an increasing trend towards global warming and is not therefore anomalous.

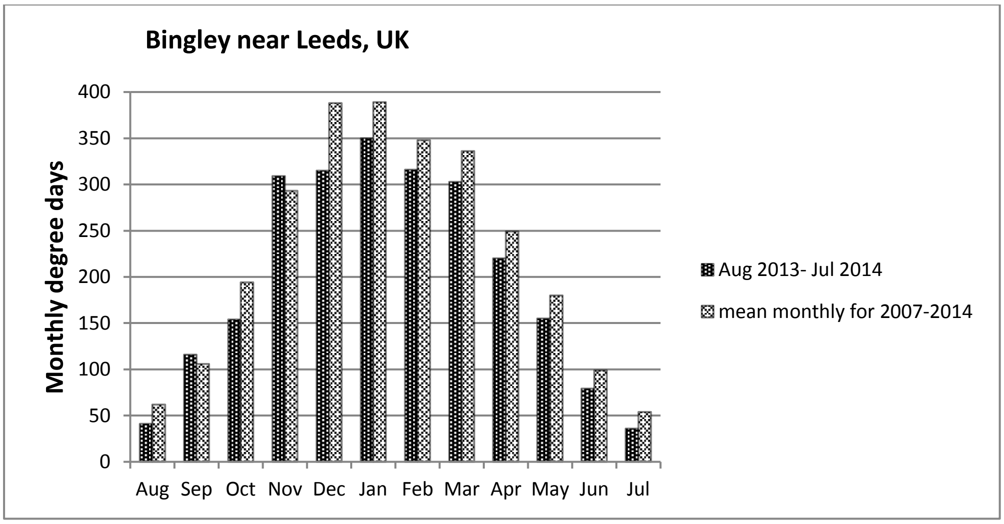


Figure 3. Monthly degree days for Bingley Met Office weather station nearest to case study locations – for monitoring period and local average for the years 2007-2014.

Temperature Stratification

Inhabitants feedback – Case B

In general BUS results suggest that overheating is more of a concern for Case B residents than cold temperature: the mean vote for winter is 1 point away from the neutral toward the 'too cold' side whereas the summer vote is 1.5 points towards 'too hot' on a 7 point Likert scale. Ground floor residents experience the least overheating in the summer (3.3 mean vote compared to 2.5 mean for the building) and the worst cold in the winter, out of all the floors (5.9 mean vote against 5.0 mean for the building) (Figure 4). The top floor is closer to average for both seasons with mean vote 4.6 for winter and 2.4 for the summer – it is perceived as neither particularly hot nor cold. On average for both seasons floor 4 is closest to the 'neutral' temperature vote. The quantitative data on the ground floor cold spots are confirmed by the comments: '…[the] temperature never gets comfortable no matter how hot the heaters are' and 'the low ceiling helps keep the flat warm, however as soon as the heaters are off the temperature drops dramatically!' From the first floor up the comments are more mixed and from the third floor up some comments state that heating is rarely needed at all in winter: '[heating] rarely needed' and 'We've only had to turn on heating a handful of times'. From the sixth floor up comments refer to no requirement for heating: 'The heating is fine. Temperature even when off is okay' and 'Personally had no need to use heating'. Comments from higher floors, where the users are dissatisfied with temperature in winter, refer to the high cost of electric heating: 'Electric heating too expensive' and thermal adaptability issues: '[heating] very good, but I'm from a hot country so I am always cold!'. What this finding illustrates is that on the higher floors occupants need less or even no heating in winter and are still comfortable (achieve similar satisfaction with temperatures as their neighbours on lower floors who do use the heating) and in particular are warmer than occupants on the ground floor. This is in line with stack effect – temperature stratification in the staircase zone. Later discussed temperature monitoring of a ground floor flat heated intermittently and the 7th floor unheated (Figure 7) confirms our BUS survey finding. The 7th floor apartment is always warmer than the ground floor, even though the ground floor apartment uses some heating. The ground floor apartment is sometimes colder even than the core open to the elements on the 10th floor (stack effect). This is due in part to inadequate floor insulation and thermal bridging at ground level and in part due to the heat stored in the fabric of the building at upper levels. By contrast in the summer, positive or neutral comments start at the ground floor and end on the 4th floor: 'As the ground floor occupier I have the advantage of sliding patio doors - happy in summer' and 4th floor comment: 'Just about adequate; need to keep windows open without restrictors.' From the 5th floor up there is a repeated reporting of severe problems with overheating and lack of ability to control it: 'The flat is unbearable in the morning all summer long - too hot to sleep!' The use of air conditioning is mentioned by 4th and 7th floor residents. The hottest perceived floor is not the top (9th), as suggested by previous research results (Mavrogianni *et al.*, 2014), but the 8th floor.

