Department for
Energy Security
& Net Zero

The effect of energy efficiency measures on summertime overheating in English homes: prevalence, frequency and intensity analysis

Overheating in Homes: Further Analysis of EFUS Data

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Introduction

This document reports analysis conducted to assess the extent to which energy efficiency measures influence the propensity of English homes to overheat. For the 616 living rooms and 591 main bedrooms in the EFUS2017 dataset that produced reliable half-hourly indoor air temperatures for the five-month study period (May–September 2018 inclusive), three metrics were employed for quantifying overheating:

- **Prevalence** of overheating, which describes the sample-wide proportion of living rooms or main bedrooms deemed to overheat according to pass/fail criteria calculated over the study period[1].
- **Frequency** of overheating, which describes, for a given room, the average number of hours per day for which a given threshold temperature was exceeded (hr/day)[2].
- **Intensity** of overheating, which describes, for a given room, the average total degree-hours per day above a given threshold temperature (°C.hr/day)[3].

Statistical tests were applied to determine the significance of differences in prevalence, frequency and intensity of overheating, between subsamples of dwellings categorised according to the following energy efficiency variables:

- Energy efficiency rating band.
- Whether fully double-glazed.
- Whether walls were insulated.
- Loft insulation thickness.
- Predominant wall type.

The energy efficiency rating is calculated by the standard assessment procedure, SAP 2012 (BRE, 2014) and shown on the energy performance certificate of English homes.

Recognising the potential impact of dwelling type on propensity toward overheating, houses and bungalows were considered separately from flats.

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[1] For living rooms, adaptive overheating criteria—as per CIBSE TM59 (CIBSE, 2017)—were used, whereby a room is deemed to overheat if its temperature exceeds an adaptive threshold temperature (for a given adaptive thermal comfort category) for more than 3% of occupied hours (0700–2200, May–Sep 2018); for bedrooms, the new mean night-time temperature criterion was used (Lomas and Li, 2023), whereby a bedroom is deemed to overheat if its nightly mean temperature (calculated for 2200–0700) exceeds a given static threshold temperature for more than seven occupied nights (2200–0700, May-Sep 2018).

[2] In Drury's (2023) evidence review of the effect of energy efficiency measures, over two dozen studies were identified in which overheating was quantified using total hours of threshold exceedance over a given time period. In many cases, the analyses followed the CIBSE TM59 overheating criterion for living spaces applied here.

[3] Drury's (2023) evidence review of the effect of energy efficiency measures on summertime overheating identified three studies where degree-hours were used to quantify the 'severity' of overheating. The term 'intensity' is preferred here, to avoid use of the pejorative 'severity' when describing exceedance of lower thresholds associated not with overheating, but rather with cold discomfort (when exceedance is desirable).

For flats, differences were assessed for a further two categorisations:

- Whether the flat was located on the top floor.
- Whether entry to the flat was above ground floor level or at basement or ground floor level.

Given the expectation that energy efficiency measures and flat floor level will also influence the degree to which a dwelling can be kept adequately warm, additional analyses were conducted examining the frequency and intensity of exceedance for a range of lower threshold temperatures, i.e., thresholds below those associated not with overheating.

All the results in this report are weighted to provide the prevalence, frequency and intensity of overheating in the English housing stock.

Materials and methods

The EFUS2017 dataset, sample selection and weighting

The analysis reported here was conducted on data drawn from the Energy Follow Up Survey (EFUS) 2017 dataset. The EFUS 2017 was a follow-up survey of a sample of respondents from the 2014/15 to 2016/17 editions of the English Housing Survey (EHS). During these EHS years, around 13,300 households completed an initial interview survey, and around 6,200 of these dwellings were physically surveyed. The EFUS 2017 used a subsample of households who had received both the physical and interview surveys: further data were collected from each participating household via three interview surveys, a summertime text survey, internal temperature data logging in up to five rooms, monitoring and/or metering of electricity and gas consumption, and external temperature data sourced from the Met Office MIDAS dataset.

Among the EFUS 2017 sample, 750 dwellings returned indoor temperature monitoring data suitable for analysis after data cleaning (BEIS, 2021). Samples for the analysis reported here were restricted to houses and flats in the EFUS 2017 dataset identified by Lomas et al. (2021) as having reliable temperature data for either the living room (506 houses, 110 flats) or main bedroom (496 houses, 95 flats) during the period May to September 2018 inclusive. At the time, 2018 was the hottest English summer on record[4] (McCarthy et al., 2019), with four heatwaves of lengths between 3 and 11 days occurring between June 25 and August 09 (PHE, 2019), and is thought to be indicative of the type of UK summer weather that could be normal in the 2050s (Madge, 2019). The May to September study period aligns with the accounting period used in present UK overheating criteria such as that defined in CIBSE TM59 (CIBSE, 2017).

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[4] Summer 2018 was the joint hottest summer season (June, July, August) in the Met Office UK national temperature series dating from 1884, and the warmest on record for England (McCarthy et al., 2019). Summer average temperatures were close to +2.0°C above the 1981–2010 average for much of southern and central England and Wales (ibid.).

The key question posed for the present research was *"Do energy efficiency measures affect the propensity to overheat in English domestic homes?"* The availability of reliable, half-hourly internal air temperature data gathered during a hot English summer, alongside dwelling physical survey data describing the presence of energy efficiency measures, marked the EFUS 2017 dataset as particularly well-suited for the analysis.

A further benefit of the EFUS 2017 dataset was the availability of weighting factors, which were "calculated to align EFUS 2017 totals for key dwelling and socio-economic variables with the national totals reported in the latest available national statistics" (BEIS, 2021). Application of these weightings in statistical analyses provides insights pertinent to the whole English housing stock. For each of the samples analysed, weightings provided in the EFUS 2017 dataset were rescaled such that the sample weightings summed to the national (i.e., English) total calculated from the full EFUS2017 sample.

Overheating threshold temperatures

Formulation of threshold temperatures varied between bedrooms and living rooms. Living room analysis relied on adaptive threshold temperatures, whereas bedroom analysis employed static threshold temperatures.

Adaptive threshold temperatures

For living rooms, daily adaptive threshold temperatures T_i°C were used for each day i, formulated as per BSEN16798 (BSI, 2019), CIBSE TM52 (CIBSE, 2013) and adopted in CIBSE TM59 (CIBSE, 2017):

$$T_i = \theta_{comf,i} + \delta \tag{1}$$

$$\theta_{comf,i} = 0.33 \cdot \theta_{rm,i} + 18.8 \tag{2}$$

where:

- $\theta_{comf,i}$ is the comfort temperature for day i;
- $\theta_{rm,i}$ the exponentially weighted running mean of the daily mean outdoor air temperature[5];
- δ is a constant value, selected depending on the thermal comfort category assumed.

Letting θ represent the indoor air temperature of a room, CIBSE TM59 determines that a room is overheated whenever the difference $\Delta T = \theta - T_i$, after rounding to the nearest whole number, is greater than or equal to 1K. The δ value is dictated by the assumed thermal comfort category, as specified in CIBSE TM59 (CIBSE, 2013):

- Category I (Cat.I), for which $\delta = 2°\mathrm{C}$.
- Category II (Cat.II), for which $\delta = 3°\mathrm{C}$.
- Category III (Cat.III), for which $\delta = 4°\mathrm{C}$.

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[5] $\theta_{rm,i} = (1 - \alpha)\theta_{od,i-1} + \ \theta_{rm,i-1}$, with $\alpha = 0.8$ as per CIBSE TM52 (CIBSE, 2013).

As per BSEN16798 (BSI, 2019), these three categories define, respectively, living spaces meeting high, medium or moderate expectation of thermal comfort in warm conditions. BSEN16798 states that Cat.II (corresponding to medium expectation) is “the normal level used for design and operation”. Meanwhile, Cat.I (high expectation) “should be selected for occupants with special needs (children, elderly, persons with disabilities)”, and Cat.III (moderate expectation) “will still provide an acceptable environment [with] some risk of reduced performance of the occupants.”

Static nightly mean threshold temperatures

For bedrooms, static nightly mean temperature thresholds $T_i = \boldsymbol{T}$°C were used. Following Lomas and Li (2023), a bedroom was deemed to overheat on any given night (2200–0700) if the mean bedroom air temperature for that night exceeded $\boldsymbol{T}$. Analysis was initially undertaken with values of $\boldsymbol{T}$ of 27°C, 28°C and 29°C, as suggested in Lomas and Li (2023).

Prevalence of overheating

Within each subsample of living rooms and main bedrooms (with houses and flats considered separately), the prevalence of overheating as per pass/fail overheating criteria was calculated. For living rooms, the criteria used were defined relative to adaptive overheating thresholds, while for bedrooms the criteria relied on mean night-time temperature criteria.

For living rooms, overheating prevalence was calculated as the nationally weighted proportion of living rooms failing the adaptive criterion using the given thermal comfort category. Similarly, sample-wide overheating prevalence in bedrooms was calculated as the weighted proportion of bedrooms failing the mean night-time heating criterion at each of the chosen threshold temperatures.

Living rooms: adaptive overheating criterion

For each of the EFUS2017 living rooms with reliable data for the study period May–Sep 2018, half-hourly temperatures logged during occupied hours (0700–2200[6]) were compared against adaptive overheating temperatures (as described in *Adaptive threshold temperatures* on page 7). Following TM59, the adaptive overheating criterion used here determined that a living room overheated—thus failing the criterion—if it had a threshold exceedance ΔT greater than or equal to 1K for more than 3% of occupied hours[7] (0700–2200, May–Sep 2018).

Three adaptive thermal comfort categories were initially adopted: Cat.I, Cat.II and Cat.III as defined in BSEN16798 and in *Adaptive threshold temperatures* above.

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[6] Temperatures logged at the beginning of each half-hour were used to represent the temperature for that half hour: therefore, the daytime temperatures considered were those logged at 0700, 0730, …, to 2130; meanwhile the night-time temperatures were those logged at 2200, 2230, …, to 0630, with each night-time calculation conducted using the 18 consecutive half-hours starting at 2200 to avoid splitting nights at midnight.

[7] As monitored temperature data were supplied at half-hourly resolution, the number of hours was given by halving the number of monitored half-hours with $\Delta T \geq 1$.

Bedrooms: mean night-time temperature criterion

For each of the EFUS2017 bedrooms with reliable data for the study period May–Sep 2018, nightly mean temperatures (calculated for the hours 2200–0700) were compared against static threshold temperatures. Following Lomas and Li (2023), the mean night-time temperature criterion used here determined that a bedroom overheated—thus failing the criterion—if the nightly mean temperature exceeded the given threshold on more than seven (5%) nights (2200–0700, May–Sep 2018).

Three threshold temperature values were initially adopted followed the suggestion in Lomas and Li (2023): $\boldsymbol{T} = 27$°C, 28°C, 29°C.

Frequency and intensity of threshold exceedance

Frequency of threshold exceedance in each room in the EFUS2017 sample was quantified via calculation of average daily (or nightly) hours above any given overheating threshold temperature, termed mean daily (or nightly) hours of exceedance ($\overline{He}$), for the study season (May–Sep 2018). Given half-hourly air temperature data for an indoor space (i.e., bedroom or living room), monitored over a total of n days (or nights) within the study season, the mean daily (or nightly) hours of exceedance are given by

$$\overline{He} = \frac{1}{2n}\sum_{i=1}^{n}\sum_{j=1}^{m}\delta(\theta_{ij} - T_i, 0) \qquad \text{[hours]} \tag{3}$$

$$\delta(\theta_{ij} - T_i, 0) = \begin{cases} 1, & \theta_{i,j} - T_i > 0 \\ 0, & \theta_{i,j} - T_i \leq 0 \end{cases} \tag{4}$$

where:

- θ_{ij} is the indoor air temperature for the j^{th} occupied half-hour of the i^{th} day (or night) (°C);
- T_i is the overheating threshold temperature for the i^{th} day (or night) (°C);
- n is the number of days (or nights) for which complete half-hourly indoor temperature data are available, and for which the overheating threshold temperature T_i can be defined[8];
- m is the number of occupied half-hours over which the daily (or nightly) sum Σ_j is taken;
- Division by 2 converts from half-hours to hours, while division by n calculates the mean daily (or nightly) figure.

Intensity of threshold exceedance in each room in the EFUS2017 sample was quantified via calculation of average daily (or nightly) degree-hours above an overheating threshold temperature, termed mean daily (or nightly) degree-hours of exceedance ($\overline{degHe}$), for the

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[8] Although all rooms included in the study had complete half-hourly indoor temperature data for all 153 days in the study period (May–Sep inclusive), for three living rooms it was only possible to define adaptive overheating threshold temperatures for 132 days, due to missing outdoor temperature data (which are required for calculation of the adaptive threshold temperatures) at the beginning of the study period.

study season (May–Sep 2018). Given half-hourly air temperature data for an indoor space (i.e., bedroom or living room), monitored over a total of n days (or nights) within the study season, the mean daily (or nightly) degree-hours of exceedance are given by

$$\overline{degHe} = \frac{1}{2n}\sum_{i=1}^{n}\sum_{j=1}^{m}\min\left(\theta_{ij} - T_i, 0\right) \quad (°C \cdot hr) \tag{5}$$

where θ_{ij}, T_i, m, n are as defined above.

