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RESEARCH PAPER

Overheating in retrofitted flats: occupant practices, learning and interventions

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ABSTRACT
The overheating risk in flats (apartments) retrofitted to energy-efficient standards has been identified by previous studies as one that is particularly high. With climate change and rising mean temperatures this is a growing concern. There is a need to understand the kinds of practices, learning and interventions adopted by the occupants of individual homes to try to reduce overheating, as this area is poorly understood and under-researched. This case study focuses on the impact of different home-use practices in relation to the severity of overheating in 18 flats in one tower block in northern England. Internal temperatures monitored in comparable flats show that the percentage of time spent above the expected category II threshold of thermal comfort according to BS EN 15251 can differ by over 70%. Extensive monitoring, covering a full year, including two summer periods, has identified emergent changes in heatwave practices linked with increased home-use skills and understanding among the research participants. Close analysis of design intentions versus reality has identified key physical barriers and social learning opportunities for appropriate adaptation in relation to heatwaves. Recommendations for designers and policy-makers are highlighted in relation to these factors.

KEYWORDS
adaptation; apartments; flats; housing; inhabitant behaviour; learning; occupants; overheating; retrofit; tower blocks

Introduction

One in six people in the European Union lives in a flat (BPIE, 2015). The overheating risk in UK flats has been identified by previous studies as particularly high, compared with other dwelling types (Beizaee, Lomas, & Firth, 2013; Lomas & Kane, 2013). In the mild UK climate, where the external summer temperature sometimes rises above a comfortable internal temperature, the vulnerability of flats is due to their relatively low external surface to floor area ratio compared with detached houses. This reduces conductive heat loss and the potential for ventilation cooling. Top-floor flats have repeatedly been found to be the most vulnerable. This is due to their minimal solar thermal protection through lack of shading from other buildings or trees and the additional solar gain from the roof (AECOM, 2012a). Contextual factors (*e.g.*, geographical location, orientation, solar gain via the thermal transmittance, excessive glazing, lack of appropriate external shading options, exposed thermal mass which cannot be adequately cooled via ventilation, and poorly insulated hot water pipes or other varying internal heat loads) have all been explored and linked with overheating (Kendrick, Ogden, Wang, & Bousmaha, 2012; Peacock, Jenkins, & Kane, 2010; ZCH, 2015). High-rise residential buildings are usually urban rather than rural and therefore impacted by the urban heat island effect – a growing concern due to global rising temperatures and predicted severe heatwaves (IPCC, 2014; Oikonomou et al., 2012; Vardoulakis et al., 2015). European Union policy is focused on lowering heating demand as this is the major load in energy consumption in the residential sector in most European countries (European Parliament, 2010). However, regulations for retrofitting also need to respond to the potential overheating risk, so that refurbishment does not worsen summer temperatures in dwellings (Sehizadeh & Ge, 2014). For example, external solar shading, although typically found in vernacular residential architecture in southern Europe and confirmed by models as an effective tool for the UK, is not obligatory in the British residential sector (BPIE, 2015). The impact of user behaviour on overheating in a domestic environment, though significant (O'Brien & Bennet, 2016), is also not sufficiently understood, despite ongoing field and modelling studies (Arethusa et al., 2014; Porritt, Cropper, Shao, & Goodier, 2012). This has implications for the validity of modelled overheating

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predictions which inform design guidelines and for overheating action plans to minimize the impact of heatwaves on public health (Lowe, Ebi, & Forsberg 2011; D'Ippoliti, 2010). Therefore, a need exists to understand better the kinds of practices and interventions adopted by inhabitants in terms of overheating. There is also a need to explore what interventions can be encouraged through design and as part of occupant guidance.

In a UK hospital study, Lomas and Giridharan (2012, p.66) point out that:

> the minimum recorded temperature […] occurred on one of the warmest nights of the year […]; on this day a Level 2 heatwave alert was issued; in response to which, night time cooling by opening windows is a recommended procedure. It seems ironic that the coolest night time temperature, […] should occur on one of the hottest nights.

This was clearly due to staff having good procedures in place for appropriate heatwave ventilation and knowing how to act on them. Within a domestic environment, however, the inhabitants need to tackle overheating using their own knowledge and skills, and the impact of their behaviour on the thermal environment needs to be carefully measured and evaluated due to its significance in this sector (Mavrogianni et al., 2014). Equally, the need to focus on the prevention of overheating may not be obvious to many inhabitants because:

- the degree of overheating risk varies for different housing typologies – flats in tower blocks are at greater risk than houses
- temperatures are higher in the city centre than in rural areas
- climate change is likely to lead to increasing heatwaves over time, which will gradually affect housing typologies previously resistant to overheating (While & Whitehead, 2013)

Inhabitants thus may lack tacit knowledge in terms of overheating control practices accumulated through experience. Nevertheless, they clearly need to cope with overheating. Adaptive thermal comfort theory states that 'If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' and that 'those with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort' (Nicol & Humphreys, 2002, p. 564). Recent studies have revealed that environmental control systems are not used by inhabitants as intended in optimized design models and this has led to significant performance failures (Brown & Gorgolewski, 2015). If these performance failures lead to widespread adoption of mechanical cooling, then there would be a significant impact on resource use (Gram-Hanssen, 2013; Janda, 2011).

Given the increasing challenge of overheating, inhabitants need to use their own appropriate tacit knowledge, where available, and modify their practices. Learning occurs most effectively within the sensory category of 'trigger and feedback', strengthened by cognitive apprehension and social learning. Sørensen (1996, p. 6) characterized this as 'a combined act of discovery and analysis, of understanding and giving meaning, and of tinkering and the development of routines'. The current study is largely focused on cognitive access to technology and trust (Glad, 2012) and enhancing certainty (Tormala, 2016). The intent is to lower the risk of inhabitants resorting to air-conditioning (AC) and improve their low-energy overheating mitigation practices.

Three key research questions arise from the above:

- What is the relationship between the indoor and outdoor air temperature profiles and inhabitant behaviour in retrofitted flats?
- To what degree do housing inhabitants exploit the opportunities to adapt the environment to their thermal requirements using the fabric and systems installed?
- How can the adoption of heat mitigation best practices be enhanced in retrofitted housing developments?

The focus of this paper is on understanding the various practices that inhabitants adopt when reacting to overheating discomfort. A test sample is comprised of 18 comparable flats (out of 200) in a typical 10-storey 1960s' UK tower block after deep retrofit. The impact of the identified practices is then compared against the heat-gain calculations and performance of the fabric and system features of the case study flats. The major differences identified in terms of inhabitants' skills, learning and understanding of their home environments prompted careful analysis of the design intentions and practices in order to highlight how both can be improved, given the severe consequences of the findings.

Case study

Tower block

The 'typical' case study for this paper (Yin, 2009) was a 10-storey tower block located in a central urban area of a major city in the North of England with deep retrofit work completed in 2012 (Table 1). Only 15.2% of UK dwellings are purpose-built flats (DCLG, 2015, Annex

Table 1. Case study building and participants' characteristics.

Case study	Deep-retrofit 1950s' apartment block
Renovation completion	2011
Number of floors	10
Dwellings	234 dwellings: one and two bedroom; owned/shared ownership/rented
	Single aspect: east (one bedroom) or west facing (mostly two bedroom)
Floor to ceiling height (m)	About 2.2
Apartment floor area (m^2)	32.2–57.2
Apartment glazing-to-floor ratio	30–88% in bedrooms; 22–44% in living/kitchen area
Thermal mass	Low (walls and ceilings clad with gypsum board, acoustic floor clad with wood panels)
Fabric *U*-values[a]	External wall SIPs panels: $U = 0.20$ W/m^{2}K, clad in anthracite panels to the west, otherwise light grey; stairwell wall: brick and block $U = 0.25$ W/m^{2}K; flat roof: $U = 0.2$ W/m^{2}K; modified bitumen membrane; double-glazing (trickle vents on the ground floor): $U = 1.57$[a] W/m^{2}K (1.71 in standard assessment procedure – SAP); concrete floor slab: $U = 0.17$ W/m^{2}K
Air permeability	Designed: $q_{50} = 7$ m^3/h.m^2; achieved: $q_{50} = 4.29$–5.33 m^3/h.m^2 (from a sample of four tests available)
Ventilation system	Mechanical extract ventilation (MEV) – extract fans in the open kitchen and bathroom
Energy standards	2006 UK Building Regulations for retrofit; Eco Homes Very Good
Demographics[a]	66% less than 30 years old; five occupants less than 18 years; 60% two-adult households, 40% single-adult (including two single parents)

Note: [a]Data are from the Building Use Studies (BUS) survey which covered the whole population of the building (response rate = 44%).
SIPs = structural insulated panels

Table 2.1), which is low compared with the European average of 32% (BPIE, 2011). Nevertheless, the typology is important because overall about 36 million households in the European Union live in high-rise tower blocks (IEA, 2006). Many of these are decades old and require upgrading to avoid overheating risks. This study focuses on the actual thermal environment and inhabitant home-use practices in hot weather spells in this most vulnerable building type, without active cooling.