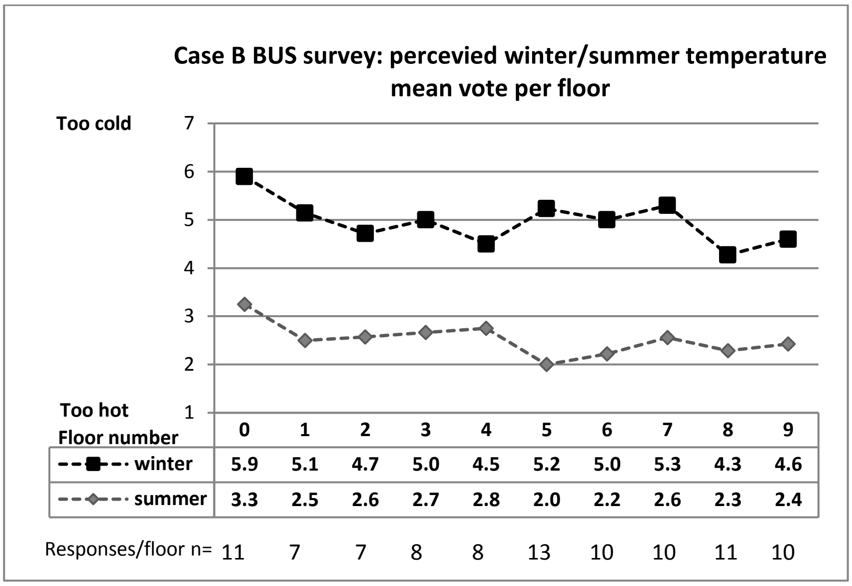


Figure 4. BUS survey results: perceived winter and summer temperature mean vote per floor.

Inhabitants feedback – Case A

In Case A the BUS results suggest that the temperature related issues experienced by the residents, both in summer and winter (Figure 5), are much less of a problem compared to the refurbished block of apartments (Figure 4). This is associated with the differences in design of the building envelope: much less glazing per floor area and better wall U-values in Case A compared to Case B. This leads to a more stable temperature profile with fewer extremes in Case A than in Case B. In winter all the residents perceive indoor temperatures as neutral apart from one who stated ‘Because I am ground floor I need my heating more than upper floor flats and I have needed it most [winter] evenings.’ In the summer, the only ‘too hot’ (2) rating is from a top floor flat. Insight into the reason behind lower satisfaction in that apartment comes through the interview: the resident prefers not to open the windows, rarely opens the balcony door and in general only relies on the mechanical ventilation with heat recovery (MVHR). However a vast majority of residents claim the MVHR does not cope with heatwaves and report the need to open windows for increased cross-ventilation to cool the interiors down. In the two storey houses, eight households rate summer temperatures around neutral slightly towards too hot. However, the contrast in these houses from ground to upstairs is revealed by these comments: ‘In the summer upstairs, opening the windows is necessary if it's hot outside’ and ‘Not great in summer but okay; bedrooms [top floor] can feel hot and stuffy for most of the time.’

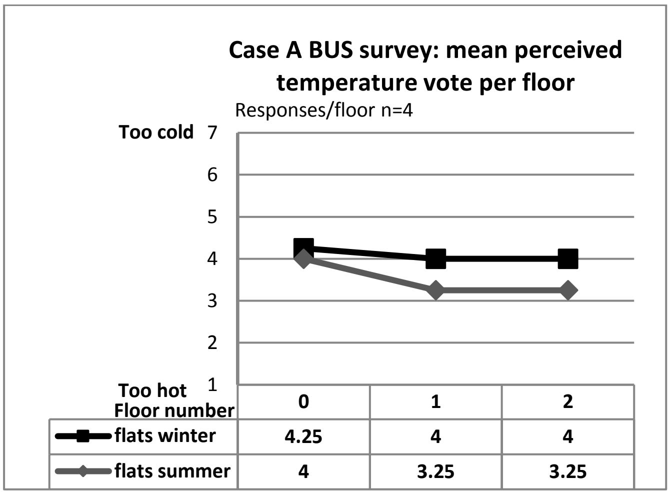


Figure 5. BUS survey results: perceived winter and summer temperature mean vote per floor for apartments.

Monitoring results

The effects of humidity on perception of warmth is not included in UK overheating guidelines as it has been found small in the range of temperature and RH experienced in the UK buildings (CIBSE Guide A, 2006, CIBSE TM52, 2013). It is covered by the (DCLG, 2012) however analysis of monitoring data for the purpose of this study is limited to dry bulb temperature. CIBSE overheating guidance refers to operative temperature, defined as mean of dry bulb and radiant temperature within an interior. As the sensors were left unattended in occupied dwellings operative temperature was not measured to keep the monitoring as discrete as possible.

Mean temperatures for ground floor dwellings compared to those higher up are lower in both developments for the warm period and the heating season as well (Table 2).

Temp. outside:		Mean temp. in dwellings [^{o}C]	
		Case B	**Case A**
<=10.5 ^{o}C	All dwellings	18.7	18.1
	Ground floor	17.0	17.2
	Above ground floor	19.1	18.6
>=15.5 ^{o}C	All dwellings	24.3	22.6
	Ground floor	23.5	21.5
	Above ground floor	24.5	23.1

Table 2. Mean temperature inside when heating is needed and when the temp. is >=15.5 (mean summer temp. for Leeds).

Interestingly when the two BUS survey results concerning satisfaction with the temperature inside are cross correlated it seems evident that both for summer and winter conditions higher comfort is achieved in Case A. This impression is confirmed with temperature monitoring for summer conditions (for the Leeds area mean summer temp. is 15.5^{o}C) – mean temperature inside is lower by almost 1.5^{o}C in Case A than in Case B (Table 2). However for the conditions outside below 10.5^{o}C, when heating is needed the mean temperature in Case B is 0.6^{o}C higher than in Case A. Thus in Case A lower temperature coexists with much fewer complaints about cold. One explanation for this may be the pre-bound effect as described by (Sunnika-Blank and Galvin, 2012). Custom questions extending the BUS survey captured perceptions of thermal comfort in previous accommodation that influences thermal expectations (Table 3). Case B residents come from higher standard, warmer and less drafty previous accommodation than cohousing residents, thus are more likely to be critical about cold in winter even if higher temperatures are achieved. Another factor explaining less criticism for lower temperatures may be the environmental attitudes all Case A residents sign in to. It has been shown through a case-study of two eco communities in Australia that environmental attitudes increase the level of acceptance for temperatures out of the normal comfort range (Daniel et al., 2014). In Case A it would be adapting to cold temperatures through wearing more clothes (Table 3). Last but not least Brager's work on adaptive comfort (Borgeson and Brager, 2011) has demonstrated that people are prepared to tolerate temperature ranges as wide as 16- 30°C depending on context and perceived degree of control in terms of adaptations. Interviews reveal that Case A residents are in general happier with their heating system and also they pay less for heating, thus keeping the temperature low is perceived as a conscious choice and not an external constraint. Further research would be needed to validate the relative impact of the above factors.