In calculation of mean daily/nightly hours of exceedance $\overline{He}$ and degree-hours of exceedance $\overline{degHe}$, the sums Σ_j were taken over the same assumed occupied hours used in the adaptive and mean night-time temperature criteria, encompassing the half-hours falling between 0700–2200 for living rooms, and 2200–0700 for bedrooms[9].

The daily/nightly threshold temperatures T_i depended on the type of overheating criterion being used, which was in turn determined by the room type: for living rooms, adaptive thresholds were used; for bedrooms, static nightly mean threshold temperatures were used. As for the pass/fail analysis of the previous section (*Prevalence of overheating*), three adaptive temperature thresholds (Cat.I, Cat.II, Cat.III) were initially adopted for living rooms (Figure 1), along with three static temperature thresholds ($\boldsymbol{T}$ = 27°C, 28°C, 29°C) for bedrooms.

A further seven temperature thresholds were added to provide insight into the frequency and intensity of exceedance at lower temperatures[10]. For living rooms thresholds are based on those in BSEN16798: three represent cold discomfort[11], Cat.−I; Cat.−II and Cat.-III; and four lie within the thermally comfortable range, Cat.0+1, Cat.0, Cat.0−1 and Cat.0−2 (Figure 1). For bedroom analyses, thresholds of $\boldsymbol{T}$ = 20°C, 21°C, …, 26°C were adopted.

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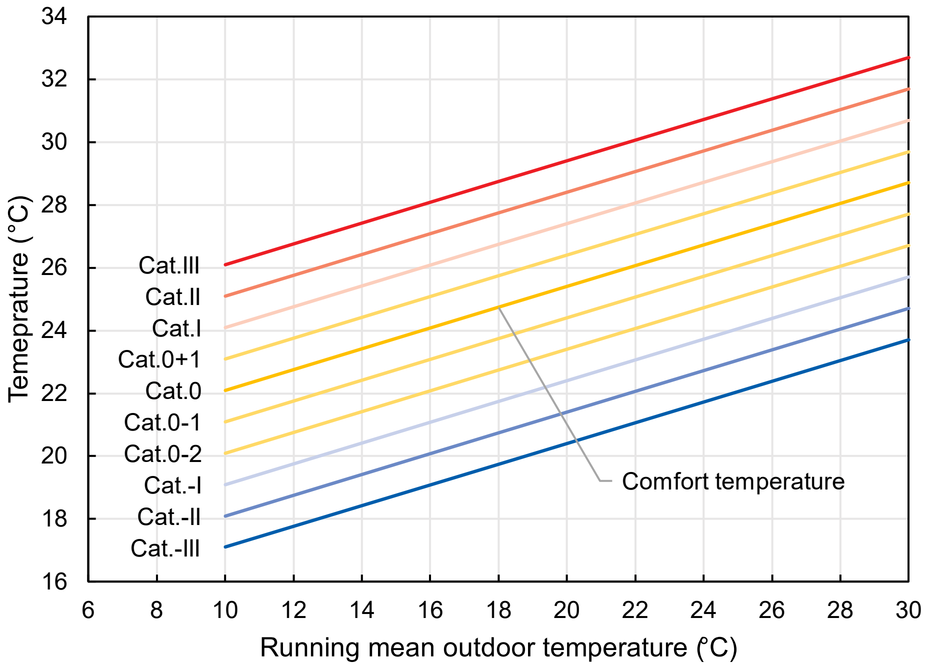
[9] Temperatures logged at the beginning of each half-hour were used to represent the temperature for that half hour: therefore, the daytime temperatures considered were those logged at 0700, 0730, …, to 2130; meanwhile the night-time temperatures were those logged at 2200, 2230, …, to 0630, with each night-time calculation conducted using the 18 consecutive half-hours starting at 2200 to avoid splitting nights at midnight.

[10] At lower threshold temperatures, use of the term “overheating” to describe threshold exceedance ceases to be appropriate; rather, incidence of exceedance of lower threshold temperatures is a more rational interpretation.

[11] In living rooms, Cat.−I; Cat.−II and Cat.−III represent thresholds providing high, medium and moderate protection against cold discomfort, while Cat.0 represents the ideal thermal comfort temperature (as per BSEN16798).

Figure 1: Adaptive overheating threshold temperatures, as defined relative to the daily running mean of outdoor air temperature, which were used to assess living rooms. [Adapted from BSEN16798 (BSI, 2019)]



It should be noted that the definitions of threshold exceedance in this section do not directly correspond to the definitions of overheating and calculation of overheating prevalence in the previous section (*Prevalence of overheating*):

- Whereas TM59 deems a space as overheating when there is threshold exceedance $\Delta T \geq 1$ K, the above formulations of $\overline{He}$ and $\overline{degHe}$ will calculate a nonzero (degree-) half-hour of exceedance whenever the half-hourly temperature exceeds the threshold (i.e., $\Delta\mathrm{T} > 0$, rather than $\Delta\mathrm{T} \geq 1\ \mathrm{K}$).
- Whereas Lomas and Li (2023) labelled bedrooms as overheating only on nights when the mean temperature exceeded a given static threshold temperature $\boldsymbol{T}$, the above formulations of $\overline{He}$ and $\overline{degHe}$ will calculate a nonzero (degree-) hour of exceedance whenever a half-hourly indoor air temperature exceeds $\boldsymbol{T}$, regardless of the nightly mean temperature.

Statistical testing for influence of dwelling characteristics

For each of the four study subsamples—living rooms in houses, living rooms in flats, bedrooms in houses, bedrooms in flats—dwellings were characterised according to 5 dichotomous categorical independent variables associated with fabric energy efficiency:

- Energy efficiency rating band (A/B/C vs D/E/F/G).
- Whether fully double-glazed (Yes vs No).
- Whether walls were insulated (Yes vs No).

- Loft insulation thickness (<150 mm vs 150+ mm).
- Predominant wall type (Cavity vs solid (including other)).
- For flats, two further variables were explored, describing floor levels:
- Flat floor level (top floor vs other).
- Flat entry level (above ground floor vs ground floor or basement).

Testing for between-categories differences in prevalence of overheating

Significance of between-categories[12] differences in overheating prevalence was tested using chi-square tests, following Lomas et al. (2021). These tests were conducted on nationally weighted counts using an effective base[13]; custom Python scripts were created for this purpose, with formulation of test statistics consistent with column proportions tests in the Custom Tables module of SPSS[14].

The validity of chi-square tests depends on the calculated expected counts all being no smaller than 5 (McHugh, 2013); thus any significant effects identified were disregarded in cases where any expected count fell below 5. It is also noted that for small sample sizes, statistical power will be diminished, resulting in a higher likelihood of a false negative (i.e., falsely concluding that there is no association).

Testing for between-categories differences in frequency and intensity of threshold exceedance

Significance of between-categories differences in frequency and intensity of threshold exceedance (quantified by mean daily hours and degree-hours of exceedance, respectively) was tested using independent t-tests, as advocated in numerous statistical texts (Brace et al., 2012; Howell, 2012; Moore et al., 2012) for assessing differences in means between samples split on dichotomous variables. These tests were also conducted using nationally weighted data and using an effective base. Again, custom Python scripts were used, this time with formulation of test statistics consistent with column means tests in the Custom Tables module of SPSS.

The validity of independent t-tests depends on the parametric assumption that sample data are drawn from approximately normally distributed populations. For the present work, normal approximation was deemed acceptable when $|skew| < 1$ (Miles and Shevlin, 2001) and $|kurtosis| < 2$ (George and Mallery, 2008). These conditions were not satisfied by either the mean frequency (daily hours of exceedance) or the mean intensity (daily degree-hours of exceedance) for many of the samples analysed. Therefore, Box Cox power transforms (Box

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[12] In the earlier analysis reported by Lomas et al. (2021), the term “categories” was used to refer to the categorical independent variables being analysed (i.e., house type, energy efficiency rating, etc. were categories). Here, “category” refers to a discrete level of a categorical independent variable (e.g., for the energy efficiency rating variable, the categories are A/B/C and D/E/F/G).

[13] The effective base is designed to reduce the likelihood of statistical tests producing significant results due to effects of weighting adjustments.

[14] Python scripting was adopted as an efficiency measure; selected results produced by the Python scripts were verified against SPSS output to ensure consistency between the two.

and Cox, 1964) were applied, wherein values y_i of the dependent variable Y were transformed to

$$y_i^{(\lambda)} = \begin{cases} \dfrac{y_i^{\lambda} - 1}{\lambda} & \text{if } \lambda \neq 0 \\ \ln y_i & \text{if } \lambda = 0 \end{cases} \tag{6}$$

where the power parameter λ was that identified by the Python scipy.stats.boxcox function as the value maximizing the log-likelihood of λ under the assumption of a normal distribution. As these Box Cox power transforms can only be applied to variables with values $y_i \geq 0$, analysis was restricted to those dwellings for which the calculated (degree-) hours of exceedance were non-zero[15]. λ values used in each transformation are presented in Tables A1 to A4 in Appendix A.

The t-tests also relied on an assumption of homogeneity of variances between samples. Levene's test was applied to check this assumption, with the Levene test statistic calculated for statistically weighted counts to reduce the likelihood of obtaining significant results due to weighting adjustment effects. Where the Levene statistic was significant at the $\alpha = 0.05$ level, Welch's t-test was used.

Although there is no strict minimum sample size for an independent t-test, it is again noted that for small sample sizes, statistical power will be diminished, resulting in a higher likelihood of a false negative (i.e., falsely concluding that there is no association). After removal of rooms with zero hours of exceedance, almost all samples had unweighted size of at least 30 (see Tables A1 to A4 in Appendix A for Ns). The only exceptions occurred when assessing the influence of loft insulation thickness in flats: there were only 46 bedrooms in flats with loft insulation data, 22 of which had zero exceedance of the Cat.III threshold (leaving unweighted N=24); meanwhile, of the 38 bedrooms in flats with loft insulation data, 11 and 18 had zero exceedance of the $\boldsymbol{T}$=28°C and $\boldsymbol{T}$=29°C nightly mean thresholds, respectively (leaving unweighted N=27 and N=20).

Prevalence of overheating

The prevalence of overheating in living rooms and main bedrooms in houses and flats are presented in Figure 2: for living rooms, overheating prevalence is as determined by the adaptive approach (Cat.I, Cat.II, Cat.III, with allowable exceedance 3% of occupied hours 0700–2200, May–Sep); for bedrooms, prevalence is as determined via the mean night-time temperature approach (Lomas and Li, 2023) (using threshold temperatures $\boldsymbol{T}$ = 27°C, 28°C, 29°C, with allowable exceedance of seven nights 2200–0700, May-Sep).

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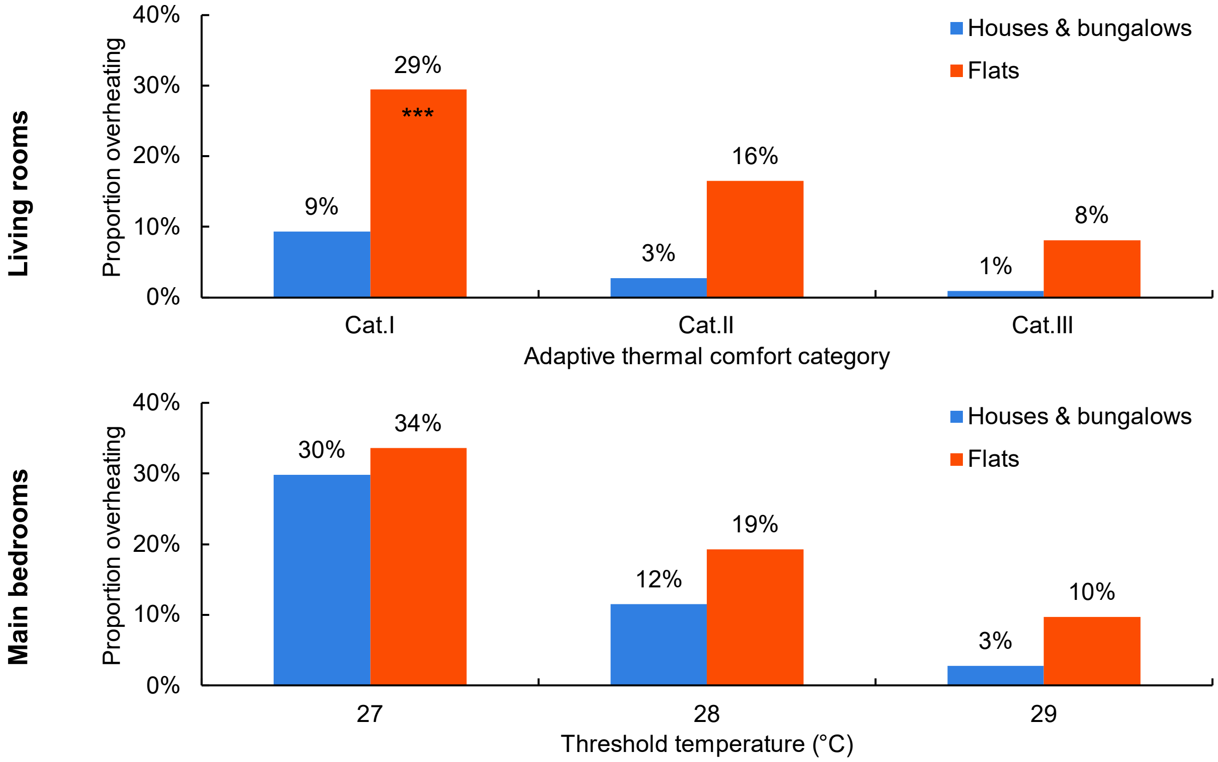
[15] Between-categories patterns in frequency and intensity of threshold exceedance obtained for subsamples with nonzero threshold exceedance were compared against corresponding patterns observed when dwellings with zero exceedance were included. Although the mean metrics themselves were reduced by the inclusion of zeroes, the between-categories patterns were generally maintained.