The private case-study refurbishment project aimed to improve a challenging neighbourhood. As such, the designers found the planning process very straightforward with little critical appraisal of the design intentions beyond the regulatory minimum for refurbishments at the time. As the use of the Standard Assessment Procedure (SAP) (DECC, 2009) overheating calculation was not mandatory, the overheating risk was neither identified nor tackled at the design stage. The study examined inhabitants' practices during the summers of 2013 and 2014 as part of a wider European Union-funded research project.

Flat design

On each floor, two cross-ventilated flats spanning the width of the block in the original layout were refurbished and extended into four single-aspect flats (Figure 1). They were equipped with continuous mechanical extract ventilation (MEV), with extractor units in the kitchen and bathroom only, and large windows in the principal rooms (with ventilation openings 20–50% of the glazed area). Window opening options were either through side-hung casements or by sliding doors where there was a terrace or a balcony available. Trickle vents were installed in the ground-floor flats only for security reasons – despite the original design intention to install them on all floors. Supply-chain issues, driven by delivery time, resulted in a change of window supplier and specification. This then resulted in windows that could be locked in a trickle position but which lacked actual trickle vents. A window opening width of 100 mm maximum (locked with a restrictor for safety reasons due to height) was another means of natural ventilation. The strategic decision to keep the original concrete structure of the existing building resulted in very low ceiling heights (about 2.2 m), with floor to ceiling glazing to counterbalance the cramped feeling. The relatively high glazing-to-floor area ratio varied for different flats between 22% and 44% for the living/dining/kitchen area and between 30% and 88% for bedrooms. Exposed concrete walls and ceilings were covered with gypsum board and insulation to hide electrical wiring and improve soundproofing. However, this minimized any benefit of the thermal mass and potential night purging. These procurement stage design and specification decisions had clear overheating consequences, which are discussed below.

Participants

A stratified 10% sample of households from across the flat types and locations in the building participated in the in-depth research study. In addition, the entire household population of the tower block ($n = 200$) was surveyed using an adapted form of the well-known

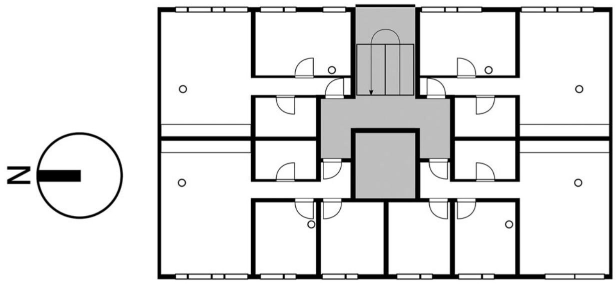


Figure 1. Four single-aspect apartments per floor accessible from the communal communication core. The location of the temperature sensors is indicated by circles.

Building Use Studies (BUS) survey (Leaman, Stevenson, & Bordass, 2010). The current authors added several questions to the survey specifically in relation to window opening, heating, ventilation and the occupants' previous accommodation. Two of the initial 21 households moved away, with two subsequent volunteer households substituted. One household withdrew their data by the end of the study. The analysis is based on the 18 households who participated throughout the study (Table 2). In 88% of these households, regular occupancy patterns prevailed, with the inhabitants generally out at work during the weekdays. The remaining 12% stayed at home most of the time, either working from home or being in retirement or remaining unemployed. One limitation of the research sample was the lack of families with children. The tower block was predominantly occupied by young individuals or couples (Table 1).

Methods

The case study used a broad variety of quantitative and qualitative methods (Table 3) to provide an in-depth understanding of inhabitant activities related to fabric and systems in a domestic environment, and the resulting thermal environment achieved.

Recruitment process

Inhabitants were recruited via posters placed in the communal areas; a research team meeting with the inhabitants organized in conjunction with the occupants' association meeting prior to the study commencing, and information letters delivered anonymously to each flat followed by door-to-door visits by the field researcher. A financial reward of £50 per household was given after the completion of all the planned research tasks.

Table 2. Monitored apartments' characteristics.

							24 July–31 August 2013			
		Glazing-to-floor ratio (%)					Average heat gains (kWh/m^2)		Mean temperature (°C)	
Apartment	Number of floors	Bedroom	Living	Orientation	Number of occupants	Occupancy[b]	Bedroom	Living	Bedroom	Living
1	1	67	44	West	1	Partial/regular	27.5	26.0	25.5	25.2
2	1	48	27	East	1	Partial/regular	19.9	17.8	23.4	23.9
3	1	48	22	East	1	Mostly home/varied	19.9	15.2	23.4	23.2
4	1	30	34	West	1	Partial	12.3	17.3	23.4	23.6
5	3	40	32	West	2	Partial	16.7	19.1	23.7	22.9
6	4	88	37	West	2	Mostly home/regular	37.3	21.7	24.5	25
7	6	49	44	East	2	Partial/regular	20.8	21.3	24.2	24.6
8	6	40	25	West	2	Partial/regular	20.5	15.1	23	23.2
9	8	40	25	West	2	Partial/regular	20.5	17.1	22.8	22.9
10	8	40	34	West	2	Partial/varied	16.7	18.4	25.4	25.3
11	9	88	37	West	2	Partial/regular	37.3	22.0	26.4	25.7
12[a]	9	88	37	West	2	Partial/regular	37.3	22.0	23.6	24.1
13[a]	9	88	37	West	1	Partial/regular	34.4	20.6	26.3	27
14	9	40	25	West	2	Partial/regular	20.5	15.1	24.7	25.3
15[a]	10	40	32	West	2	Partial/regular	21.7	20.3	26.6	26.2
16[a]	10	53	33	East	2	Partial/regular	24.0	20.4	22.5	22.6
17[a]	10	40	32	West	1	Partial/regular	17.9	21.9	23.9	23.4
18[a]	10	40	25	West	1	Partial/regular	17.9	15.3	24.5	26.8

Notes: [a]Apartment selected for in-depth analysis.
[b]Partial/regular = weekdays about 08:30–18:00 away from home; partial/varied = weekdays away from home daily but not fixed times mostly; home/regular = regular pattern of up to half a day away from home mostly; home/varied = irregular pattern of up to half a day away from home.

Table 3. Aims, focus and research methods applied in the case study presented.

Aim	Focus	Methods used
Evaluation of building-related overheating risk	Fabric and systems as designed and as built	Design and construction audit – design and commissioning documents audit verified with on-site visits (mechanical ventilation air flow rate check, thermal imaging, photographic survey) Interview with the design team (May 2013) Standard assessment procedure (SAP) check Air tightness certificate check Simple heat gains calculations using weather data from the MIDAS MET Office database
Evaluation of thermal environment achieved	Bedrooms and living rooms temperature monitoring	Dry bulb temperature monitoring (I-button sensors) for one year; half-an-hour readings (24 July 2013–24 July 2014)
	Thermal comfort guidance in BS EN 15251 and CIBSE Guide A (2015)	Measured temperatures analysis against guidance criteria
Overheating mitigation practices	Mechanical ventilation system operation Window/doors operation Windows shading operation Home-use skills and understanding Constraints like occupancy profile and other	Repeated observation and conversations during home visits for one year (about four days in the case study every seven to eight weeks) Interview Building Use Studies (BUS) survey (February 2014) Usability survey (January 2014) Residents' Facebook group content analysis
Overheating practices learning	Tacit knowledge from previous accommodation Home-user's guide (HUG) Handover process Collective home-use learning opportunities Impact of increased understanding due to participation in research	BUS survey extended with bespoke questions Home User's Guide check Interview (July 2014) Facebook group content's analysis Analysis of change in the temperature profile during hot spells in subsequent summers

Occupant feedback and home-use practices

An in-depth building performance evaluation (BPE) methodology (Guerra-Santin & Tweed, 2015) was adopted in parallel with an investigation into specific overheating mitigation practices. Tacit knowledge, learning opportunities and the usability of controls were examined as well as occupant understanding and skills (Stevenson, Carmona-Andreu, & Hancock, 2013). An ethnographic approach (Hammersley & Atkinson, 2007) guided home visits every seven weeks for the duration of the monitoring period. This involved repeated researcher observation of fabric and system settings, a walk-through with the inhabitants, informal discussion between the researcher and inhabitants in their homes, detailed notes taken of each visit and a photographic/thermographic survey of the complete tower block. The resulting analysis informed the questions for the final semi-structured interview with the inhabitants at the end of the study. Additional data on inhabitant practices related to overheating and their understanding of the available mitigation methods were acquired through content analysis of a closed Facebook group of the inhabitants which operated during the study and beyond (Baborska-Narożny, Stirling & Stevenson, 2016).

Temperature monitoring and evaluation

All 18 participating flats were monitored continuously from 24 July 2013 to 24 July 2014 using three wireless iButton sensors DS1923 to log temperature and relative humidity (RH) levels in the living room and bedroom every 30 min. This interval was deemed adequate for the purposes of the study, which was mainly to examine diurnal temperature profile patterns in relation to inhabitant practices. The sensors were placed by the researcher on internal walls or fixed furniture at a height of 800–1000 mm and away from direct sunlight, as recommended (Figure 1). In order to extend the period between visits for downloading data and thus keep the number of visits manageable, the sensors were set for a low resolution allowing an accuracy of better than ±0.5°C within a temperature range of −10°C to 65°C according to the manufacturer's data sheet. Temperature error analysis indicated faulty readings in 0.1% of cases, which were removed from further calculations. Radiant heat monitoring could not be performed due to practical constraints of minimizing the visibility and maximizing the robustness of the equipment installed in flats. This is a typical limitation found in other field studies (Beizaee et al., 2013).