	Previous accomodation - mean rating				***Clothing - mean rating***				
	How would you rate your previous home in terms of comfort? Scale 1-7 (unsatisfactory-satisfactory)	*Temperature Winter: scale 1-7 (too cold - too hot)*	*Temperature Summer: scale 1-7 (too cold - too hot)*	*Air Still / Draughty: scale 1-7*	*How many layers of clothing do you have now?*	*…and how would you compare the number of layers of clothing in your previous accomondation at this time of year? [% of answers]*			
						1 - less	2 - same	3 - more	4 - I don't know
Retrofit (n=95)	4.7	3.1	4.3	4.2	1.9	16%	52%	25%	7%
Co-housing (n=20)	3.5	1.8	4.0	5.7	2.5	50%	40%	5%	5%

Table 3. Prebound in Case A and Case B – responses to custom questions extending BUS survey.

Factors influencing winter and summer temperatures

Stack effect overall

In the winter – influence of stack effect.

A thermal imaging survey performed in winter indicated substantial stack effect causing a 5°C temperature difference in the staircases in Case B (Figure 6). This was confirmed with temperature monitoring results in the block of apartments: the mean annual temperature on the 10th floor, in the core circulation area sheltered from the elements with a metal grill, is 4.5°C higher than on the ground floor and in the cold spell of winter the minimum temperature on the 10th floor is 6°C higher than the ground floor (Table 2). This significant difference suggests being one of important factors behind lower heating demand experienced by the residents of higher floors as shown in the BUS survey section. The stack effect in the core affects directly the closed zones of apartments. A further step would be to develop a model that accounts for stack effect in heat loss calculations depending on a dwelling's location and size of walls adjacent to staircases. Besides heat losses through the walls there is also an air supply into dwellings through a gap under the front door – this means that the apartments located higher are supplied with up to 6°C warmer air than the ground floor ones. A comparison of minimum daily mean temperatures for December 2013 - February 2014 achieved in an 8th floor inhabited unheated apartment with a ground floor one with similar heating habits (heating is rarely used) indicates a correlation of the inside and neighbouring core temperatures: blue for the ground floor and red for top floors (Figure 7). This graph also shows that the temperature in the 8th floor unheated apartment is more stable. Interestingly there are repeated instances when core on the 10th floor is warmer than the ground floor apartment (black arrows in Figure 7). Residents of both apartments rate them as too cold however the resident of the warmer one is more critical about the temperature – rating '1' compared to '2' from the colder apartment. Interviews and repeated home visits gave more insight into the reasons behind residents' restraint from using heating: economic for the 8th floor: 'It's cheaper to buy blankets' and environmental for the ground floor 'I'm an environmentalist and try to save resources'. The ground floor resident also claimed to 'feel cold a bit less' and interestingly was unaware of how low the temperature was in his apartment: he stated that the 21°C advised by the government was too high, but he aimed for 18°C, whereas the mean temperature achieved when the temperature outside was equal to or less than 10.5°C is 15.1 °C both for the living room and bedroom.

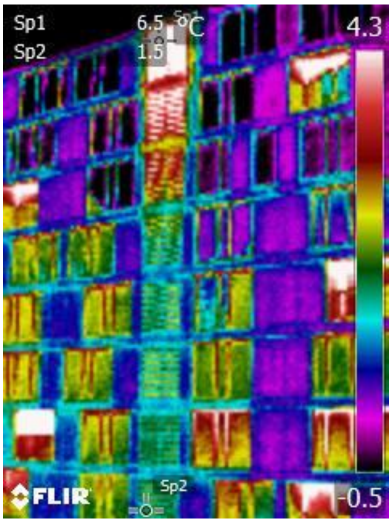


Figure 6. Stack effect visible on thermal image in the staircase core in Case B (16.02.2014, 23:43pm).

	Case B: Dry bulb temperature (annual monitoring results) [°C]			
	Staircase		Outside of the building	Bramham MetOffice weather station (10miles away)
	Ground floor	Floor 9		
Minimum	1.5	7.5	-1	-2.3
Maximum	25	29	29	Max 29.3
Mean	**12.92**	**16.43**	**11.14**	**10.47**
Median	12.5	16	10.5	10
Mode	11	12.5	9.5	10.5
Range	23.25	21.50	30	31.6

Table 4. Results of annual dry bulb temperature monitoring outside and on different levels of a staircase sheltered from the elements by metal grill (Case B).