Figure 2: Overheating prevalence in living rooms and main bedrooms in houses and flats



Proportions calculated for nationally weighted samples. Annotating marks indicate significance of between-column differences, as determined by chi-square tests: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels. Chi-square analysis for living room overheating prevalence using Cat.II and Cat.III thresholds was invalid due to expected counts below 5.

Comparing living rooms in houses and flats, prevalence of overheating is between 3 and 8 times greater in flats: Cat.I living room prevalence in flats being 29% compared with 9% in houses, and Cat.III prevalence 8% in flats compared with 1% in houses. For bedrooms, there is again higher prevalence in flats compared with houses, but with smaller differences: similar levels of prevalence are reported for a mean night-time temperature threshold of 27°C (30% houses, 34% flats), while at the 29°C threshold, prevalence is around three times greater in flats compared with houses (10% cf. 3%).

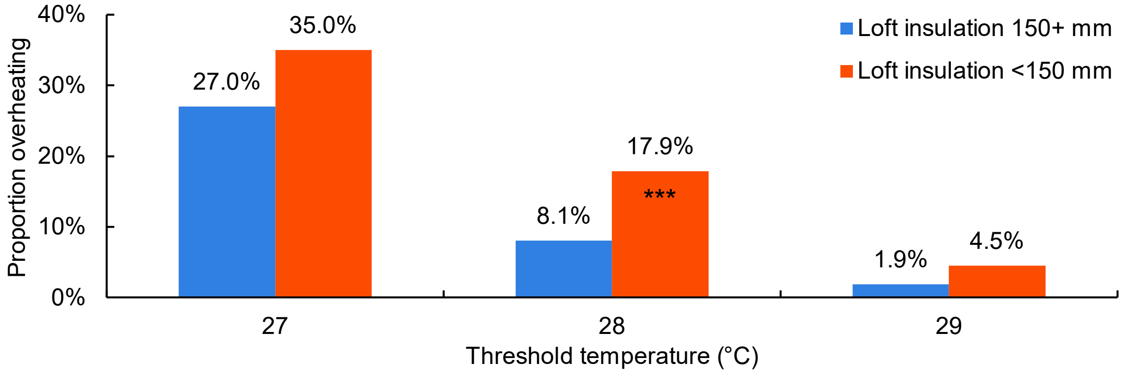
Although comparing prevalence of overheating in living rooms and bedrooms (Figure 2) appears to indicate a higher prevalence in bedrooms for both flats and houses, it is important to note that there is no direct equivalency between the adaptive overheating categories (Cat.I, Cat.II, Cat.III) and the mean night-time temperature thresholds (27°C, 28°C, 29°C). The greater difference in prevalence between living rooms and bedrooms in houses, compared with the corresponding difference for flats, is nonetheless interesting, indicating that the higher prevalence of daytime (living room) overheating in flats (compared with houses) is not carried over to night-time (bedroom) overheating. This is likely a consequence of the relative locations of living rooms and bedrooms in houses and flats: while houses will typically have bedrooms on upper floors and the living room on the ground floor, flats are much more likely to have all rooms on the same floor, thereby informing greater similarity in room temperatures and propensity to overheat[16].

Effects of energy efficiency measures

For both living rooms and bedrooms, in both houses and flats, there were very few significant effects of energy efficiency measures on the prevalence of overheating. Bar charts presented in this section show only those results where significant ($p < 0.05$) between-categories differences were identified in chi-square tests (as described in *Testing for between-categories differences in prevalence of overheating)*.

In bedrooms in houses with loft insulation less than 150 mm thick, there was a significantly higher (p<0.01) prevalence of overheating (17.9%) compared to bedrooms in houses with 150 mm or more of insulation (8.1%), at the 28°C mean night-time temperature threshold (Figure 3). There were, however, no significant effects associated with loft insulation thickness in house bedrooms for other mean night-time temperature thresholds. Likewise, there were no significant differences for living rooms in flats, or for bedrooms or living rooms in houses.

Figure 3: Prevalence of overheating in bedrooms in houses, by loft insulation thickness



Annotating marks indicate significance of between-column differences, as determined by chi-square tests: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Effects of flat floor and entry level

For flats, being located on the top floor (cf. any lower floor) or having entry above ground floor level (cf. ground floor or basement entry) was associated with significantly higher prevalence of overheating in both living rooms and bedrooms (Figure 4). For both flat floor level and flat entry level, the significant differences were observed for the Cat.I and/or Cat.II thresholds for living rooms (p < 0.05), and for thresholds of T = 27°C and 28°C for bedrooms (p <0.01, except for

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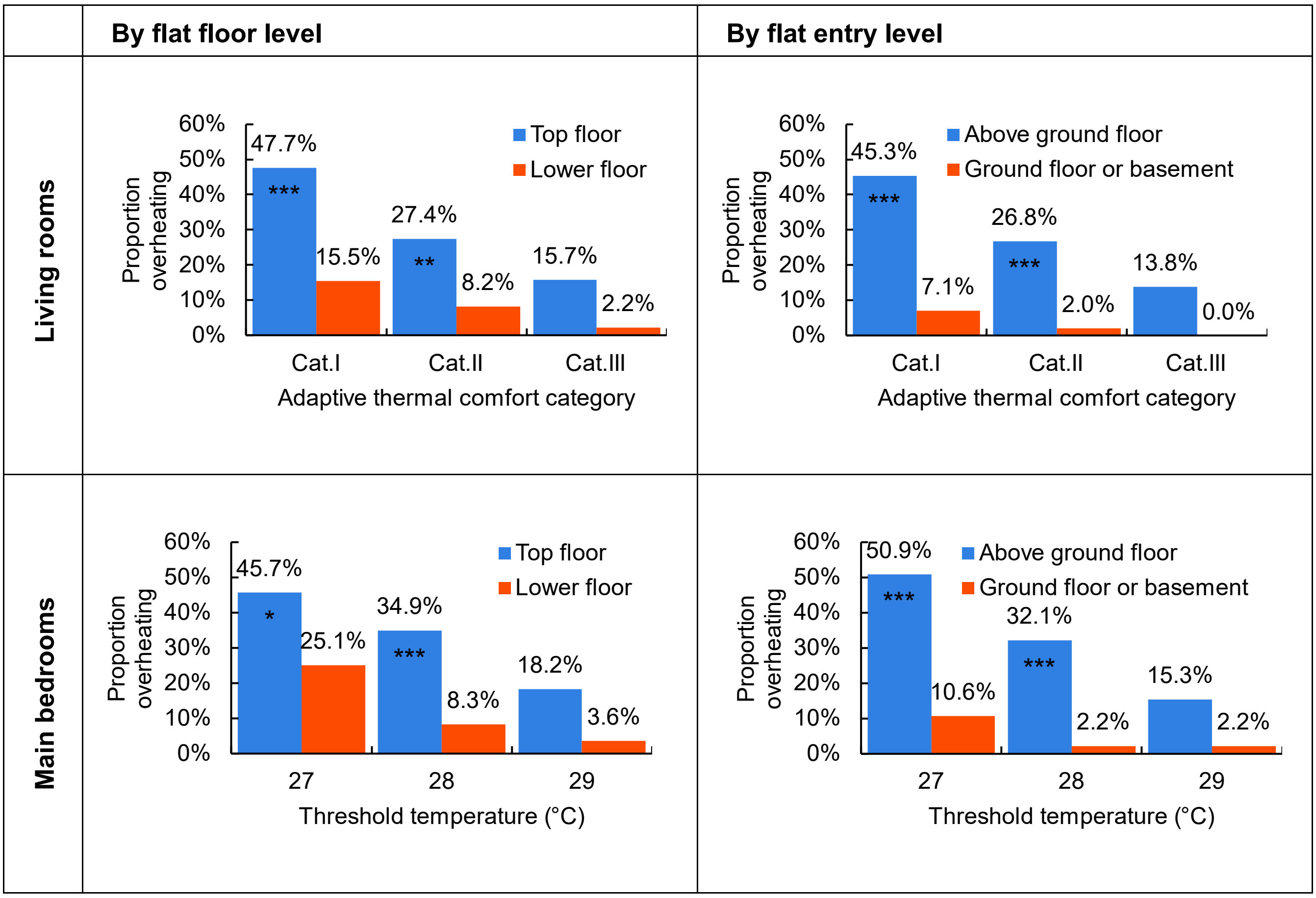
[16] Lomas et al. (2021) discuss the thermal physics potentially contributing to lower prevalence of overheating in ground floor living rooms compared with bedrooms on upper floors, noting that: (i) ground floor rooms are more shaded by the surrounding environment than upper floors; (ii) ground floors may be thermally more heavyweight, having a solid floor; (iii) warm air generated during the day will rise to spaces above, while cool air is more likely to pool on the ground floor; and (iv) bedrooms on upper floors may be directly below a hot roof or loft/attic space.

flat floor level with T = 27°C, where the difference was only marginally significant, p<0.1); there were, however, no significant differences for the higher Cat.III and T = 29°C thresholds.

Figure 4: Prevalence of overheating in flats, by flat floor level and flat entry level

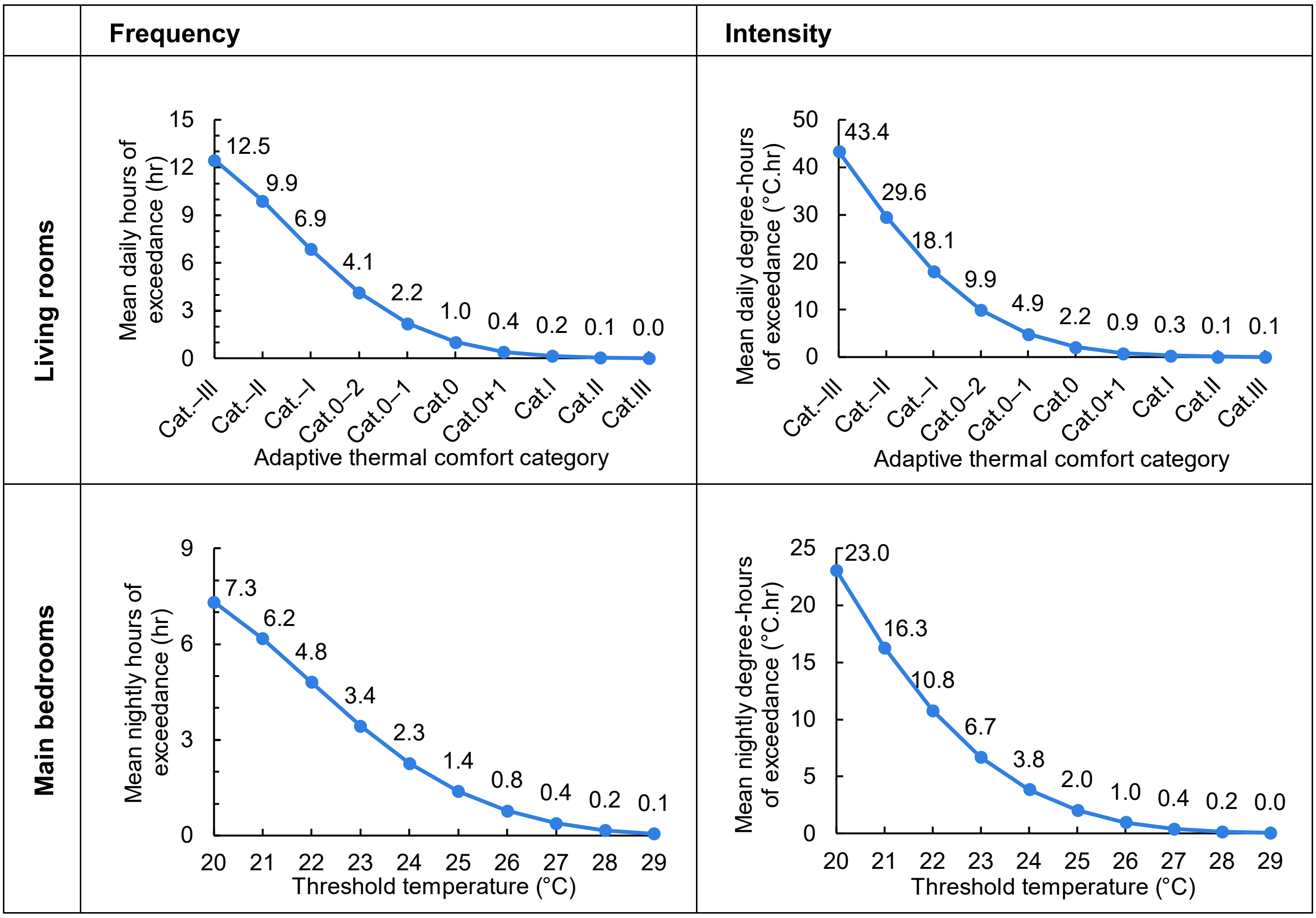


Annotating marks indicate significance of between-column differences, as determined by chi-square tests: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Frequency and intensity of overheating in houses