Analysis and discussion

Evaluation of thermal environment

Weather

To understand the internal thermal environment in relation to external weather conditions, meteorological data were retrieved from the MIDAS Land Surface Observation database run by the Meteorological Office for Bramham weather station located 10 miles (15.4 km) from the study site (UK Meteorological Office) (Figure 2). During the monitoring period between 24

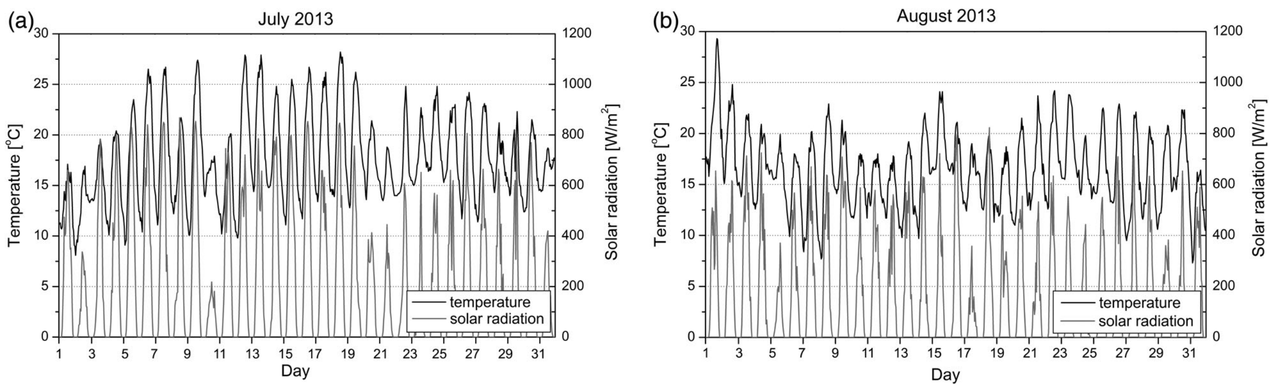


Figure 2. External temperature and solar radiation for (a) July and (b) August 2013 retrieved from Bramham MET office weather station.

July 2013 and 24 July 2014 the maximum extreme temperature of 29.2°C occurred between 17:00 and 19:00 hours on 1 August 2013, triggering a 'heatwave' in this location for this period only, according to the 'Heatwave Plan for England' (NHS, 2015). Both the July monitoring periods of 2013 and 2014 were relatively warm compared with the long-term average for the same period, but below record temperatures (Table 4). However, the summer of 2013 was hotter than that of 2014 and a period during July and August 2013 was therefore selected for the monitoring results analysis. Another vital reason for focusing on the first summer period was that it showed the practices and interventions unaffected by any research feedback and instead based on the typical occupant learning situation, *i.e.*, relying on tacit knowledge from previous accommodation, home owners' guide, on-line resources, trial and error etc. This provided a better representation of the challenges related to overheating of the retrofitted flats.

The external environment of the tower block generated considerable overheating potential due to relatively little overshadowing and an inner-city location subject to the urban heat island effect. A strong albedo effect was observed (but not monitored) with a black asphalt car park running continuously along the west side of the building, resulting in excessive heat due to the build-up of solar gain during the day, whereas the east facade looked onto a green landscaped area which provided a cooling effect.

Table 4. Average monthly temperature for Leeds.

	Average monthly temperature for Leeds (°C) (1961–1990)[a]			
	Mean	Warmest	2013[b]	2014[b]
July	14.8	18.8	17.7	17.3
August	14.5	18.3	16.5	14.5

Notes: [a]MET Office statistics for Leeds:
[b]UK Meteorological Office (2015).

Monitored temperatures

During the monitoring period between 24 July and 31 August 2013 the mean internal temperature in the monitored flats was almost 8°C higher than the average external air temperature of 16.7 with 24.4°C registered in the bedrooms and 24.6°C in living rooms. These results suggest uncomfortably warm bedrooms according to the UK Chartered Institution of Building Services Engineers (CIBSE) guidance, which states that above 24°C the quality of sleep may be compromised (CIBSE, 2015). CIBSE static overheating criteria for bedrooms relates to occupied hours only and these are typically assumed to be between 23:00 and 07:00 hours; however, it is worth noting that four out of the 95 BUS survey respondents and one of the 18 in-depth study households worked in shifts, which meant that their sleeping hours did not match those considered in the earlier studies (Lomas & Kane, 2013). Prevailing occupancy patterns for the 18 households were established based on repeated home visits and interview findings. These were then applied to all the flats to enable a comparison of their thermal environments. Temperatures in bedrooms were examined for the period 22:30–07:00 hours on weekdays (8.5 h/day) and 22:30–09:00 hours on weekends (10.5 h/day). The living rooms were examined for 07:00–08:30 and 18:00–22:30 hours on weekdays (6 h/day) and for 09:00–22:30 hours for weekends (13.5 h/day). Results indicate a significant variation in the thermal environment across the flats (Figure 3) with a 4.7 and 4.3°C range in mean temperature in bedrooms and living rooms respectively (Table 5). Major overheating occurs in 44% bedrooms and in 28% of living rooms according to CIBSE static criteria for an overheating risk. Within the 39-day period analysed, the maximum annual 1% allowance for temperature over the threshold of 28°C for living rooms and 26°C for bedrooms was exceeded. The total annual occupied hours calculation yielded a constant occupancy pattern throughout the

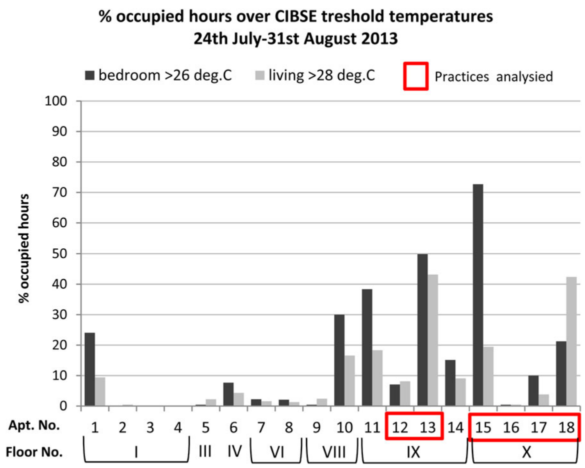


Figure 3. Percentage of occupied hours above 26°C in the bedroom and 28°C in the living room (24 July–31 August 2013).

year of 3303 h for bedrooms and 2964 h for living rooms. Unsurprisingly, the BUS survey prompted 43% of the respondents ($n = 95$) to complain about overheating with occupants commenting that their homes were 'Like an oven in the summer' and that 'The heat in summer is unbearable.' This would seem to confirm the CIBSE guidance and indicates that the *subjective* overheating issue was as severe for occupants as the physical measurements would seem to suggest. The BUS survey is clearly not a proxy for a thermal comfort study (Nicol & Roaf, 2005), but it does confirm the significance of the perception of overheating issue at the time it was carried out in February 2014. Thermal environment variation between different flats is further demonstrated by a more detailed thermal comfort model analysis in the following section.

Ventilation issues

A gap between the ventilation design intention and the observed inhabitant practices clearly created some of the overheating issues. The home visits and survey results confirmed that only 6% of BUS respondents used the ventilation system as intended (*i.e.*, keeping the MEV fans on continuously in the kitchen area and bathroom), while a further 3% kept just one fan switched on continuously, usually in the bathroom. Significantly, 32% of respondents never switched the fans on at all and a further 17% felt that the question was simply not applicable. This practice during hotter periods indicates a major gap in the inhabitants' understanding of the MEV role in overheating mitigation. Keeping the MEV

Table 5. Living and bedroom temperatures in occupied hours (24 July–31 August 2013).