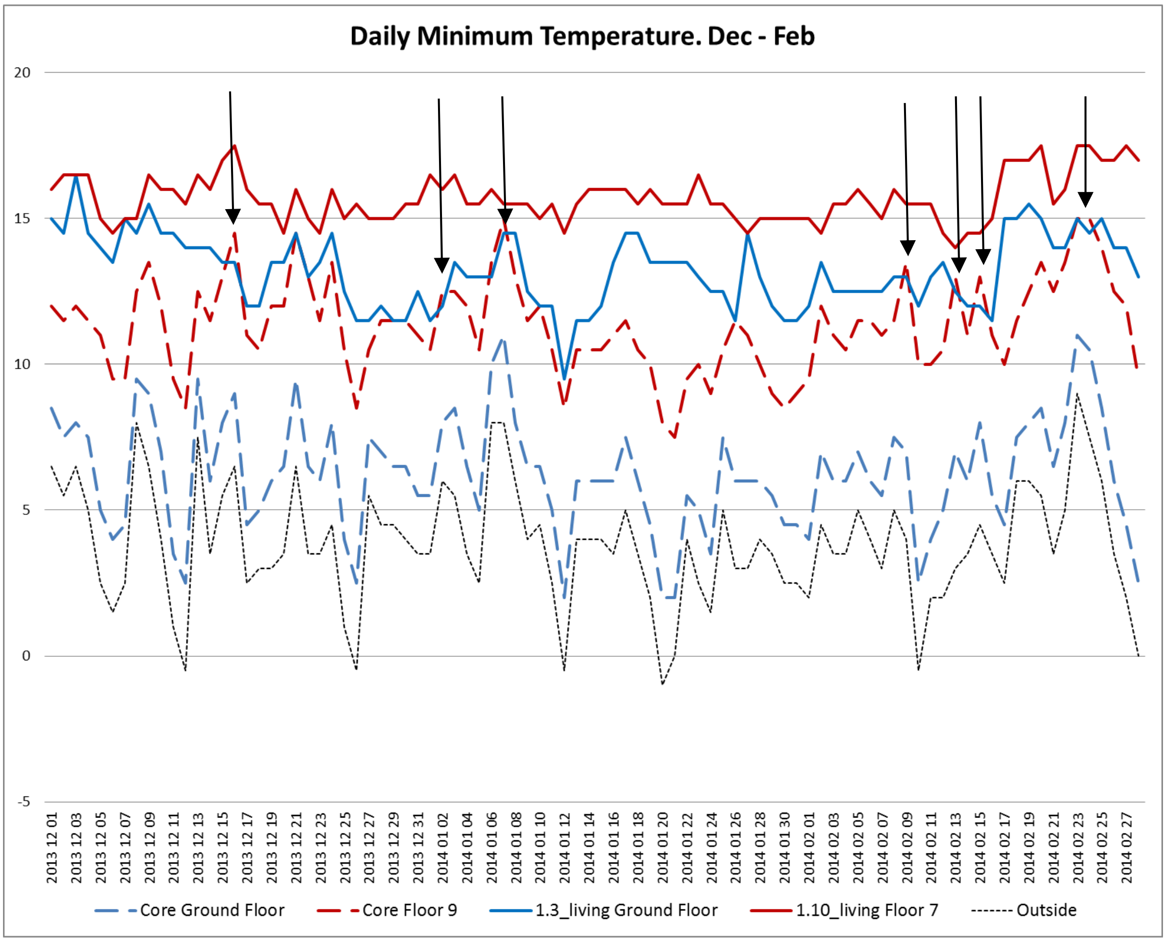


Figure 7. December 2013-February 2014 minimum daily temperatures: outside the building, in inhabited intermittently heated ground floor apartment, unheated 7th floor apartment, and staircase at ground and top floor.

Winter thermal comfort practices

Interviews conducted with 20 participants in each development provided insight into how they manage thermal comfort during the heating season. It has been established that the residents achieve comfort through a selection of the following: having the heating on, wearing additional clothing/wrapping in blankets instead of having the heating on or to keep the temperature lower, moving the furniture in order to sit in direct proximity to radiators (A), using 'draft excluders (B), using the oven to bake something when it's too cool, instead of turning the heating on (A), switching the extractor fans off to save the heat and prevent cold drafts, sealing the extracts vents, closing the trickle vents, keeping the bedroom doors closed for the night, using additional heaters (B), using electric blankets (B).

In the summer – stack effect and other factors

The same stack effect that helps to keep the apartments on higher floors warmer than the ground floor ones in the winter works also in the summer; then it helps to keep the ground floor flats cooler. The maximum temperature at ground floor level in the core is 4 degrees lower than both outside and on the 10th floor. Interestingly excellent ventilation of the staircase space prevents the build-up of heat in the core. Hot air escapes through the metal grills and the maximum temperature inside this space never goes above the maximum outside, that is 29°C. Unfortunately this does not apply to air tight apartments where the trapped heat builds up to 34.5°C.

For Case B, SAP 2005 indicated high risk of overheating for all the apartments regardless of their position in the block. The measurements and residents feedback covering a heat wave confirm that prediction for the majority of dwellings but in significantly varied intensity (Figure 8) that was not captured by the SAP prediction. The severity of overheating experience in some higher floor apartments is evident when mitigation practices are observed (Figure 8). On the other hand in some apartments residents are only happy with the temperature in their dwellings in summer.

For Case A apartments and houses SAP 2009 predicted ‘not significant’ risk of overheating. However Figure 8 indicates that overheating does happen there and, again, major differences between dwellings can be observed. Some Case A dwellings, houses in particular, experience comparable overheating issues as some Case B apartments.