For both living rooms and bedrooms, as the threshold temperature was increased, the frequency and intensity of exceedance decreased (Figure 5). For living rooms in houses, the mean frequencies of exceedance were 0.16, 0.06 and 0.02 hours per day for Cat.I, Cat.II and Cat.III respectively, while the mean intensities of overheating were 0.33, 0.13 and 0.05°C.hr per day for Cat.I, Cat.II, Cat.III. For bedrooms in houses, mean frequencies of exceedance were 0.39, 0.16 and 0.06 hours per night for T = 27°C, 28°C and 29°C respectively, while the mean intensities of overheating were 0.41, 0.15 and 0.05°C.hr per night for the same respective threshold temperatures. For both living rooms and bedrooms, as the threshold temperature decreased, the frequency and intensity of exceedance increased.

Figure 5: Mean frequency and intensity of threshold exceedance in houses



Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms.

Effects of energy efficiency measures

The significance of differences in the frequency and intensity of threshold exceedance were assessed using independent t-tests applied to mean Box Cox transformed frequency and exceedance values for rooms in houses having non-zero exceedance (as described in *Testing for between-categories differences in frequency and intensity of threshold exceedance*).

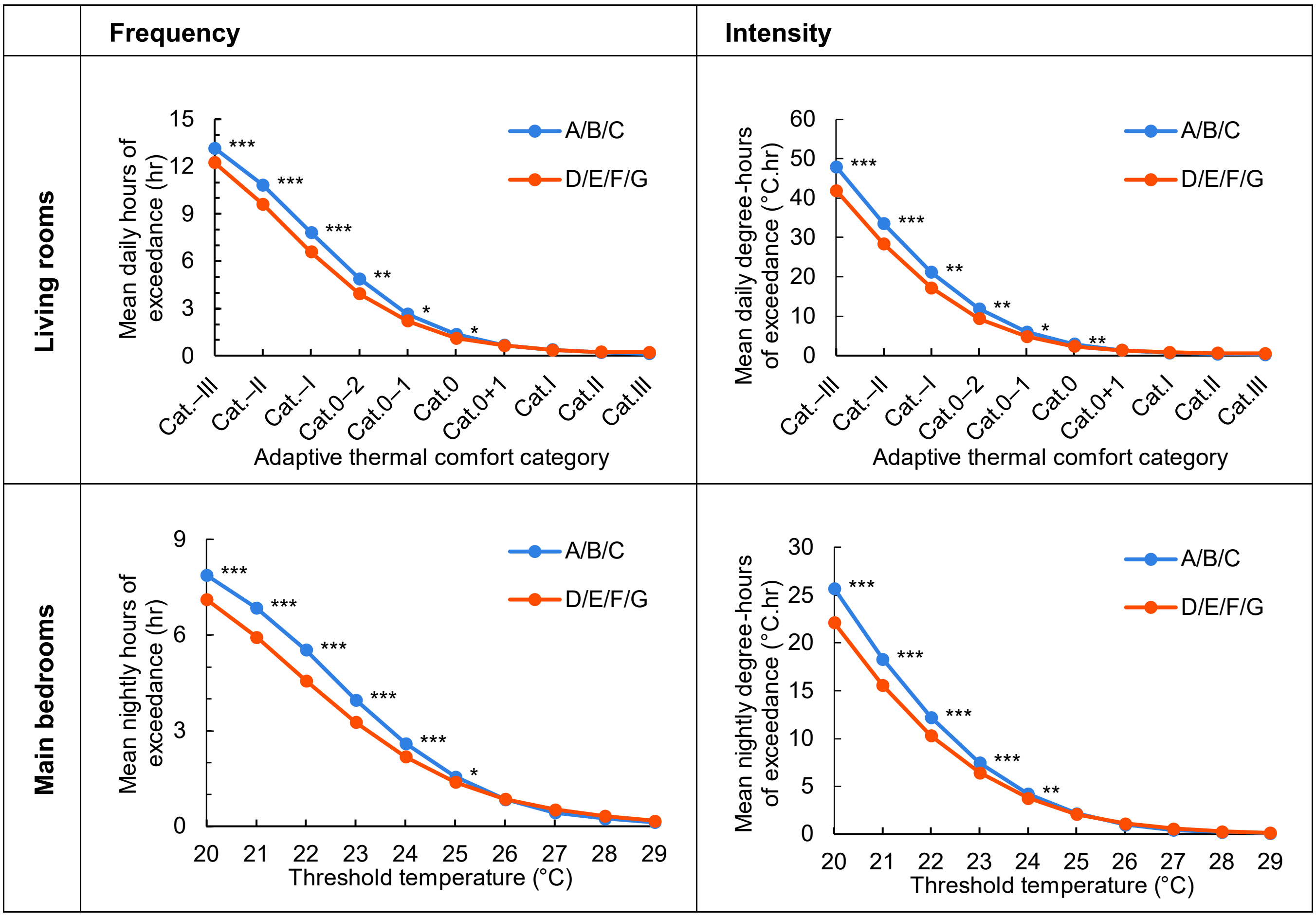
All five energy efficiency measures examined were associated with significant differences (p<0.05) at one or other threshold temperature for either or both of mean transformed frequency and intensity of exceedance, for at least one room type (living room or main bedroom). Mean frequencies and intensities of exceedance — for living rooms and bedrooms with non-zero hours of exceedance and categorized according to energy efficiency — are visualized in Figure 6 to Figure 10. Annotating marks indicate significant differences in mean Box Cox transformed frequency and intensity as identified by application of independent t-tests.

In general, the tests revealed significant differences at lower thresholds (Cat.0−1 and below for living rooms, T = 23°C and below for bedrooms), with greater energy efficiency broadly associated with higher frequency and intensity of exceedance; however, these differences generally ceased to be significant at the higher thresholds — those associated with overheating (Cat.I, Cat.II, Cat.III for living rooms, T = 27°C, 28°C, 29°C for bedrooms) — and in some cases were reversed, with greater energy efficiency being associated with significantly lower frequency and intensity of overheating.

Effect of energy efficiency rating band

When categorising houses by energy efficiency rating band (Figure 6), a higher energy efficiency rating (band A/B/C, cf. D/E/F/G) was associated with significantly higher (p <0.05) mean transformed frequency and intensity of exceedance in living rooms, for the Cat.0−1 threshold and below, and in bedrooms, for the T = 24°C threshold and below. However, upon reaching the higher thresholds (those associated with overheating) there were no significant differences in either mean transformed frequency or intensity of exceedance in living rooms or bedrooms.

Figure 6: Mean frequency and intensity of threshold exceedance in houses, by energy efficiency rating band, for rooms with non-zero exceedance at each given threshold

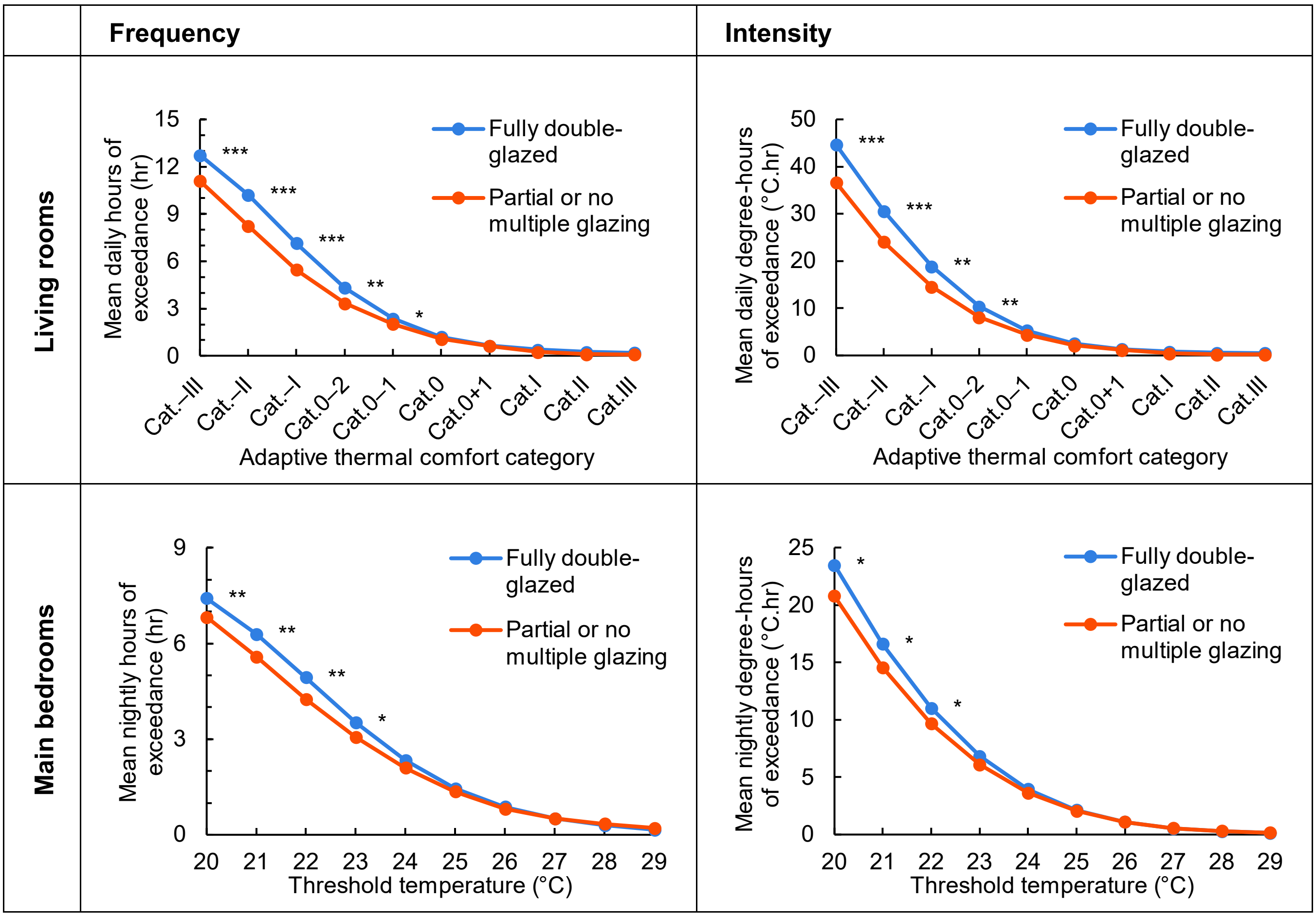


Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Effect of glazing type

When categorising houses by glazing type (Figure 7), full double-glazing (cf. partial or full single-glazing) was associated with significantly higher (p <0.05) mean transformed frequency and intensity of exceedance in living rooms, for the Cat.0−1 threshold and below. In bedrooms, the mean transformed frequency was significantly greater (p <0.05) in fully double-glazed houses, for the $\boldsymbol{T}$ = 22°C threshold and below; however, mean transformed intensity was only marginally significantly greater (p <0.1) in fully double-glazed dwellings for $\boldsymbol{T}$ = 22°C and below. At higher thresholds associated with overheating, there were no significant differences in either mean transformed frequency or intensity of exceedance, across both living rooms and bedrooms.