	Living					Bedroom				
			Temperature (°C)					Temperature (°C)		
Apartment	Number of hours > 28°C	% of hours > 28°C[a]	Minimum	Maximum	Mean	Number of hours > 26°C	% of hours > 26°C[b]	Minimum	Maximum	Mean
1	**29.5**	9.4	19.5	31.5	25.4	**86.5**	24.0	21.5	29.0	24.8
2	1.5	0.5	18.0	31.5	23.7	0	0.0	18.0	25.5	22.1
3	0	0.0	20.0	26.5	23.4	0	0.0	20.0	25.5	22.5
4	0	0.0	21.5	27.0	23.9	0	0.0	21.0	25.5	23.2
5	7.0	2.2	17.0	29.0	23.2	1.5	0.4	19.5	26.5	22.9
6	13.5	4.3	22.0	30.0	25.1	26.5	7.6	19.5	27.5	23.8
7	5.0	1.6	20.0	28.5	24.7	8.0	2.2	20.0	27.0	23.4
8	4.0	1.3	19.0	28.5	23.5	7.5	2.1	19.0	27.5	22.6
9	7.5	2.4	19.0	31.5	23.3	1.5	0.4	19.0	26.0	22.6
10	52.0	16.6	20.0	30.5	25.6	**108.0**	30.0	20.5	29.5	24.9
11	**57.5**	18.3	220	33.0	26.1	**138.0**	38.3	22.0	34.5	25.9
12	25.5	8.1	20.5	31.5	24.4	25.5	7.1	19.0	29.0	23.2
13	**135.5**	43.2	23.5	35.0	27.6	**173.5**	49.9	23.0	30.5	25.8
14	28.5	9.1	21.5	30.0	25.5	**54.5**	15.1	20.0	29.0	24.3
15	**61.0**	19.4	23.5	30.0	26.5	**251.5**	72.7	22.5	30.0	26.3
16	1.5	0.5	18.0	28.0	23.0	1.5	0.4	18.0	26.5	21.6
17	12.0	3.8	18.5	32.5	23.7	**36.0**	10.0	20.0	28.5	23.6
18	**133.0**	42.4	23.0	33.0	27.5	**76.5**	21.3	20.0	29.0	24.0

Notes: [a]Total occupied hours: living room = 314; 07:00–08:30 and 18:00–22:30 hours weekdays and 09:00–22:30 hours weekends.
[b]Total occupied hours: bedroom = 360; 22:30–07:00 hours weekdays and 22:30–09:00 hours weekends.
Outside temperature: 0.7% of hours above 28°C.
Values shown in bold = annual overheating time criterion limit exceeded (33 h for bedroom and 29.5 h for living room).
Monitoring period analysed: 24 July–31 August 2013 (39 days).

fans off altogether, instead of switching them on only intermittently, occurred in all the flats except for one, *i.e.*, the best performing in summer 2013 – number 16 (Table 6). Interestingly in one of the flats most prone to overheating, *i.e.*, number 13, poor shading practices in the bedroom with an excessive 88% glazing-to-floor ratio were partially mitigated by keeping the MEV fan continuously on in the en-suite bathroom. Other studies of continuous mechanical ventilation in housing have had similar findings in relation to occupant behaviour (Balvers et al., 2012), but these have mostly focused on air quality or heat loss with no particular interrogation of the interrelationship between overheating issues and inhabitant understanding and use of technology.

A total of 30% of respondents kept their windows open constantly on the latch to provide a 100 mm air gap during hot spells, but a higher percentage (46%) only opened the windows when they were at home due to security issues for ground-floor inhabitants and the risk of window damage on higher floors from high winds while the occupants were away. This latter risk was explicitly identified in the Home User's Guide (HUG), explaining that the restrictors were not designed to withstand adverse weather conditions. Additionally, the property managing company sent notices to each household reminding them that they would be liable for any damage resulting from leaving unattended windows open. However, only 33% of the sampled inhabitants were aware of the trickle ventilation option in terms of the various practices related to the window design (Table 6). The interviews indicated that those who were aware of this option had previous experience with similar windows and thus expected, and actively sought, such functionality. Unfortunately, the trickle lock on the windows was not mentioned in the HUG, leading to further occupant misunderstanding. Instead, misleading guidance stated that air circulation in a flat could be achieved by regulating trickle vents that were not actually installed. As the heat built up in the sealed interiors during the day due to external heat gains, those who kept their windows closed while they were away (as advised) experienced severe overheating when coming home late in the afternoon. To mitigate this, they then opened the windows wide releasing the restrictors altogether – an action actively discouraged by the facility manager due to safety issues arising from the poor design of the large size of the windows, which could swing wildly without any restriction. The severity of overheating experienced even prompted some inhabitants on the top four floors to keep their front doors wedged open for cross-ventilation, despite the security issue arising from this action (Table 6). All the interviewed residents admitted having the windows open without restrictors at some point during the summer, knowing this was against the guidelines.

A portable AC unit was bought by one of the participating households and used temporarily during the hot period in July and August 2013. The occupants would switch it on in the afternoon after they returned from work. This was partly a result of the occupants not having any shading in the living room and keeping the MEV system switched off in order to 'save electricity'. They did not realize that their individual AC unit (800 W) was potentially using more power than the MEV system within their home (2–5 W per fan depending on trickle or boost fan-speed mode).

Adaptive thermal comfort

The dynamic thermal comfort variation analysis (Lomas & Giridharan, 2012; CIBSE, 2015) reported here was based on temperature measurements in all the occupied bedrooms and living rooms during the key monitoring period referred to previously. It indicated significant differences between flats in terms of temperatures (Figure 1). Ideally, a residential building should comply with the comfort criteria for category II according to guidance issued in the UK (CIBSE, 2015, pp. 1–17). If the measured temperature exceeds the recommended threshold II boundary temperatures in relation to the changing outdoor running mean temperature, then the thermal comfort is affected negatively. Results for each flat show very different thermal conditions in comparable flats with significant comfort issues arising according to this guidance:

- 22% of the sample flats (numbers 11, 13, 15 and 18 – ninth and tenth floors) overheat for over 20% of the occupied time, and the living rooms in numbers 13 and 18 overheat for over 40% of the occupied time
- 28% of the sample flats (numbers 2, 5, 8, 9 and 16 – ground floor, second, sixth, eighth and tenth floors) are too cool for about 20% of the occupied time (Figure 4)

Interestingly, the inhabitants made no comments about their flats being too cool in summer. It was only the overheating that raised complaints. The above results are highly significant with a high variation in thermal conditions between nearby free-running flats, ranging from 'too cool' for 23% of the time when occupied (number 16) to 'too warm' for 49% of the time (number 13) (Figure 5). This trend was established in relation to the contextual factors described above and the occupancy profile for 'young working adults with no children'.

The coolest flat in the sample is on the top floor, which is generally regarded as the most vulnerable

Table 6. Occupant practices for the selected 9th and 10th (top) floor apartments.

Apt. Floor Orientation	No. occupants/Age range	Apt. empty weekdays)	Shading		Ventilation							% time over (summer 2013)	
					Mechanical Extract Vent.		Windows opening		Doors blocked open		Additional fans		
			living	bedroom	living	bathroom	living	bedroom	front	bedroom		living >28°C	bedroom >26°C
12 IX West	2 30-40	7:00-18:00	Venetian blinds – closed 50% most of the time	Venetian blinds – closed 50% most of the time	On only when frying	On only when showering	All weather balcony doors open on trickle 24/7, wide in the morning and afternoon	Balcony doors open on trickle 24/7, wide in the morning and afternoon	Occasionally in the afternoon	Closed	None	7%	8%
13 IX West	1 30-40	Leave: 8:30-9:00 Return: 18:00-19:00	None	Venetian blinds – closed for the night	Off	On	Balcony doors usually locked, open when at home and hot	Usually locked, open when hot in the evening	Never	Closed	None	**43%**	**50%**
15 X West	2 30-40	8:30-17:15	Venetian blinds – closed when dark, in hot spells in the afternoon/evening	Venetian blinds – 50% closed 24/7	Off	On only when showering	When hot 10cm gap 24/7	When hot 10cm gap 24/7	Only when cleaning the flat (vacuuming)	Open	None	**19%**	**73%**
16 X East	2 30-40	8:15-17:30	None	Black out curtains – closed 24/7 with a gap for openable window	On	On	All weather 10cm gap 24/7, hot spells: when at home open wide 24/7	All weather: open 10cm, hot spells: when at home open wide 24/7	In hot spells most of the time when at home during the day	Open	Tower fan in the living room open window; in hot weather – on when at home (inc. night)	1%	None
17 X West	One adult 40-50	Leave:9:00 Return: 18:00-18.30	Venetian blinds – 50% closed 24/7	Venetian blinds closed during the night	Off (2013) On boost when away otherwise on trickle, off at night (2014)	Off (2013) On boost when away otherwise on trickle, off at night (2014)	Hot weather balcony doors open on trickle 24/7, wide in the morning and afternoon	Hot weather open on trickle 24/7, 10 cm gap in the morning and afternoon	Hot weather when at home in the afternoon	Open	Tower fan in living area 2.5m away from the window, in hot weather on in the afternoon/evening	4%	**10%**
18 X West	One adult 30-40	Leave: 8:30-9:00 Back: 18:00-19:00	None	Venetian blinds - 75% closed 24/7	Off	On only when showering	When hot 10cm gap when at home (2013) When hot 10cm gap 24/7 (2014)	When hot 10cm gap 24/7	In hot spells 5 min when returning home – never unattended	Open	None	**42%**	**21%**

Practices evaluation in relation to overheating prevention/mitigation:

% bold =annual allowance exceeded	Most ineffective
	Ineffective
	Effective
	Most effective