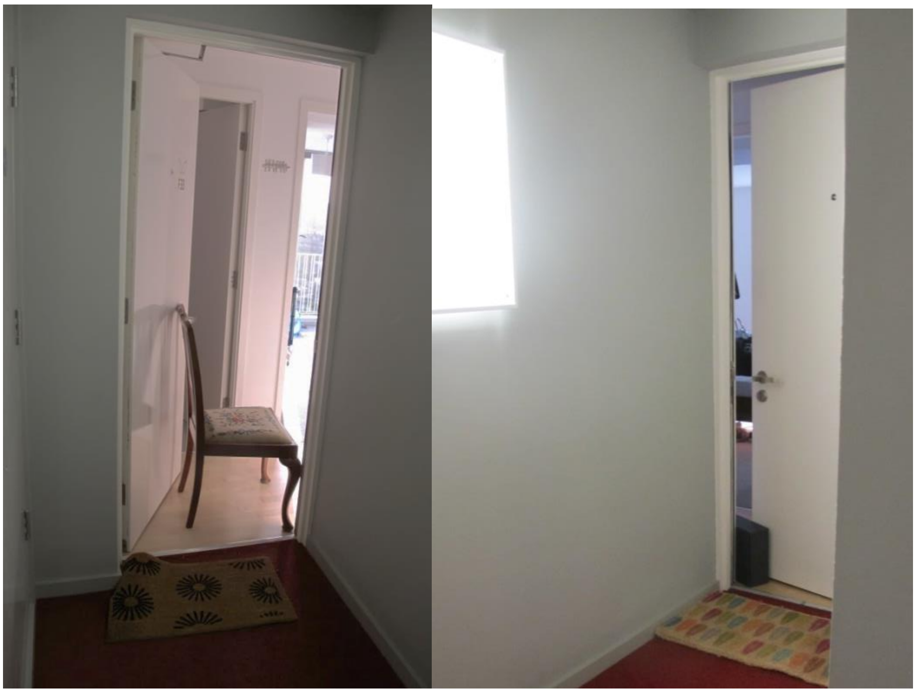
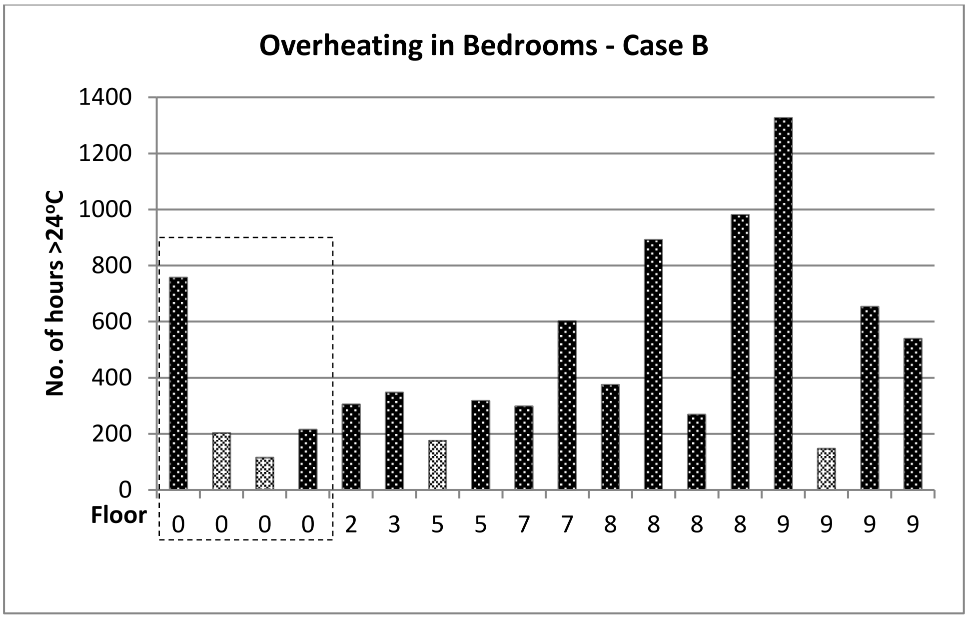


Figure 8. Case B: front door blocked open for cross-ventilation – security impaired for the sake of increased cross-ventilation. Photo MBN.

In Case B the temperature in the bedrooms between 10pm and 8am exceeds 24^{o}C, which is the threshold above which sleeping may be impaired (CIBSE, 2006), for a mean of 322 hours in the ground floor apartments and 704 hours for the top 3 floors. On average this overheating happens with varied intensity for minimum one hour across 56 nights on the ground floor and 89 nights on the three upper floors. Significantly lower overheating between east and west-facing bedrooms in this analysis (Figure 9) is influenced by the time frame examined; between 10pm-8am east-facing flats are only beginning to heat up whereas the west-facing one are only starting to cool down. In Case A the difference between average overheating hours in ground floor bedrooms (12.5 hours) and those on higher floors (362 hours) is even more distinct. Even though mean values indicate strong correlation between floor level and overheating intensity, the variations in overheating hours for apartments on the same level (Figure 9) suggest that other factors must be considered. Interestingly none of the Case A ground floor bedrooms experience overheating (all south-facing), whereas one ground floor bedroom in Case B overheats more than any other below the top two floors as discussed later. Further analysis is thus focused on ground floor apartments because of consistent low temperatures in Case A and anomalies in Case B that need examining.