Figure 7: Mean frequency and intensity of threshold exceedance in houses, by whether fully double-glazed, for rooms with non-zero exceedance at each given threshold



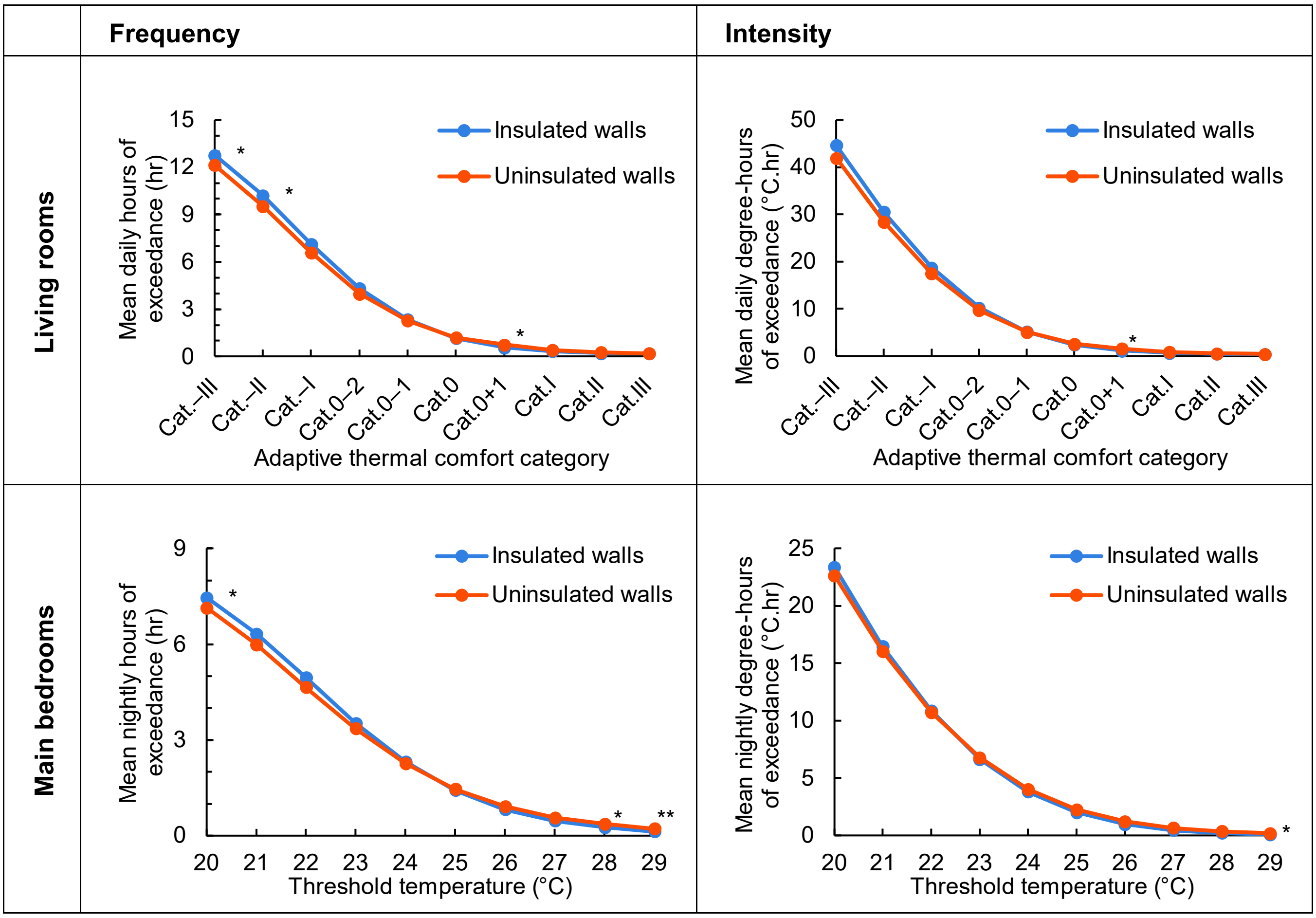
Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent $\boldsymbol{t}$-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Effect of wall and loft insulation

When categorising houses by presence of wall insulation (Figure 8), the presence of insulated walls (cf. uninsulated walls) was associated with only marginally significantly higher (p <0.1) mean transformed frequency of exceedance in living rooms, for the Cat.−II threshold and below, and in bedrooms for $\boldsymbol{T}$ = 20°C only. However, at the T = 29°C threshold, the mean transformed frequency of overheating was significantly greater for bedrooms in houses with uninsulated walls (mean 0.21 hr) compared with those with insulated walls (mean 0.13 hr), suggesting that wall insulation may reduce the frequency with which bedrooms in houses overheat.

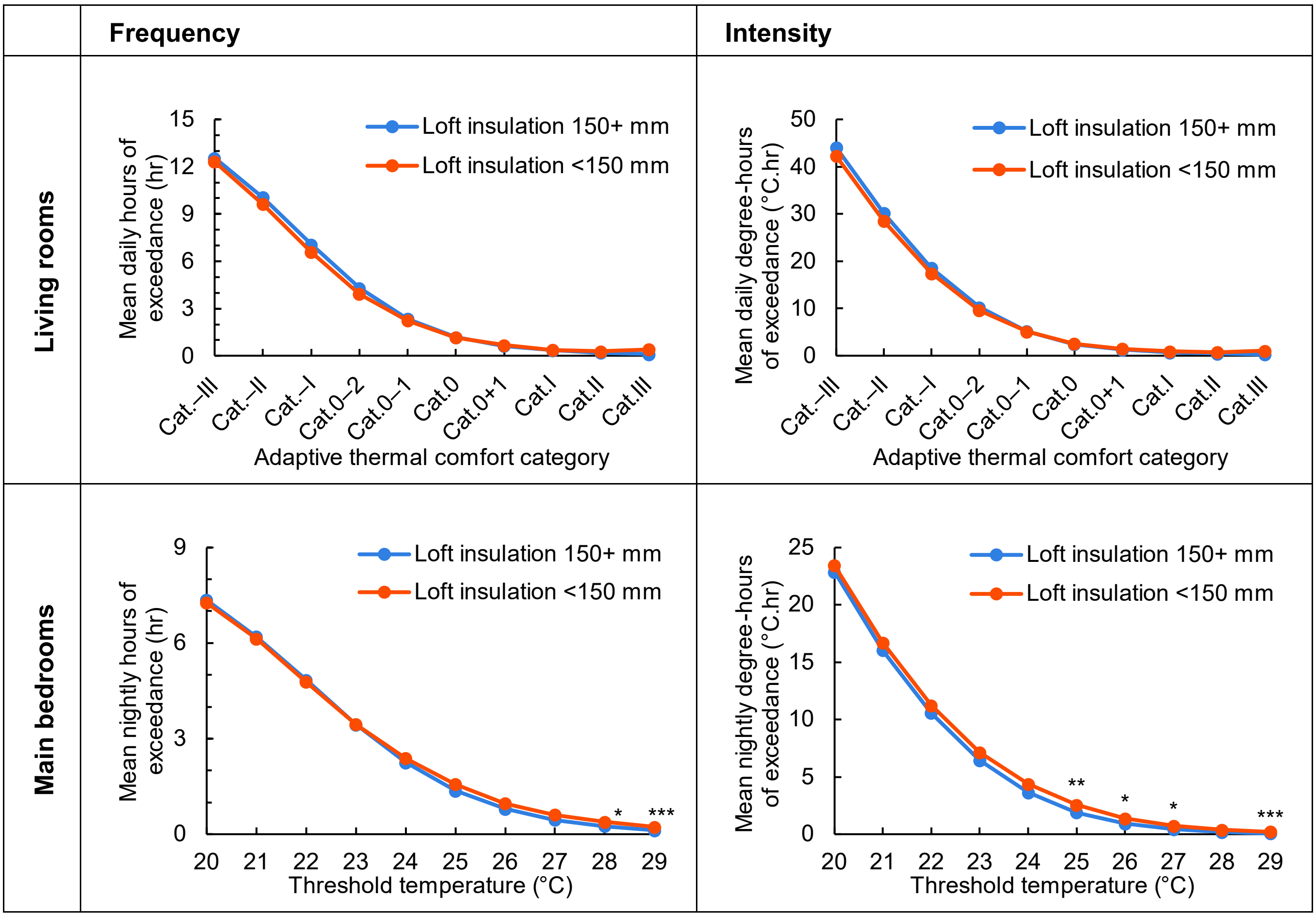
Similarly, when categorising houses by loft insulation thickness (Figure 9), loft insulation over 150 mm thick (cf. less than 150 mm) was associated with no significant effects at lower thresholds in either living rooms or bedrooms, but was associated with significantly lower (p <0.01) mean transformed frequency and intensity of overheating in bedrooms at the T = 29°C threshold. In bedrooms in houses with loft insulation over 150 mm thick, the mean frequency was 0.12 hr/night, compared with 0.23 hr/night in houses with less than 150 mm of insulation. The mean intensity was 0.08 °C.hr/night in those with 150+ mm insulation, compared with 0.22 °C.hr/night in those with less than 150 mm of insulation. This result suggests that additional loft insulation may help to reduce the frequency and intensity of overheating in bedrooms in houses.

Figure 8: Mean frequency and intensity of threshold exceedance in houses, by whether walls were insulated, for rooms with non-zero exceedance at each given threshold



Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: **, * significant at p<0.05, p<0.1 levels.

Figure 9: Frequency and intensity of threshold exceedance in houses, by loft insulation thickness, for rooms with non-zero exceedance at each given threshold

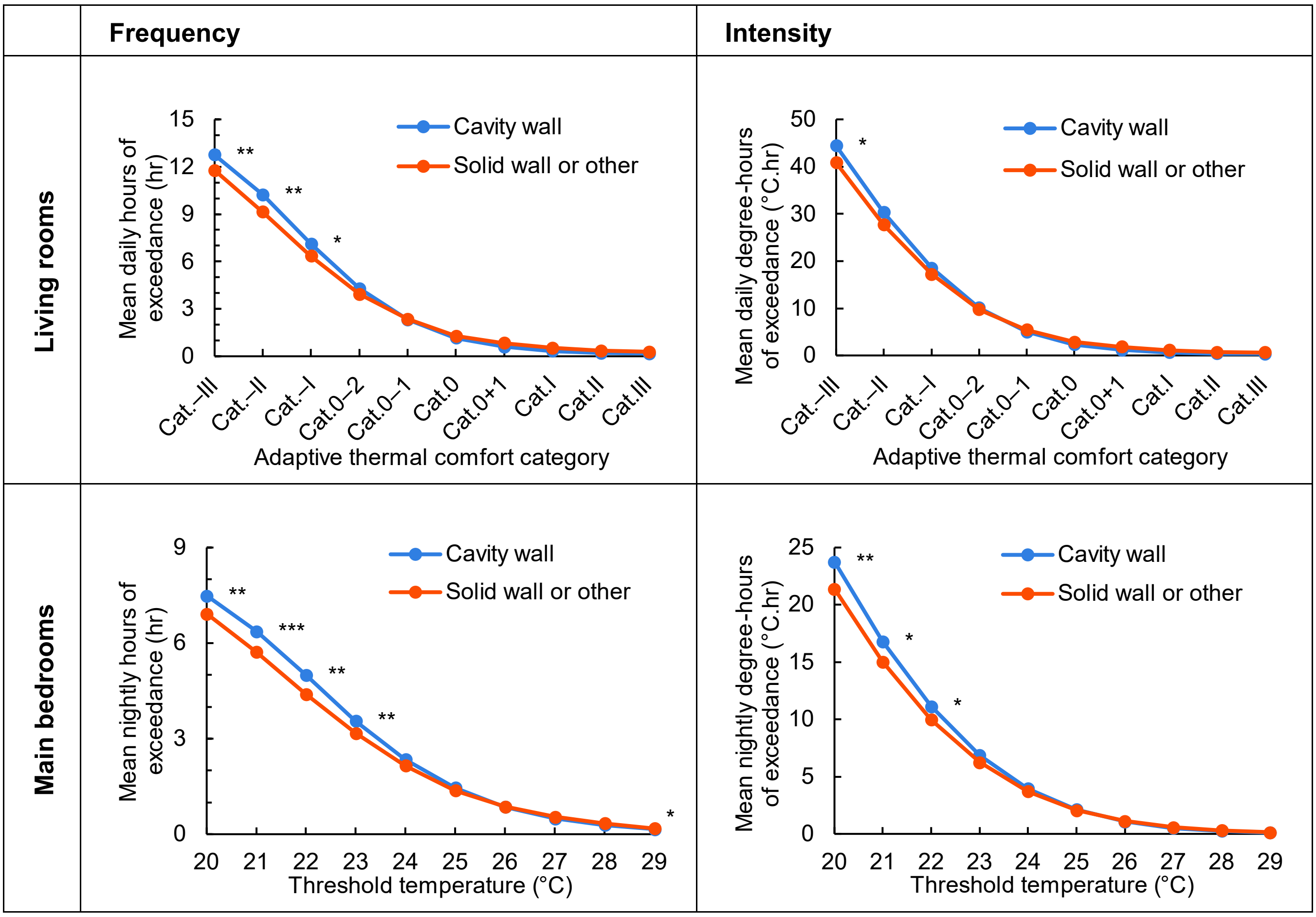


Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Effect of predominant wall type

When categorising houses according to predominant wall type (Figure 10), cavity wall construction (cf. solid or other construction) was associated with a significantly greater mean transformed frequency of exceedance (p <0.05) in living rooms for the Cat.−II and Cat.−III thresholds, and in bedrooms for the $\boldsymbol{T}$ = 23°C threshold and below. At thresholds associated with overheating, there were no significant differences in mean transformed frequency of overheating, other than a marginally higher frequency in the bedrooms of solid wall houses at the T = 29°C threshold. Cavity wall construction was associated with significantly higher (p <0.05) mean transformed intensity of exceedance in bedrooms at the $\boldsymbol{T}$ = 20°C threshold, but otherwise there were no more than marginally significant differences in mean transformed intensity across both living rooms and bedrooms.