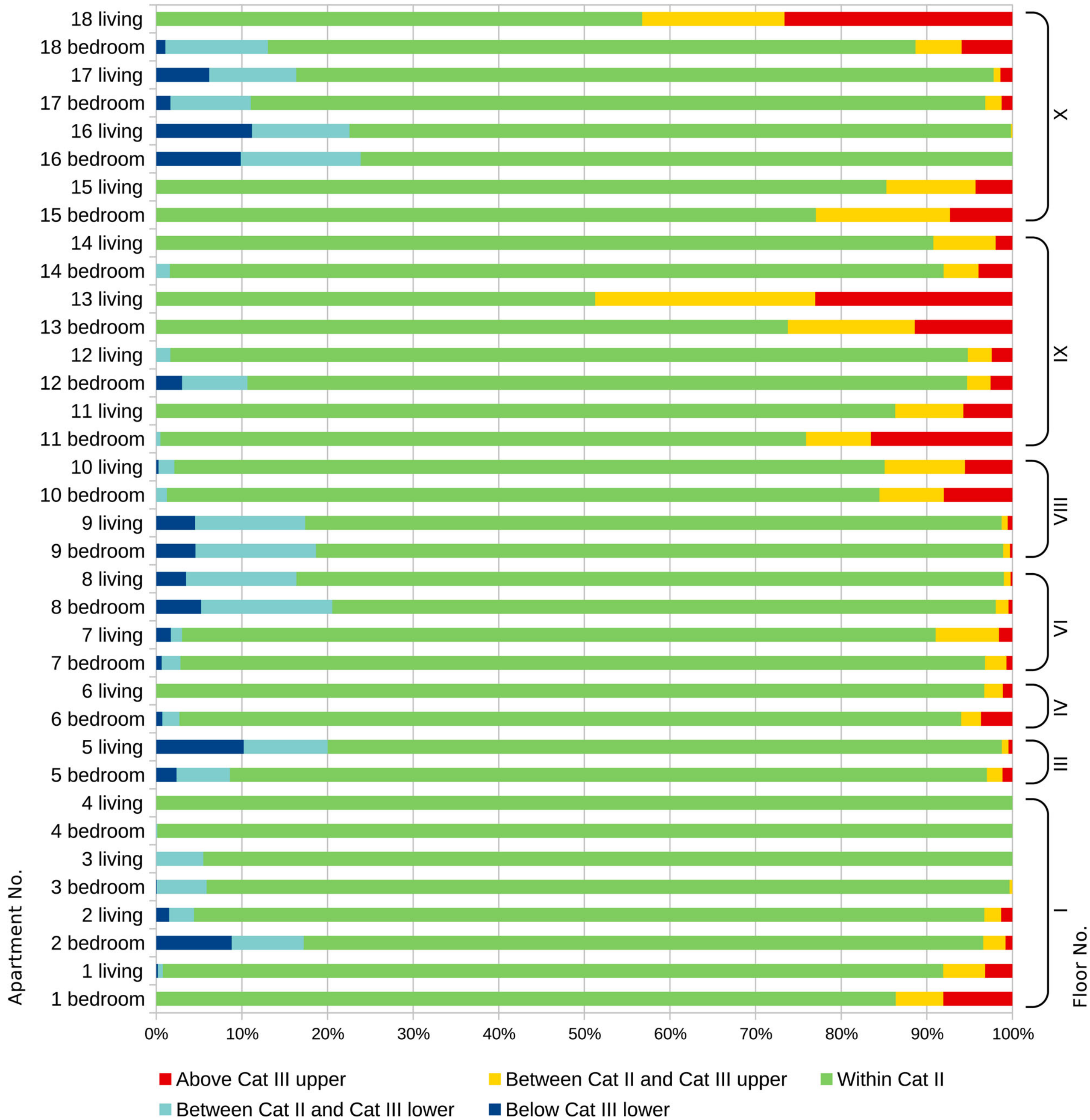
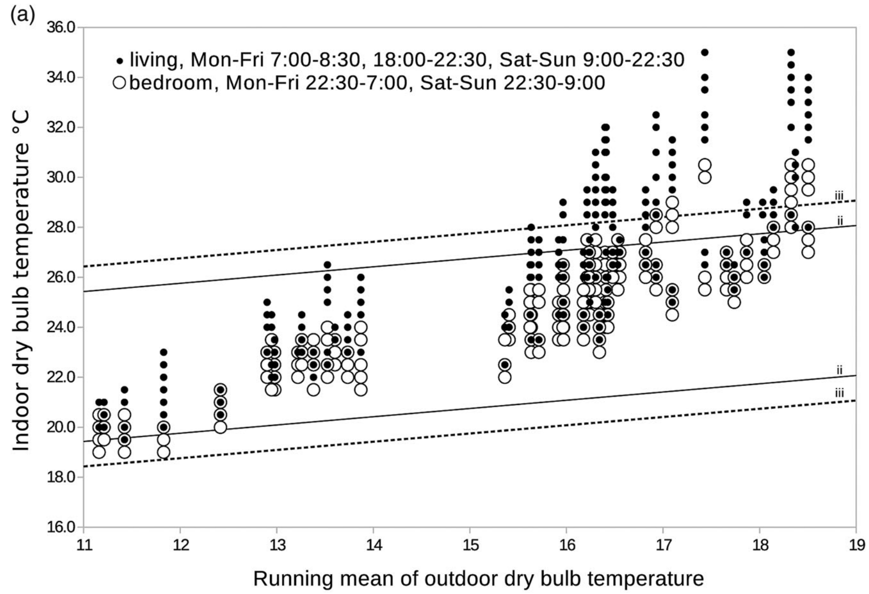


Figure 4. Percentage of occupied time when the monitored internal temperatures lie within the boundaries set in BS EN 15251 – time span analysed: 24 July–31 August 2013.

floor in terms of overheating (Mavrogianni, Taylor, Davis, Thoua, & Kolm-Murray, 2015) and the warmest flat is on floor nine – one floor below. In fact, all the flats on floor nine experience overheating, but significant differences between them are still evident; the living room temperatures in the two comparable and adjacent west-facing flats (numbers 12 and 13) are above the BS EN 15251 category II threshold for 5% and 49% of the time respectively (BS EN 15251, 2007). The latter finding suggests that inhabitant practices are a major source of the overheating variation for similar contexts, with some inhabitants having effectively prevented overheating while others clearly were unable to do so. This is further explored below and in Figure 6 and Table 6. Results presented in Figure 1 are also in line with a general trend of flats on the upper levels in a tower block being warmer than those located lower down. This has been linked with the observed stack effect in the staircase partially open to the elements, but more research is needed to understand the impact of staircase design on temperatures in adjacent flats (Baborska-Narożny, Stirling, & Stevenson, 2016).



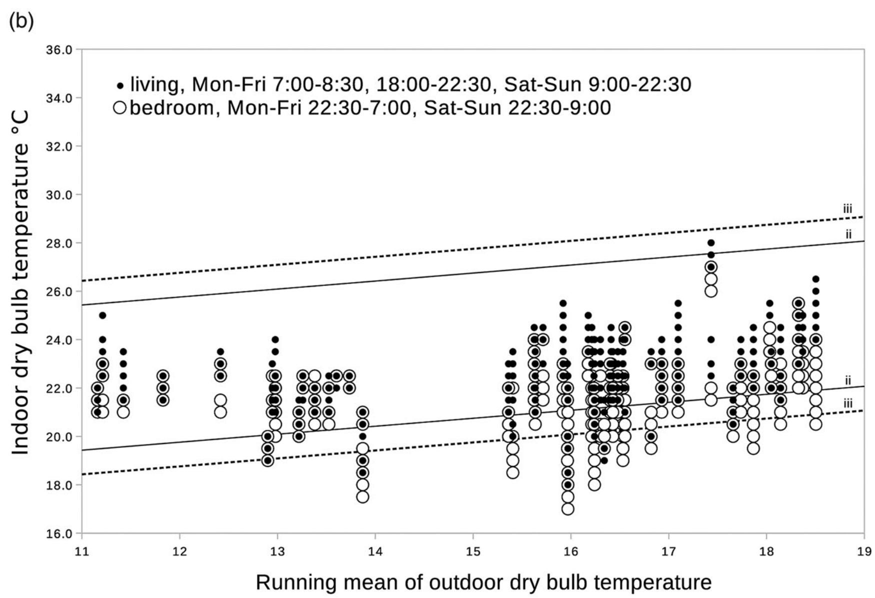


Figure 5. Internal temperature during occupied hours: bedroom and living room (24 July–31 August 2013) compared with BS EN 15251 category II and III limits (apartments 13 (top) and 16 (bottom)).

Heat gains

In order to reveal the importance of inhabitant practices against the varied contextual factors in relation to overheating, simple heat-gain calculations for each sampled flat were compared with the monitored temperatures. The calculations covered the same 39-day period of summer 2013 (Table 2). The aim was to see if the overheating vulnerability matches the variation in the actual temperatures between flats in terms of contextual factors.