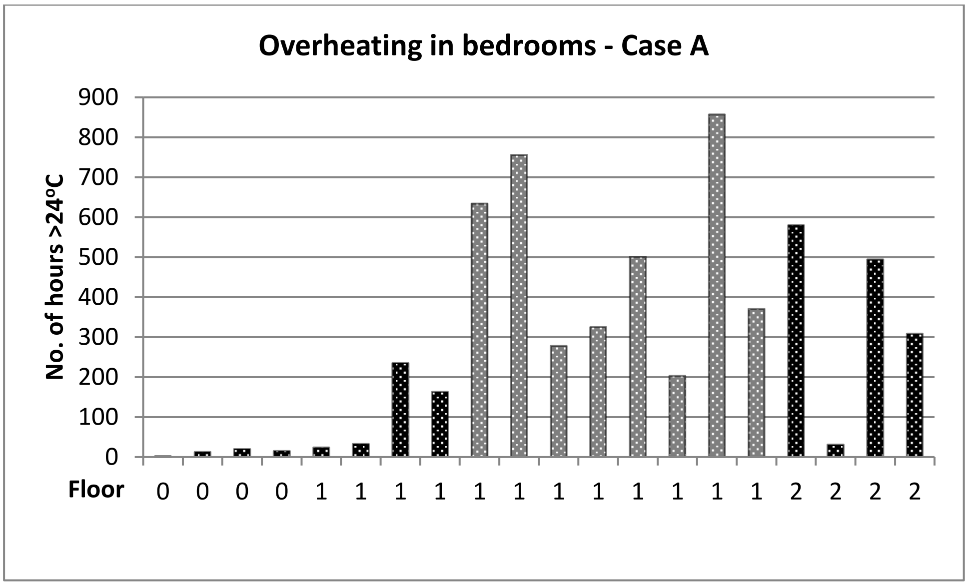


Figure 9. Overheating in bedrooms between 10pm-8am. Light grey data points on Case B graph are east-facing apartments – the rest is west-facing; Grey data points on Case A graph are bedrooms in houses – the rest are apartments in blocks of flats.

The physical context of ground floor apartments that were monitored is shown in Figure 10. East-facing bedrooms overlook a large green area with grass and low vegetation covering a west-facing slope. In the direct vicinity of east-facing apartments there are paved patios bordered with stone-filled gabions. West-facing apartment ‘1.2’ also faces a lawn however ‘1.1’ is adjacent to a gravel covered private zone and paved walkway. Beyond the walkway there is main, tarmacked parking for the development one level lower. From the parking level there is access to a basement level fully glazed towards the west. Thus Apartment 1.1 is the only ground floor one in the sample that does not have a ground floor slab but another floor underneath.

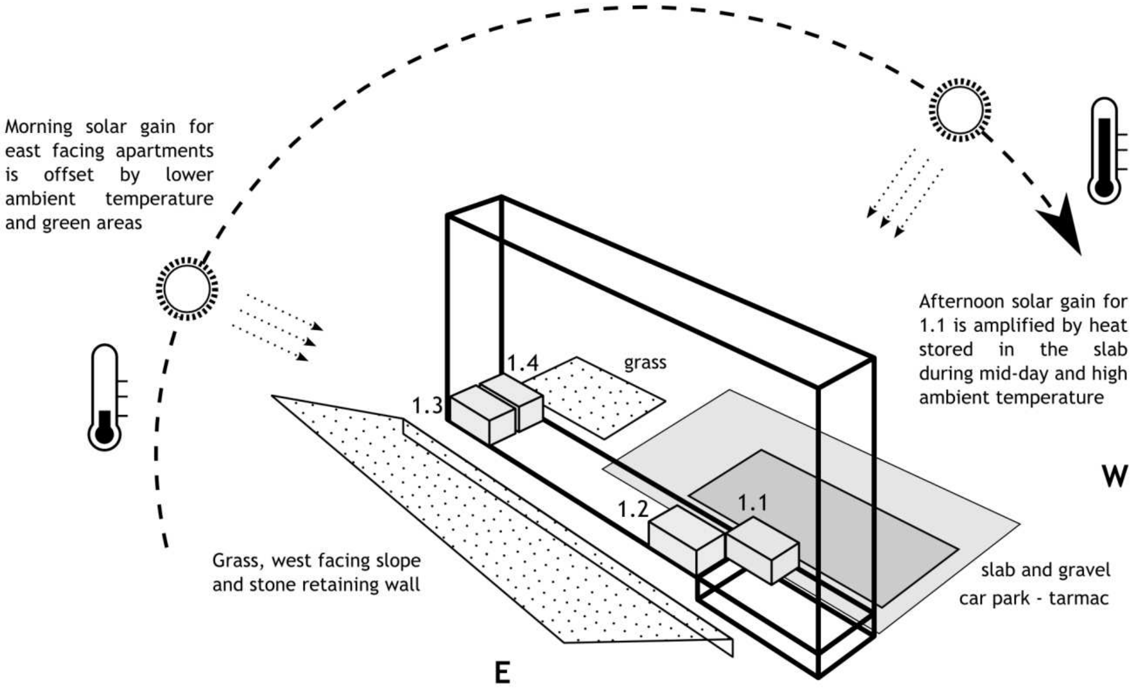


Figure 10. Physical context of monitored ground floor apartments in Case B.