Figure 10: Mean frequency and intensity of threshold exceedance in houses, by predominant wall type, for rooms with non-zero exceedance at each given threshold



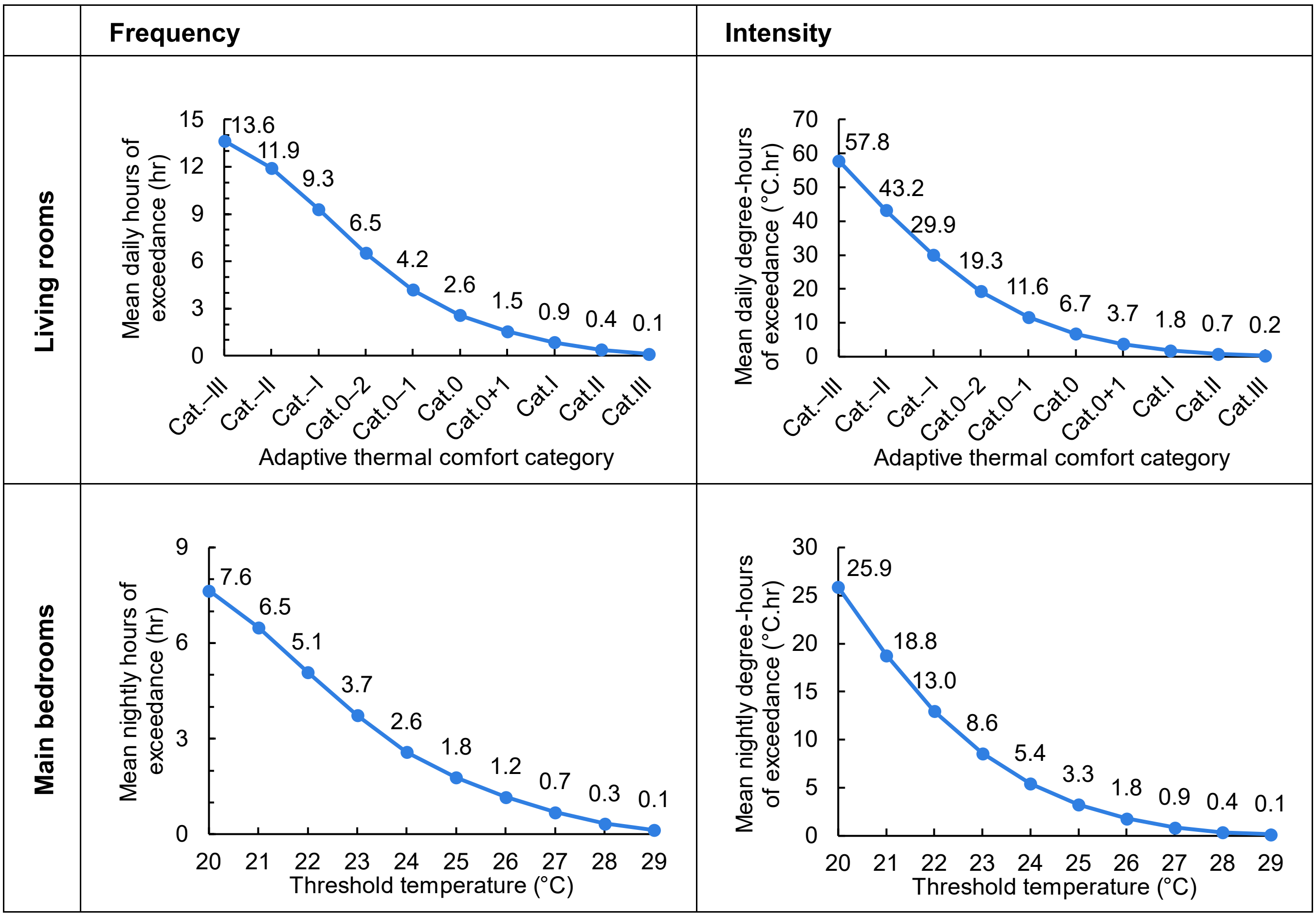
Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Frequency and intensity of overheating in flats

The frequency and intensity of overheating in flats is visualised in Figure 11, using graphs showing nationally weighted mean daily hours and degree-hours of exceedance at varying thresholds: Cat.−III, Cat.−II, …, to Cat.III for living rooms, and T = 20, 21, …, to 29°C for bedrooms.

For living rooms in flats, the mean frequencies of exceedance were 0.85, 0.37 and 0.12 hours per day for Cat.I, Cat.II and Cat.III respectively, while the mean intensities of overheating were 1.79, 0.72 and 0.24°C.hr per day for Cat.I, Cat.II, Cat.III. For bedrooms in flats, mean frequencies of exceedance were 0.70, 0.34 and 0.14 hours per night for T = 27°C, 28°C and 29°C respectively, while the mean intensities of overheating were 0.87, 0.36 and 0.14 °C.hr per night for the same respective threshold temperatures. Compared with houses (Figure 3), both the frequency and intensity of exceedance were consistently higher in flats than in houses, for both living rooms and bedrooms, and for all thresholds considered for each room type.

Figure 11: Mean frequency and intensity of threshold exceedance in flats



Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms.

Effects of energy efficiency measures

In flats, as for houses, the effects of energy efficiency measures on frequency and intensity of threshold temperature exceed were analysed using independent t-tests applied to mean Box Cox transformed frequency and exceedance values for rooms in flats having non-zero exceedance (as described in *Testing for between-categories differences in frequency and intensity of threshold exceedance*).

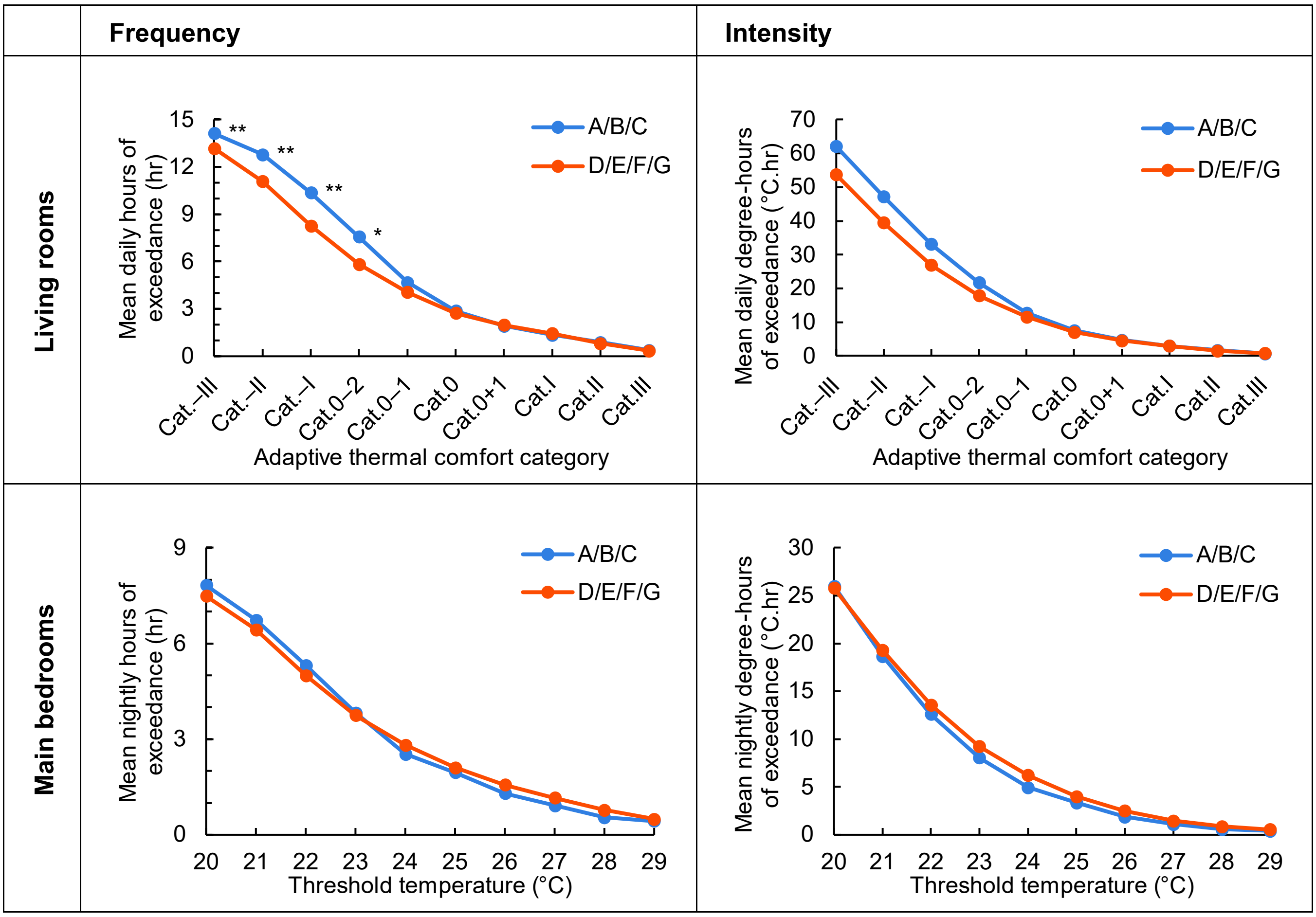
Three of the five energy efficiency measures examined — energy efficiency rating band, whether fully double-glazed, and whether walls were insulated — were associated with significant differences (p <0.05) in either or both the mean transformed frequency and intensity of threshold exceedance for at least one room type (living room or main bedroom). However, there were no significant effects associated with either loft insulation thickness or predominant wall type.

In general, any significant differences between energy efficiency categories that where present occurred at lower thresholds (Cat.0–2 and below for living rooms, $\boldsymbol{T}$ = 23°C and below for bedrooms). The more energy efficient homes were broadly associated with higher mean transformed frequency and intensity of exceedance, however, these differences generally ceased to be significant at the higher thresholds, i.e., those associated with overheating (Cat.I, Cat.II, Cat.III for living rooms, $\boldsymbol{T}$ = 27°C, 28°C, 29°C for bedrooms).

Effect of energy efficiency rating band

When categorising houses by energy efficiency rating band (Figure 12), a higher energy efficiency rating (band A/B/C, cf. D/E/F/G) was associated with significantly higher (p <0.05) mean transformed frequency of exceedance in living rooms, for the Cat.−I threshold and below. However, at higher thresholds the difference between mean frequency of living room overheating decreases, and the t-tests on mean transformed values cease producing significant results. Examining mean transformed frequency and intensity of exceedance in bedrooms, and mean transformed intensity in living rooms, there were no further significant differences between energy efficiency rating band groups.