The calculations used meteorological and design data with regard to glazing type, glazing and floor area (UK Meteorological Office, 2015). The total solar irradiation on the horizontal plane was firstly divided into direct and diffuse components based on the correlation between the hourly values of extraterrestrial radiation and horizontal global and diffuse irradiation according to Muneer (2004). Secondly, a solar radiation incident on the vertical planes of walls and windows was calculated using a model validated for a wide range of locations in the UK (Muneer, 1987; Muneer, 1990). The solar gains were all calculated for unshaded windows in order to highlight the variation in overheating vulnerability between flats resulting from their designed glazing-to-floor ratio. The difference in total solar transmittance between clear and tinted glazing in

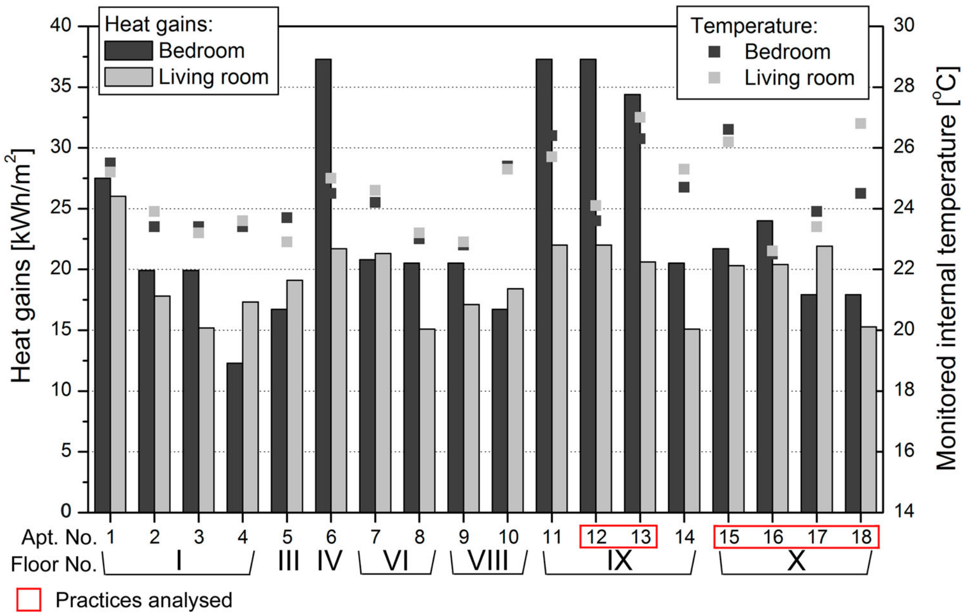


Figure 6. Heat gain versus mean temperatures monitored in each apartment, 24 July–31 August 2013.

different parts of the windows was also taken into account (Table 7). In the flats located on the highest floor additional solar gains from the roof were also included, generating approximately 10% of total solar gains for those particular flats. Solar gains from outer walls were ignored to simplify the calculations on the basis that (1) the outer walls were not significant compared with the other variables and (2) problems existed with obtaining reliable results. The external opaque cladding in the case study building is ventilated through a 30 mm air gap situated behind it and a 10 mm distance between the panels. There is no standard calculation methodology dealing with such a case. Rough estimation (assuming that the gap was not ventilated) indicated that solar gains through the walls would not exceed 5–6% of the total heat gains in the examined flats. Experiments and complex computational fluid dynamics (CFD) modelling (Gagliano, Nocera, & Aneli, 2016; Suárez, Sanjuan, Gutiérrez, Pistono, & Blanco, 2012) showed that solar heat gains coming from ventilated walls could be approximately 30–50% lower compared with walls constructed with non-ventilated cavities. What is more, during summer nights the cooling effect of the ventilated cladding was observed. Calculating the overall effect of external walls with ventilated cladding on heat gains needs further guidance, but in this case study it was deemed insignificant due to small external opaque area.

The main occupancy types related to the period of occupancy and the number of inhabitants per flat and per bedroom were established through home visit data. These were then used to calculate the internal heat gains. These were the only user-related variables that informed the calculations. Other internal loads were assumed to be the same for all flats, with an average usage pattern based on interviews and home visits notes, in the absence of sub-metering data. The HUG identified that the sample flats were all equipped with the same appliances and lighting specified at the design stage. This was then verified with a walk-through tour of each flat. The equipment-related heat load was based on manufacturer specifications related to the appliances and CIBSE Guide A (Table 8). It is recognized that this is also a limitation and that the resulting heat-gain calculation is indicative only.

The results (Figure 6) show a weak positive correlation of 0.170 for the living room and 0.386 for the bedroom between heat gains and temperatures (Figure 7), which may indicate the importance of inhabitant behaviour despite the potential limitation of the modelling. However, there also appears to be some correlation

Table 7. Properties of glazing systems included in heat-gain calculations.

Number	Element	Total solar energy transmittance g (–)	Solar direct transmittance τ_e (–)	Solar direct reflectance ρ_e (–)	Solar direct absorptance α_e (–)
1	Clear glazing	0.63	0.56	0.29	0.15
2	Tinted glazing	0.44	0.38	0.17	0.45

Table 8. Equipment in the dwellings and adequate heat gains included in the heat-gain calculations.

Room	Appliances	Operation time/number of cycles per day	Consumed power per h or cycle
Living/kitchen	Television set	2 h/22 h	50 W operation; 1 W – standby mode
Living/kitchen	Laptop computer	2 h	30 W
Living/kitchen	Electric hob	1 h	725 W
Living/kitchen	Fridge (small)	24 h	30 W
Living/kitchen	Electric kettle	Two cycles	110 Wh
Living/kitchen	Hot water boiler	6 h	85 W
Living/kitchen	Washing machine plus tumble dryer	Two cycles (per week)	5100 Wh
Living/kitchen	Lighting	1 h	12 W/m^2
Bedroom	Laptop computer	2 h	30 W
Bedroom	Lighting	1 h	12 W/m^2

between two peak temperature for the bedrooms of flats 11 and 13 where the exceptionally high glazing-to-floor ratio (Table 3) coexists with poor user practices. Flat 13 is included in the practice analysis in relation to overheating (Table 6). At the same time, it is clear that the ground-floor flats are persistently cooler, apart from flat 1, which does not have direct contact with the ground, having a gym positioned below it.

Overheating prevention and mitigation practices

A closer examination of inhabitant practices is used here to illustrate how the inhabitants adjusted their domestic thermal environments to suit their individual needs. Six flats with varied overheating level from the top two floors are selected: two adjacent ninth-floor flats (numbers 12 and 13) and four top-floor flats (numbers 15–18). The identified temperature variations on the vulnerable floors are linked with the varied inhabitant practices and interventions in relation to overheating (Table 6). Behavioural thermal adaptation unrelated to the building fabric and services, such as the use of showers, cold drinks etc. identified in other studies (AECOM, 2012b), is not discussed here.

Shading

The home visits revealed that all the bedroom windows, but only half of the living room windows, were equipped with internal blinds. The bedroom venetian blinds were originally part of the standard specification provided by the developer, with living room blinds added by the occupants themselves, and some also modifying the standard bedroom shading. Furniture and information technology equipment often prevented occupants from being able to open the windows, and the layout of the flats also made it difficult to move these items in relation to the specific configuration of the full-height glazing. The window opening was typically obstructed when the blinds were pulled down. Six of the rented and owned flats surveyed lacked any blinds in the living room. Interestingly, some owners changed the specified blinds for bespoke blackout blinds in their bedrooms, but did not add any in the living room, which was nevertheless a prime area of overheating. Interviews revealed that shading choices were guided by lighting preferences rather than by solar gain considerations with occupants unaware that the blackout blinds could be more effective than the venetian blinds in terms of reducing solar gain during the daytime. None of the practices related to the use of blinds was optimal for the prevention of overheating, which would have involved significantly reducing the solar gain in all windows (Table 4) and exploiting the night-time cooling potential of the full-height glazing. The latter would involve actually keeping the internal blinds open between dusk and dawn when there is no solar gain and when the external temperature is lower than the internal one.

Tacit knowledge and learning practices

While over half ($n = 58$) of the BUS survey respondents ($n = 95$) in the case study reported that their previous accommodation had provided comfortable temperatures in the summer, only a quarter ($n = 27$) felt the same about their new flat (Table 9). A significant number of occupants ($n = 26$) experienced a severe overheating problem in their flat compared with their previous accommodation. None of the sample participants had used continuous MEV before, and in the usability survey developed for the study (Baborska-Narożny and Stevenson, 2016) half of the participants said they had received no home handover demonstration tour when they first moved in and were not aware of the HUG. Of those who acknowledged having a HUG, only 15% found it useful. This may be because many of the participants were actually renting their flats from the original owners, in which case there was no formal provision for another handover demonstration or provision of a HUG.

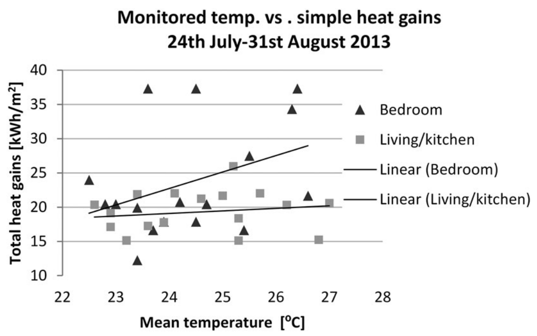


Figure 7. Correlation of the calculated heat gains per m^2 with the monitored temperatures.

Without either of these, it is highly unlikely that the inhabitants would be able to use their homes effectively to avoid overheating, given their lack of tacit knowledge in relation to this type of flat and ventilation system if these were new to them.