Case B ground floor aptm.	Aspect	Solar exposure on 1st August			Temp. outside during solar exposure [°C]		Type of surfaces in direct vicinity	User behaviour during solar exposure		Ground floor slab	Bedroom temp. 1st August [°C]	
		Time	Duration [hours]	Direct insolation [kWh]	When exposure starts	Max		Occupancy pattern	Bedroom window opening behaviour		When exposure starts	Max
1.1	west	1:15-5:45pm	4.5	2.14	23	29	gravel, paving, tarmac	away	closed because away (patio doors)	No – another level below	26	34.5
1.2	west	1:15-5:45pm	4.5	2.18	23	29	grass, stone	away	closed because away	Yes	23	27.5
1.3	east	5:50am-1pm	7.2	4.4	18	25.5	grass, stone	at home	closed at night (patio doors)	Yes	22.5	28
1.4	east	5:20am-1pm	7.7	5.15	18	25.5	grass, stone	at home for part of the time	slightly open throughout the night (patio doors)	Yes	22.5	26.5

Table 5. Contextual and user related factors in four Case B ground floor apartments related to solar gain and overheating performance.

All the Case B apartments are equipped with mechanical extract ventilation and in all sample apartments the fans were off in the monitored heatwave period. Figure 11 shows temperature variation in the four ground floor bedrooms between 1st-3rd August 2013 – the hottest days of the 2013 heatwave. On 1st August the temperature outside reached the maximum for the whole monitoring period: 29°C. The graph shows that one ground floor apartment overheats much more than three others: for three consecutive days it reached the maximum of almost 35°C around 5:30pm. The maximum temperature for the other three bedrooms is within the range of 26.5-28.5°C: at around 10am for east and 5:30pm for west-facing bedrooms. Correlation of solar exposure duration (and direct insolation level) for each apartment with the maximum temperature inside indicates that the hottest bedroom is not the one most exposed to solar radiation (Table 5). On the contrary: the hottest bedroom is in one of two west-facing apartments ('1.1' and '1.2') that are equally exposed to 4.5 hours of solar gain, which is only 58% of the highest solar exposure in the sample: 7.7 hours for apartment '1.4'. Residents of both west-facing apartments have similar occupancy patterns: they're out throughout the solar exposure time and both apartments are closed with all windows shut. What's more the cooler west-facing bedroom has the lower share of openable window area. The hot apartment, like both east-facing ones, has sliding patio doors that allow half of the glazed area to open. In the cooler apartment '1.2' only one-third of glazed area can be opened and even that not fully but limited with restrictors to 10cm. That design feature is overridden by most residents in the heatwave and 'bespoke' solutions are invented to fix the window in an open position. Two distinct features of apartment '1.1' were identified that are assumed to be major contributors to significantly different performance during heatwave. Firstly '1.1' is the only ground level apartment in the sample that does not actually have ground floor slab: this section of the building has another level beneath it. The spaces below are also fully glazed towards the west and are heated in winter thus heat transfer in that direction is very limited. Secondly '1.1' is the only apartment in the sample that faces large paved, gravel and tarmacked surfaces instead of predominantly grass. Low albedo value (tarmac α=0.10) tends to increase the temperature of a surface exposed to solar radiation thus contributing to the heat island in an urban context (Taha, 1988, 1997). However it is not included in the SAP model. For calculating overheating risk the SAP model treats east and west orientations as equal. Table 5 indicates that the effect of solar exposure through east and west-facing windows it not the same: west-facing apartments, even though they are shaded by other buildings and so have shorter solar exposure time, heat up to the same or even higher temperatures than the east-facing ones. This can be explained by the indication that when heating by solar exposure started in east-facing apartments the outdoor temperature was 5°C lower than when it started in west-facing apartments. What's more, thermal radiation by stone and paving must have been reduced after lower night time temperatures. As a result opening the windows cools interiors to lower temperatures than in the afternoon when the air is warmer and heated surfaces add to the radiant contribution: minimum temperature in both east-facing apartments is always lower than in the west-facing ones. Also, the east-facing residents are in when the heating-up happens and can react by opening windows before the temperature reaches extreme values. The peak temperature is achieved at around 10am and then it starts to cool down before the residents come back from work. Having similar occupancy patterns the west-facing ground floor residents (understandably keeping windows closed when away for safety reasons) are in a much more vulnerable position: the whole period of solar exposure happens when they are away, windows are closed so heat builds up and when they come home it's more difficult to cool the flat down. In interview the resident of west-facing hot flat '1.1' states 'The overheating has been really bad. […] it has been like that most days; when I've been coming from work the heat just hits you'. On the other hand the resident of east-facing ground floor apartment '1.4' states: 'Maybe in my apartment it's not so hot because of the stone in the garden. In winter possibly that's why it's a lot colder inside, but in summer the stone might keep the sharp air. So it's not hot as you cannot breathe or it makes you tired. It's hot, but as soon as I open the window it cools down straight away'. This effect is not available in apartments located higher. The resident of the east-facing 9th floor apartment explained that during the heatwave on a weekend: '… we'll usually leave the flat by 10 o'clock at the latest and I'll either go into the garden or we'll go somewhere and do something. […] if it's nice outside I'd rather be outside but I would like to feel as if it was a choice…' They feel forced to leave the dwelling because of too high temperature.