Figure 12: Mean frequency and intensity of threshold exceedance in flats, by energy efficiency rating band, for rooms with non-zero exceedance at each given threshold

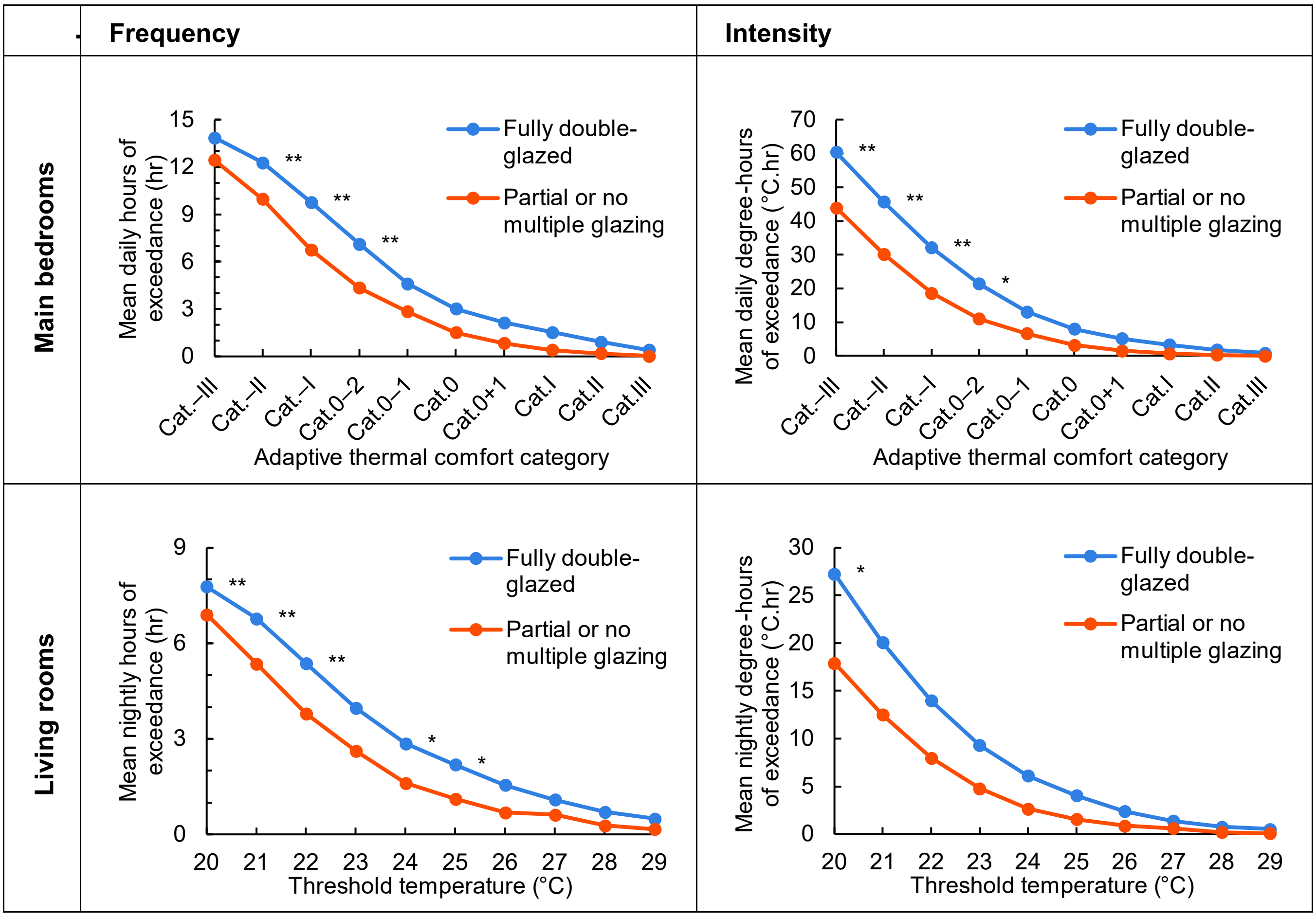


Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: **, * significant at p<0.05, p<0.1 levels.

Effect of glazing type

When categorising flats by glazing type, (fully double-glazed cf. partially or fully single-glazed), full double-glazing was associated with significantly higher (p <0.05) mean transformed frequency or intensity of exceedance in living rooms, for the Cat.0−2 threshold and below (Figure 13). In bedrooms, mean transformed frequency was significantly greater (p <0.05) in fully double-glazed flats, for the T = 22°C threshold and below; however, mean transformed intensity was only marginally significantly greater (p <0.1) in fully double-glazed flats for T = 20°C. At the higher thresholds associated with overheating, there were no significant differences in either mean transformed frequency or intensity of exceedance, either for living rooms or bedrooms, although both mean frequency and intensity remained comparatively higher in those rooms in flats with full double-glazing compared to those with partial or full single-glazing.

Figure 13 Mean frequency and intensity of threshold exceedance in flats, by whether fully double-glazed, for rooms with non-zero exceedance at each given threshold

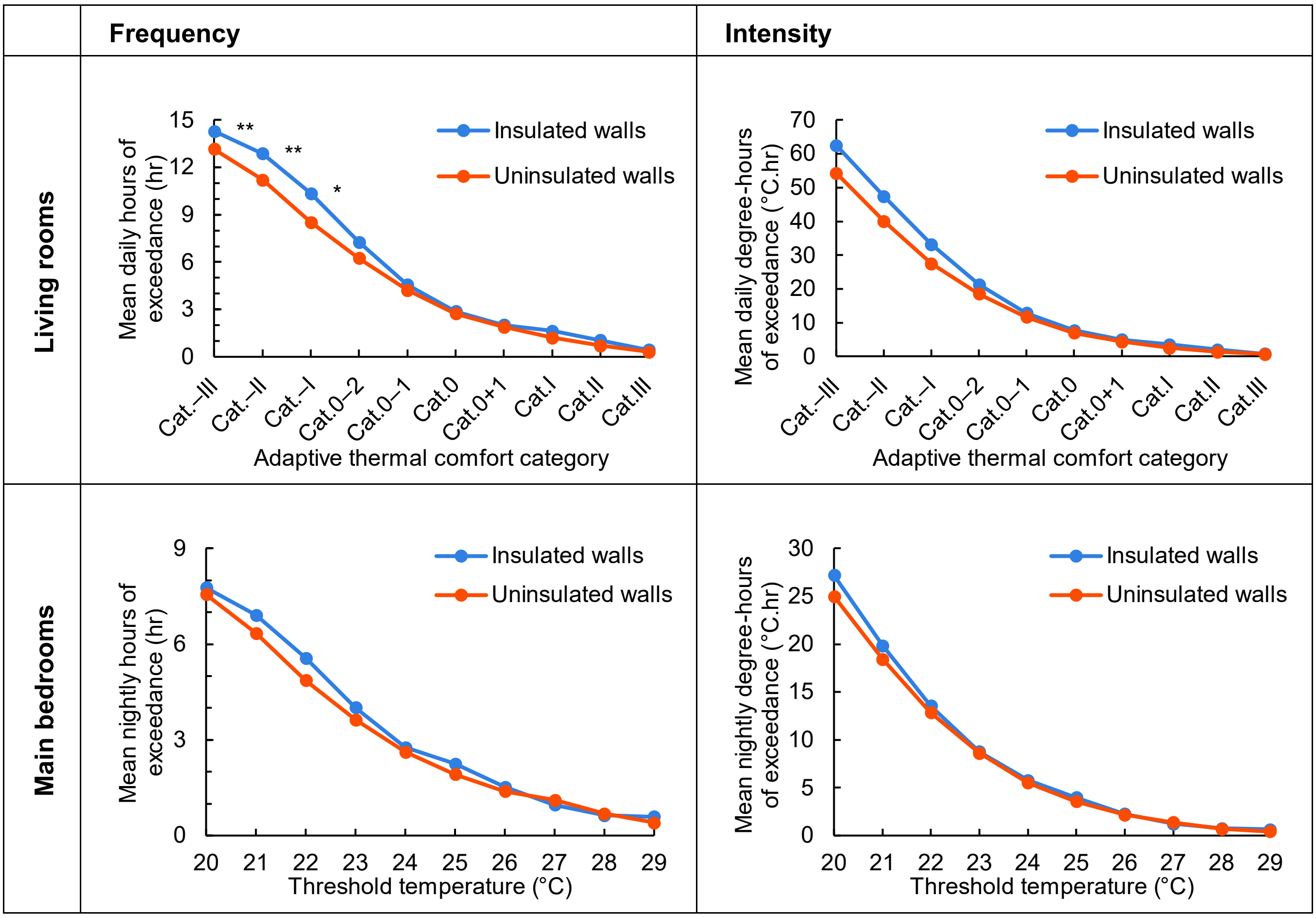


Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: **, * significant at p<0.05, p<0.1 levels.

Effect of wall insulation

When categorising flats by whether they had insulated walls (Figure 14), presence of insulated walls (cf. uninsulated walls) was associated with significantly higher (p <0.05) mean transformed frequency of exceedance in living rooms, for the Cat.−II threshold and below. No other significant effects were identified, for either intensity of exceedance in living rooms, nor for frequency or intensity in bedrooms.

Figure 14: Mean frequency and intensity of threshold exceedance in flats, by whether walls were insulated, for rooms with non-zero exceedance at each given threshold

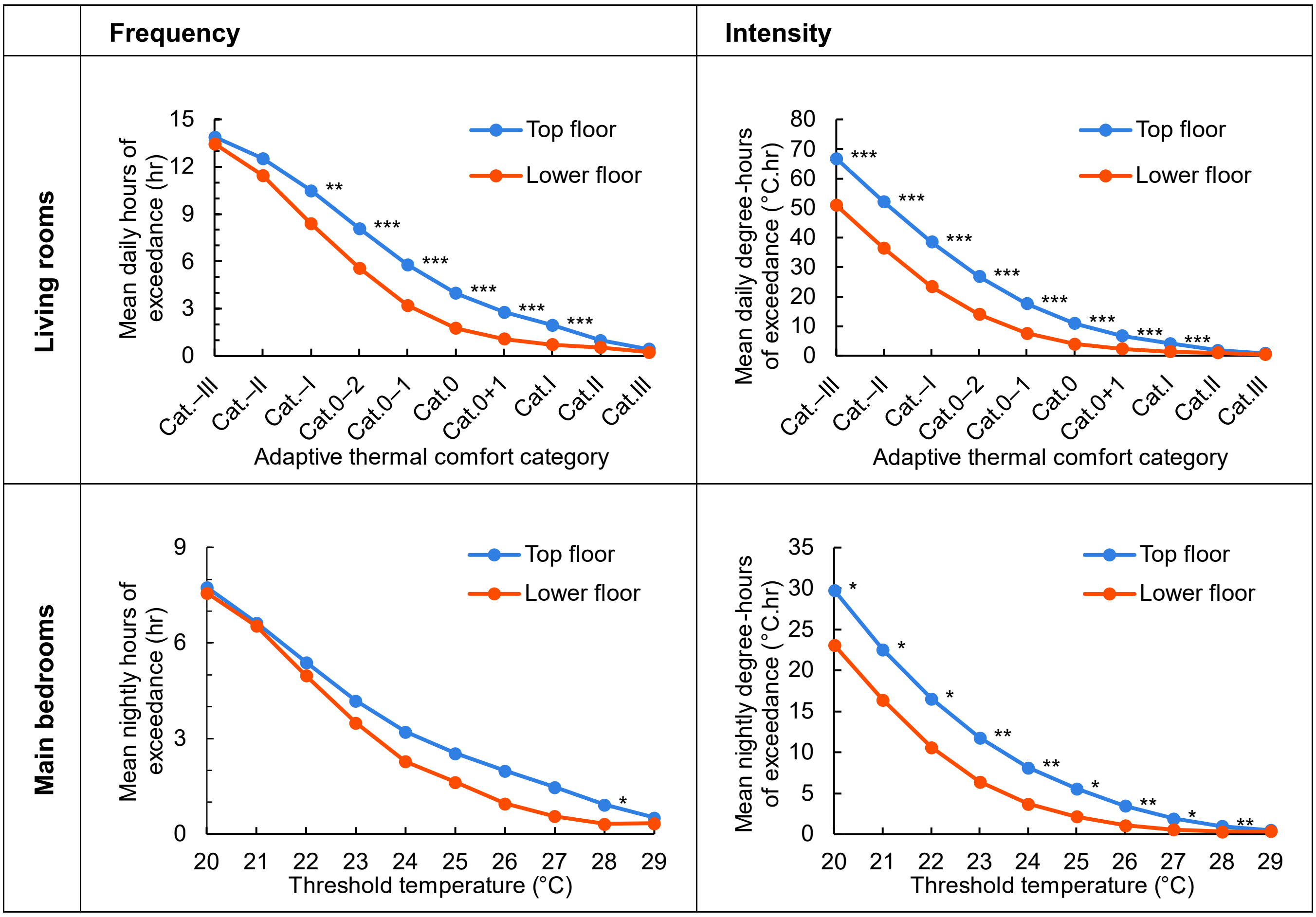


Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: **, * significant at p<0.05, p<0.1 levels.

Effects of flat floor level and flat entry level

When categorising flats by floor level (Figure 15), being located on the top floor (cf. any lower floor) was associated with strongly significantly greater mean transformed frequency and intensity of exceedance in living rooms across a wide range of thresholds: Cat.−I (p <0.05) and Cat.0−2 to Cat.I (p <0.01) for frequency; and Cat.−III to Cat.I (p <0.01) for intensity. This result indicates that a flat being located on the top floor of a building is not only significantly associated with greater mean transformed frequency and intensity of living room overheating at the Cat.I threshold, but also with maintenance of temperatures above lower thresholds. Meanwhile, for bedrooms, there was significantly higher (p<0.05) mean transformed intensity of exceedance in top floor flats across a range of thresholds (T = 23°C, 24°C, 26°C, 28°C), along with marginally significant (p <0.1) increases in mean transformed intensity at all other thresholds T from 20°C to 27°C, and in mean transformed frequency for T = 28°C.