These findings are significant because during the interviews 85% of the participants indicated that they used their own tacit knowledge and trial-and-error procedures as the main means of developing their practices to manage thermal comfort. Trial and error, as described by the inhabitants, was not a sustained and systematic review of all the options available, but rather a simple 'sensory trigger and feedback' process followed by social learning from other inhabitants. This social learning included observing others, sharing experiences through a closed Facebook group and participating in the action research available to them via this study. The available means of learning in relation to specific practices (Table 10) shows that some inhabitants found that effective practices were easy enough to discover through simple trial and error or observation, while for many other inhabitants it was virtually impossible.

Learning ventilation practices

Inhabitants observing others wedging their front doors open to help cool their homes associated this with the strong draft experienced when they tested such a practice while entering their own flat, making this practice for thermal comfort very obvious and easy to learn. At this stage of learning, a persona-based analysis (Haines & Mitchell, 2014) highlighting how different occupant personalities work with practices could help to estimate the likelihood of a particular persona adopting or rejecting such a practice. Indeed, all the participants in the sample were aware of the 'front door wedging' option, but only some adopted it, which suggests that it was either an unacceptable option for some or possibly their persona did not naturally engage with this type of trial-and-error learning.

The occupant experience in relation to the MEV presented a different picture in terms of learnt practices. Firstly, there was no neighbourly discussion concerning whether or not ones' neighbours had their MEV fans switched on, other than a Facebook discussion described below. Potential differences in MEV use were not visible to both parties, and in many cases was simply an unknown factor, as discussed above. Secondly, there was no sensation of air movement when the fans were working due to their operational low air flow levels, which meant there was no sensory trigger available to provide feedback to occupants in relation to the MEV functioning. Finally, the main sensory trigger linked with the MEV fans being perceived as switched on was often the unwelcome buzzing noise it generated: 23% of BUS respondents indicated this noise as the main reason for turning the MEV system off altogether, negating any interaction or learning. Another visible 'trigger' association in relation to ventilation for some occupants was the need to remove condensation after having a shower. Indeed, according to the BUS survey, the most common practice by occupants was to have their bathroom MEV fan switched on only when showering, showing a clear understanding that these fans removed excess moisture. However, only 9% of the BUS respondents and 10% of the in-depth sample occupants had both the kitchen and bathroom fans working continuously in their flats throughout the monitoring period, as designed for. It would have required a sustained and focused effort for individual households to test and compare the impact of having the MEV fans 'on' and 'off' in order to discover that keeping them continuously on would help prevent overheating. This link was not made explicit in either the HUG or the MEV guidance, so it is hardly surprising that MEV use did not change seasonally as indicated in another paper exploring usability issues of continuous mechanical ventilation (Baborska-Narożny & Stevenson, 2016). About half of the inhabitants overall therefore

Table 9. Overheating experience previous versus case study accommodation (extended Building Use Studies (BUS) survey).

	Perceived air temperature in summer						
	Too hot				Too cold		
Accommodation	1	2	3	4	5	6	7
Previous	8%	7%	17%	55%	6%	3%	4.5%
Case study building	24.5%	20%	28%	26%	0%	1.5%	0%

Table 10. Overheating prevention and mitigation practices learning opportunities as identified in the case study.

Learning about…		Overheating prevention & mitigation practices							Understanding of related energy load
		Trickle vents open	Keeping MEV fans 'on' continuously	Opening windows		Blocking front doors open	Shading windows	Additional fans/air conditioning	
Learning through…				Wide	Trickle				
Tacit knowledge	Prior experience	Varies	No experience	'Yes'	Varies	No experience	Varies	'Yes' from commercial setting/ cars	Previous interest in electricity consumption
Sensory learning	Trigger and feedback	Low air flow not evident	Low air flow not evident; evident noise, condesation removal after shower	Air movement not always evident without cross-ventilation	In hot weather effect not evident	Immediate effect (strong draft – cross-ventilation activated)	Visual effect stronger than cutting off solar radiation	If installed immediate cooling effect	Bills based on: Assumptions – feedback delayed Meter readings – high load visible
Individual Cognitive learning	Home User's Guide	Described (installed on Floor 1)	Type specified; no explanation of impact/ need for	No mention					Specification enables finding manuals (online)
	Reading labels, manuals	Not available	Advice to keep 24/7	Prohibited by manufacturer's label; 10cm gap on latch allowed	Not available			Available	Energy load from manufacturer's label
	Testing if practice effective, monitoring	Difficult + (installed on Floor 1 only)	Systematic trial & error would show effect			Immediate effect visible via air temp. measurement	Systematic trial & error would show effect	Immediate effect visible via air temp. measurement	Impossible without techn. knowledge & equipment
Social learning	Home Handover Demo. Tour	Varied testimonies		Not intended thus not covered	Varied testimonies	Not intended thus not covered			Not covered
	Observing others	Practice hardly visible	Practice invisible	Practice visible	Practice invisible	Practice visible		Practice invisible	n/a
	Closed Facebook group	Repeated discussions on overheating mitigation – quality of peer feedback varies							
	Research feedback	Discussed (50% of the sample came to feedback meetings, 40% asked for advice during home visits)							
	Talking to neighbours	Never recalled							

Learning opportunities enhancing practice adoption:

Red	Not supportive
Orange	Supportive for some
Yellow	Highly supportive for some
Green	Highly supportive for everyone
Grey	Contradictory message – learning challenge

remained unaware of an efficient method to prevent overheating, as sensory learning was not helpful and the generic advice to keep the fans on proved insufficient. Similar learning contexts were analysed in relation to trickle windows opening or trickle vents (Table 10). Worryingly, the use of new AC units for overheating mitigation is well within the sensory learning category, given that people in the UK now have prior experience of using AC in their cars. Cost barriers, both initial and operational, were also mentioned in the BUS comments. However, it was not easy for inhabitants to trace the operational costs, given the wide variety of electricity tariffs, energy suppliers and direct-debit electricity payments associated with their use of energy. Electricity meters were not accessible to inhabitants and readings could only be taken intermittently by the facility manager on their behalf. This, together with the lack of smart meters, gave the inhabitants few tools with which to understand their own energy consumption.

Another challenging learning context was observed in relation to window opening. The inhabitants were once again provided with contradictory information: explicit written advice by the manufacturer, physically sealed to each window frame, prohibited the release of the restrictors. However, a social norm developed for opening windows beyond the restrictor width during heatwaves and few inhabitants actually followed the original advice given. This social norm was further strengthened by the sensory feedback of increased air flow for inhabitants, and was clearly stronger than the manufacturer's advice. The critical role of sensory learning in adopting a practice is *the level of certainty it brings* – cognitive learning based on advice is only taken into consideration if it is trusted to address the needs of the inhabitant. In fact, the HUG provided erroneous information, describing the role of trickle vents that were not even installed, giving it low credibility among inhabitants. Action research provided an opportunity for some inhabitants to find information perceived as more credible, and they sought advice from the researcher directly. They followed this advice even though it merely suggested the actual deployment of MEV equipment that was already installed in the flat from the start.

As Guerra-Santin and Tweed (2015) note: 'In post-occupancy or in-use performance evaluation, the most important audience for feedback are the users (occupants, owners, managers) and the designers' (p. 180). This one-year study provided an opportunity for the researchers to observe the inhabitant-learning process and to intervene through feedback at a group level (feedback meetings) and an individual level (individual visits). Aggregated feedback on ventilation practices as well as energy consumption with tailored individual advice was given to those participants who showed an explicit interest in the research results and in improving their home-use practices. This action-research approach resulted in four inhabitants starting to use their MEV continuously during the study, including one inhabitant repairing the MEV fan that had been broken since he had moved in. Once the inhabitants in flat 9 started to use the MEV on boost and to leave their balcony doors fixed on trickle ventilation mode while they were away, as advised. They also decided their AC unit was no longer necessary as there was no longer a build-up of heat in the flat. However, practices deployed in flat 9 in summer 2013 meant that these inhabitants did not use the MEV at all, fearing its high electricity cost. They were unaware that the MEV fan load was only 2 W compared with their portable AC unit, which was 800 W. This led to them resorting to active cooling with potentially up to 160 kWh additional electricity use for just one flat.

At the end of the study in mid-July 2014, four in-depth study participants (in flats 3, 5, 6 and 17) took part in a closed residents' Facebook group thread focused on overheating. The thread was initiated by a non-participant. The participants used the opportunity to disseminate some of their newly adopted ventilation practises and planned interventions in relation to solar heat gain reduction. Three of them pointed towards the research feedback as the source of 'invaluable' overheating-related 'advice and insights'. This reveals a dynamic learning need that the standard HUG guidance did not respond to.