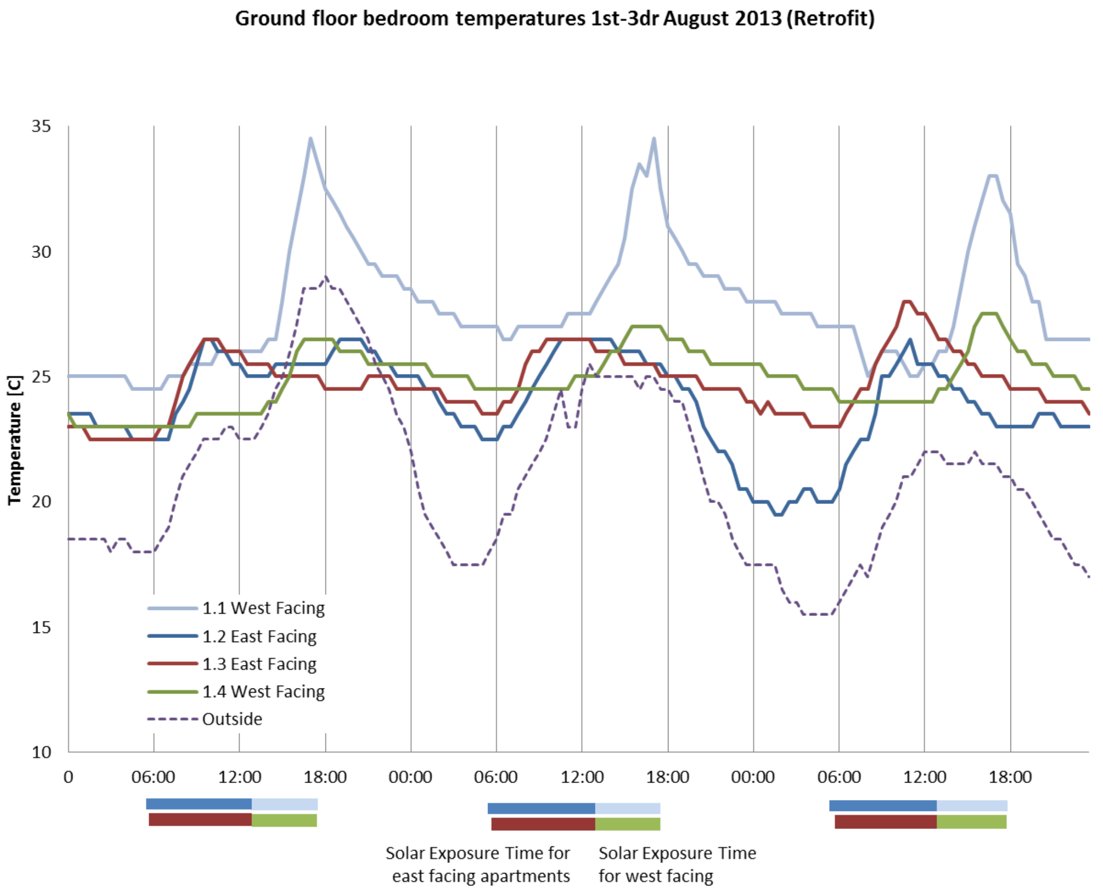


Figure 11. Daily temperatures in east and west-facing ground floor bedrooms – Case B.

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Conclusions

This study points towards temperature differences between dwellings located on different floors in line with temperature stratification in the staircase area. This difference - noticeable to the residents and confirmed with monitoring - was identified in two storey houses, where spaces are linked with an internal staircase, as well as a ten storey apartment block where apartments are separated from the communal staircase with more limited air exchange between the zones. It is recognised that it is not possible to strictly compare performance of buildings representing different energy standards. However it was felt important to highlight what the overall difference was with the combined factors in each typology, given that they are in the same climate zone and given that both are relevant typologies for the UK (low rise housing and high rise slab block). Occupants' perceptions of seasonal thermal comfort experienced in the developments over a period of one year in one UK city were compared. Such a comparison adds another (human perception related) dimension to energy and carbon footprint focused discussion about the value of different energy standards for residential buildings.

The study has also identified other factor - physical and user related - that contribute to variations in overheating. These provide a further insight as to why residents experience different comfort levels in different parts of a building or on different floors of an apartment block. While this case study cannot be generalised across all typologies, it demonstrates real effects that are occurring and the issues arising out of these. The UK SAP model needs to include stratification and external thermal factors such as albedo of external surrounding areas – more research is needed in this area. There should be separate guidance regarding overheating related to east and west-facing openings.

In Case B apartments, the lack of shading to large west and east-facing windows has led to overheating issues. These are exacerbated for most by temperature stratification at higher floor levels. Overheating can be so severe that people are ready to temporarily compromise on safety in their homes by leaving the front door open to diminish the high summer temperatures through increased cross ventilation. This behaviour was not apparent in any of the ground floor apartments.

Heating strategies are closely linked with ventilation strategies. In cold weather the heating and drive for energy conservation leads to compromised air quality as fans are switched-off and ventilation extract points sealed. This is clearly not ideal and alternative forms of more efficient heating and ventilation are required.

On the issue of insulating the ground floor slab, there are no clear results: in Case A clearly more insulation would be beneficial however in Case B the declared U-value for the ground floor slab is 0.17, which is high, but this is not verified and the problems reported are similar as in Case A.

It can be clearly seen from the rich data obtained by examining peoples comfort levels and heating practices that simple physical models with correlations of comfort temperature do not account for what is really happening in homes. It is important that future modelling of comfort levels takes the details of residents heating practices into account. One promising way forward here is nascent research on agent-based modelling related to building performance evaluation that attempts to account for some of these practices in order to provide a probability estimate of comfort, rather than an optimal level.

Brager's work on adaptive comfort (Borgeson & Brager, 2011) has demonstrated that people are prepared to tolerate temperature ranges as wide as 16-30^{o}C depending on context and the perceived degree of control in terms of adaptations such as those discussed in this study. The emphasis therefore must be on designing buildings that are robust and tolerant, offering a wide range of adaptation opportunities such as a variety of opening window positions, potential shading, other ventilation options, and other comfort taking practices. These can help overcome some of the inevitable temperature stratification issues with housing as well as addressing potential shortfalls in heating and ventilation technologies.

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