The most successful flat in summer 2013 (number 16) largely avoided overheating through a combination of measures and interventions that either followed or ignored the standard guidance and involved context-specific bespoke practices aimed at securing excellent air change rates:

- having the MEV continuously on (as designed)
- leaving windows open on the latch 24/7 regardless of the weather variation (discouraged by the manufacturer's labels and the HUG)
- wedging the doors open every afternoon during the heatwave and placing a tower fan in a wide open window in the living area during the heatwave (not mentioned in the guidance)

In terms of using internal shading to prevent overheating, participant interventions were limited to the bedroom where the standard venetian blinds were substituted with heavy blackout curtains. Surprisingly the windows remained unshaded in the living room. The lack of shading in this area was due to the owner-occupier's preference for lots of daylight and was

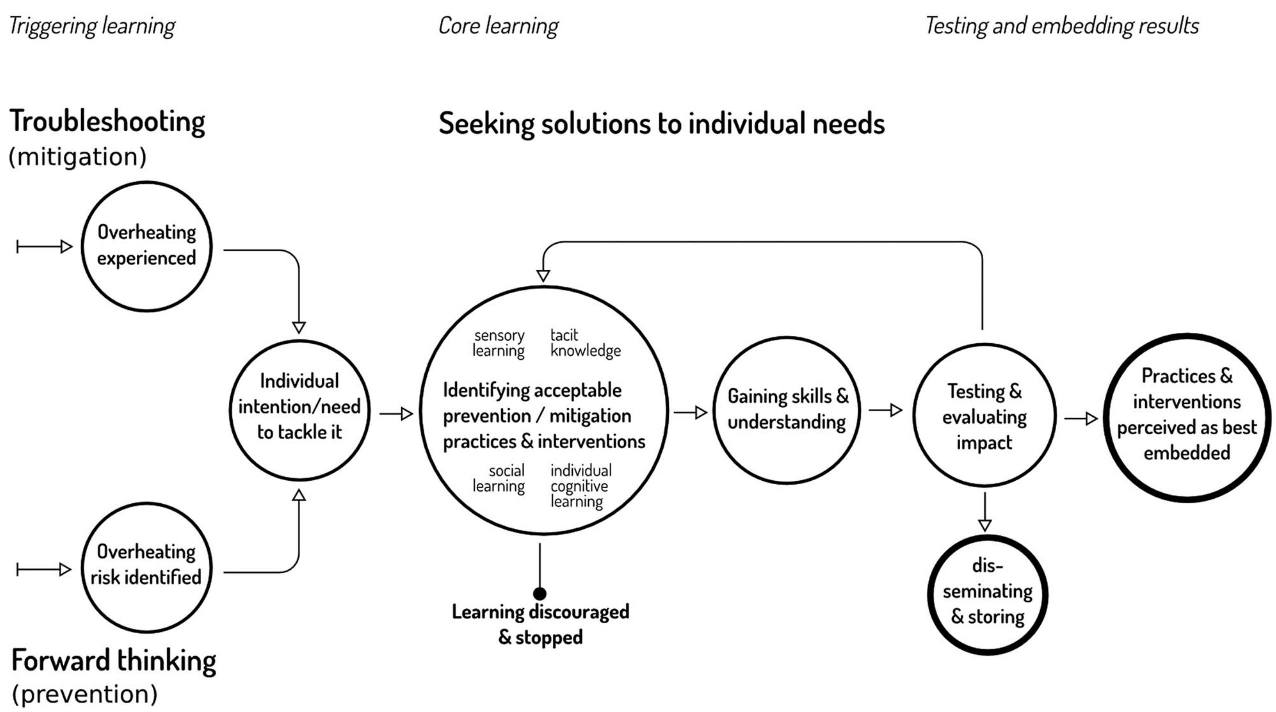


Figure 8. Overheating challenge: learning and adaptation process.

compensated for by their wedging the front door open all afternoon and evening to create cross-ventilation. This degree of flexibility in inhabitants' overheating adaptation in a domestic environment has already been established some time ago by Dubrul (1988), but has not been well researched in relation to retrofitted flats.

Typically inhabitants went through three phases of learning in relation to overheating: a trigger response and core learning followed by testing and then embedding results (Figure 8). Trigger responses may be prompted by forward thinking when an overheating risk has been identified and, for example, solar gain is prevented by effective use of internal shading or by troubleshooting when overheating is already being experienced. An example of this is when windows and front doors are wedged wide open to cool down an 'oven-hot' flat that was left sealed and unshaded all day. This key learning difference linked with either prevention or mitigation measures seems to be related to inhabitants' tacit knowledge in relation to overheating, and their understanding of the practices and interventions available to control the thermal environment in their flat. This area needs further research. Core learning involves individual inhabitants developing practices and interventions that respond to their individual needs and are perceived as normatively acceptable. Not all the practices are equally visible and easy to understand (Table 10) and they can be learned in different ways through tacit knowledge, sensory learning, individual cognitive learning or social learning. There is a vital role for a clear HUG and other cognitive and social learning options to encourage the preventive and low-energy practices that may be difficult to link intuitively with overheating reduction. As the above discussion suggests, learning at this stage can be very easily hindered by poor guidance. Having tested a new practice and finding it to be efficient, the next stage of embedding learning would ideally involve disseminating the findings among those who face similar issues. In this case study, an opportunity was provided through both closed Facebook group activity and expert/research feedback (Vlasova & Gram- Hanssen, 2014, p. 515).

Conclusions

This case study evaluated inhabitants' home-use practices in a retrofitted UK tower block and the associated bedroom and living room temperature profiles. Although the case study flats were prone to overheating due to poor design (*e.g.*, lack of adequate shading for overly large windows with poor control for ventilation), the findings show that inhabitant actions can largely avoid overheating in their flats. Although the monitored period in summer 2013 did not exceed a daily running mean of 18.5°C, there were nevertheless significant overheating issues reported by the inhabitants. Typically, overheating was avoided in the given context by always opening windows when the external temperature is lower than the internal one, and using internal shading during the day to reduce solar gain (Porritt et al., 2012). However, none of the sample households adopted such a scenario, partly because the open windows could not be left unattended and partly because inhabitants were not aware of best practice. Worryingly, the flats were not fitted with any shading at all in the living areas and only with venetian blinds in bedrooms. A total of 25% of the sample inhabitants did not add any further shading, stating a preference for maintaining the excellent daylight levels, but they did use the shading already provided. This suggests that provision of internal shading to all the windows is desirable despite the conflict between daylight preferences and optimum shading scenarios identified in a field study in another northern European country (Simone, Avantaggiato, de Carli, & Olesen, 2014). This recommendation is a pragmatic solution given the exorbitant cost of installing more effective fixed external shading in a tower block of this type after the original retrofit.

As hot weather is predicted to become more frequent and severe in the UK, the perceived overheating that is already occurring in a relatively cool summer is a disturbing finding. Poor levels of inhabitant understanding of the means to prevent overheating in their dwellings appear to be linked to flats that overheat. Some inhabitants adopted very efficient practices, while others clearly failed to do so. This deserves further research in order to understand why these discrepancies occur. The coolest flat was paradoxically due to inhabitants developing a hybrid pattern for mitigating overheating. This included the use of MEV, but not the use of shading and thus they needed to compensate for this by introducing cross-ventilation via the wedged front doors. This contravened the fire safety requirements and is clearly an undesirable practice. Nevertheless, the inhabitants have clearly traded the immediate gain of comfort against safety in this instance, which perhaps illustrates their level of need for increased comfort and also the desirability of providing safe methods for cross-ventilation.

The majority of inhabitants in this study did not experience overheating in their previous accommodation and had no experience of MEV systems. Learning to deploy the MEV to prevent overheating proved to be a particular challenge as this system provides no instantaneous trigger for learning. Sustained trial and error therefore did not occur and as a result only 9% of households had the MEV working continuously (as was the design intent) to mitigate any overheating during the summer. This reveals a clear gap in inhabitants' understanding of MEV. Both the home-user guidance and the home demonstration tour failed to provide inhabitants with the necessary understanding of the ventilation and shading scenarios offered by the design intentions. The most widespread inhabitant practices were those that could be easily observed by other inhabitants (*e.g.*, window opening) as well as those learned through sensory trigger and feedback. The majority of inhabitants did not discover the best possible overheating mitigation strategies when acting independently, but instead relied instead on social media or action-research interventions. This suggests that a collective learning process can have a significant role for improving the ways in which inhabitants tackle overheating.

There are clear lessons to be learnt from this study in terms of closing the gap between design intentions and building performance by helping inhabitants to learn and manage their own ventilation strategies:

- robust design strategies should respond to different inhabitants' needs and preferences for ventilation and shading, paying particular attention to window design and ventilation systems
- home-user guidance and home demonstration tours that include adequate and accurate details on appropriate ventilation and shading strategies are vital for retrofitted domestic developments to avoid overheating issues
- home-user guidance should be checked to align with retrofit construction and services as built
- inhabitants need to be made aware of practices that clearly support overheating mitigation to avoid the risk of them installing AC units unnecessarily
- MEV systems need to be designed to provide a clear trigger response and feedback for inhabitants so that they know they are either working well or not working
- design intentions need to include the ergonomic ability for inhabitants to learn easily how to use their homes in relation to robust ventilation and shading strategies to prevent overheating
- window and shading design should take into account increasingly adverse weather conditions in order to maintain ventilation and shading options; in particular, conflict between blinds and access to open windows should be avoided
- collective learning opportunities for housing inhabitants to understand how to mitigate overheating need to be embedded as part of the management process.

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