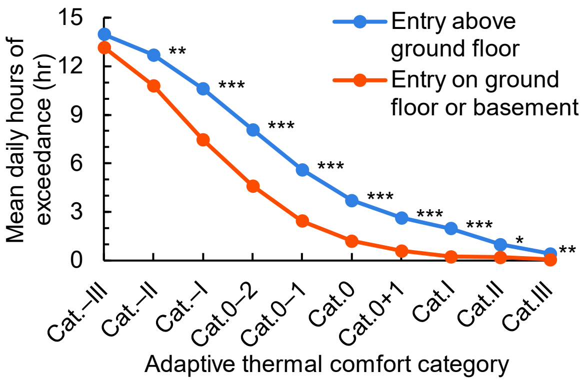
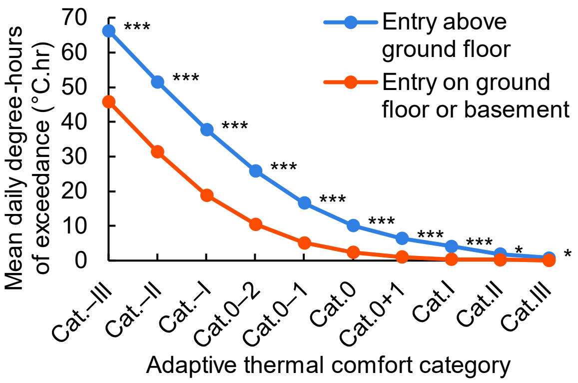
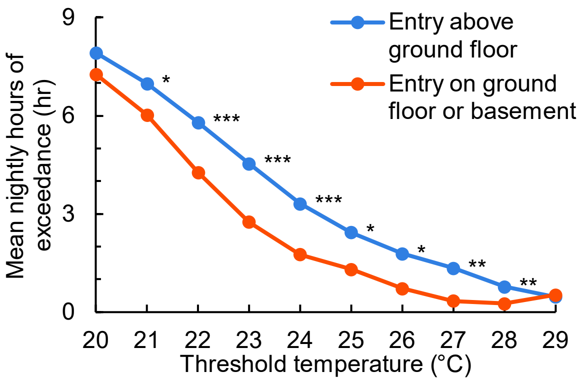
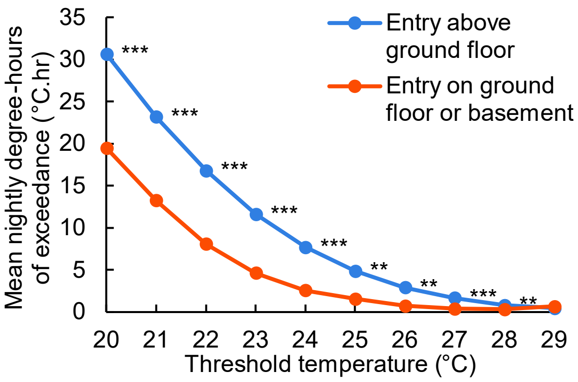
Figure 15 Mean frequency and intensity of threshold exceedance in flats, by flat floor level, for rooms with non-zero exceedance at each given threshold



Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

When categorising according to flat entry level (Figure 16), entry above ground floor level (cf. ground floor or basement) was associated with significantly higher frequency and intensity of exceedance across a broad range of thresholds for both living rooms and bedrooms. In living rooms, the mean transformed frequency was significantly greater (p <0.05) in flats with entry above ground floor for the Cat.−II to Cat.I thresholds, as well as the Cat.III threshold; meanwhile, the mean transformed intensity was significantly greater (p <0.01) for the Cat.−III to Cat.I thresholds. In bedrooms in flats with an entry above ground floor, the mean transformed frequency was strongly significantly greater for the T = 22°C, 23°C and 24°C thresholds (p <0.01), as well as for the T = 27°C and 28°C thresholds (p <0.05); meanwhile, mean transformed intensity was significantly greater for every threshold from T = 20°C to 28°C (p <0.05), with strong significance (p <0.01) for all but the 25°C, 26°C and 28°C thresholds. These results suggest a greater propensity toward higher indoor air temperatures in both the living rooms and main bedrooms of flats with entry above ground floor, both at temperatures associated with overheating, and those associated with cold discomfort.

Figure 16 Mean frequency and intensity of threshold exceedance in houses, by flat entry level, for rooms with non-zero exceedance at each given threshold

	Frequency	**Intensity**
Living rooms		
Main bedrooms		

Upper limits for frequency: 15 hours/day for living rooms; 9 hours/night for bedrooms. Annotating marks indicate significance of between-categories differences, as determined by independent t-tests applied to mean Box Cox transformed values: ***, **, * significant at p<0.01, p<0.05, p<0.1 levels.

Summary and conclusions

The overall findings of this work are presented in two sections. Firstly, the prevalence, frequency and intensity of overheating in the living rooms and bedrooms of the English housing stock is reported, along with the impact of energy efficiency measures on overheating. Then, the frequency and intensity of exceedance of lower threshold temperatures are reported. This approach identifies whether energy efficiency measures help keep homes warmer even though they may not result in overheating.

- Prevalence describes the proportion of living rooms or bedrooms in which indoor temperatures exceed a given overheating threshold temperature for more than a maximum allowable proportion of occupied hours.
- Frequency describes the number of hours per day during which the threshold temperature is exceeded.
- Intensity gives the average daily degree-hours (°C.hr) above the threshold temperature.

The analysis is based on the EFUS 2017 sample of 616 living rooms (506 in houses, 110 in flats) and 591 main bedrooms (496 houses, 95 flats) monitored throughout 2018, England's hottest summer. The living room analyses used adaptive thresholds under the assumption that they were occupied during the daytime hours 0700–2200, while the use of mean night-time temperature thresholds for bedrooms followed after Lomas & Li (2023), under the assumption that the bedrooms were being used for sleep during night-time hours (2200–0700). Throughout, the analysis was conducted separately for houses and flats. For flats, the effect on temperatures of flat floor level and entry level was also assessed. In this summary, only results significant at less than a 5% level are noted.

Effects of energy efficiency measures on overheating

The reported analysis has assessed the impact of five dwelling energy efficiency characteristics: energy efficiency rating band; whether fully double-glazed; whether walls were insulated; loft insulation thickness; and predominant wall type. Prevalence, frequency and intensity of overheating were calculated using adaptive thresholds (Cat.I, Cat.II, Cat.III) for living rooms, and mean night-time temperatures for bedrooms ($\boldsymbol{T}$ = 27°C, 28°C, 29°C).

Comparing the prevalence of overheating in flats with the prevalence in houses, it was found that the living rooms in flats overheated with between 3 and 8 times greater prevalence than those in houses. Bedrooms in flats also recorded a higher prevalence of overheating than those in houses, but to a lesser extent (up to 3 times greater prevalence in flats that houses).

Results of statistical tests for assessing the significance of differences in prevalence, frequency and intensity of overheating depending on energy efficiency measures are summarised in Table 1. There were very few significant associations between energy efficiency measures and prevalence, frequency and intensity of overheating, for either living rooms or bedrooms in either houses or flats. In summary:

- In the living rooms of houses, there were no significant differences in the prevalence, frequency or intensity of overheating for any of the energy efficiency measures examined.
- In the bedrooms of houses, there were no significant differences in prevalence, frequency or intensity of overheating, with just two exceptions:
- Most importantly, there was a significantly higher prevalence, mean frequency and mean intensity of overheating in the bedrooms of houses which had less than 150mm of loft insulation, compared with houses having more than 150 mm of loft insulation.
- There was a significantly higher mean frequency (but not intensity or prevalence) of overheating when walls were uninsulated, rather than insulated.
- In flats, significant effects were observed for floor level and entry level in both living rooms and bedrooms:
- Overheating occurred with significantly greater prevalence, mean frequency and mean intensity in both the living rooms and bedrooms of flats situated on the top floor of a building (compared with any lower floor), or with an entrance on a floor above ground level (compared with ground floor or basement entry); the only exception was the absence of a significant effect on the frequency of bedroom overheating associated with flat floor level.

Table 1: Summary of factors associated with significant effects on prevalence (P), frequency (F) and intensity (I) of overheating in the living rooms and main bedrooms of English houses and flats

Dwelling characteristic	**Whether significantly associated with greater overheating (p<0.05)**											
	Houses						**Flats**					
	Living rooms			**Bedrooms**			**Living rooms**			**Bedrooms**		
	P	**F**	**I**	**P**	**F**	**I**	**P**	**F**	**I**	**P**	**F**	**I**
Energy efficiency rating A/B/C (cf. D/E/F/G)												
Fully double-glazed (cf. partially or fully single-glazed)												
Uninsulated walls (cf. insulated)					●							
<150 mm loft insulation (cf. 150+ mm)				●	●	●						
Cavity walls (cf. solid or other)												
Top floor flat (cf. lower floor)	—	—	—	—	—	—	●	●	●	●		●
Flat entry above ground floor (cf. ground or basement)	—	—	—	—	—	—	●	●	●	●	●	●

● indicates a difference significant at the p<0.05 level for at least one overheating threshold: Cat.I, Cat.II, or Cat.III for living rooms; ***T*** = 27°C, 28°C, or 29°C for bedrooms.
Significance of differences in prevalence was assessed via chi-square tests applied to nationally weighted proportions; significance in differences in frequency and intensity were assessed via independent *t*-tests applied to mean Box Cox transformed frequency and intensity metrics for rooms with non-zero hours of exceedance.

Effects of energy efficiency measures on temperatures below overheating thresholds

Statistical tests were also conducted to assess the effects of energy efficiency measures at thresholds below those associated with overheating. The results are salient for assessing whether (and which) energy efficiency measures contribute positively to prevention of temperatures associated with cold discomfort. At lower (sub-overheating) thresholds, higher frequency and prevalence of exceedance are both desirable and expected in dwellings with additional energy efficiency measures. Given that the influence of outdoor temperatures has not been examined in this work, it is not possible to surmise whether increased exceedance of sub-overheating thresholds may or may not lead to increased exceedance above overheating thresholds in future warming scenarios, although it is noted that the summer of 2018 is thought typical of summers that may be normal by the 2050s (Madge, 2019).

For living rooms, thresholds of 1°C, 2°C, …, up to 7°C below the Cat.I adaptive threshold were assessed. The lowest three of these — falling 5°C, 6°C and 7°C below the Cat.I threshold and referred to as Cat.−I, Cat.−II and Cat.−III — correspond to the lower limiting temperatures for Cat.I, Cat.II and Cat.III adaptive thermal comfort categories in BSEN16798: that is, they define living spaces meeting high, medium or moderate expectations of thermal comfort in cold conditions. For bedrooms, mean night-time temperature thresholds of $\boldsymbol{T}$ = 26°C, 25°C …., down to 20°C, were assessed.

At lower threshold temperatures — Cat.−I, Cat.−II, Cat.−III for living rooms, and T = 20°C, 21°C, 22°C for bedrooms[17] — many of the energy efficiency measures analysed were significantly associated with a greater mean average frequency and intensity of threshold exceedance (Table 2). In summary, for houses:

- In living rooms, the frequency and intensity of threshold exceedance was on average significantly greater for houses in higher energy efficiency rating bands (A/B/C rather than D/E/F/G), and in houses with full double-glazing.
- In the living rooms of houses with cavity wall construction, rather than with solid wall or other construction, the frequency of exceedance was on average significantly higher.
- In the bedrooms, there was on average a significantly higher frequency and intensity of threshold exceedance for houses in a higher energy efficiency rating band, and for houses with cavity wall construction rather than solid or other construction.
- In bedrooms, the frequency of threshold exceedance was on average significantly higher in houses with full double-glazing.

Summarising the results for flats:

- In the living rooms, the frequency of threshold exceedance was on average significantly higher in flats in higher energy efficiency rating bands, with full double-glazing, and with insulated walls. The intensity of exceedance was also significantly greater on average for those in flats with full double-glazing.
- In bedrooms, frequency of exceedance was on average significantly higher in flats that were fully double-glazed.
- The influences of floor level and entry level was much the same as observed for exceedance of overheating thresholds: frequency and intensity were on average significantly higher in both living rooms and bedrooms in flats whose entrance was located above ground floor level (compared with ground or basement entry); meanwhile, frequency and intensity were on average significantly higher in living rooms of top floor flats (compared with those on lower floors), but not in bedrooms of such flats.

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[17] While the Cat.−I, Cat.−II and Cat.−III adaptive thresholds correspond to levels of cold discomfort (as per BSEN16798), the 20°C, 21°C, 22°C nightly mean temperature thresholds do not represent (and should not be interpreted as thresholds for) cold discomfort in bedrooms.

Table 2: Summary of factors associated with significant effects on frequency (F) and intensity (I) of threshold exceedance, at sub-overheating threshold temperatures, in living rooms and main bedrooms of English houses and flats

Dwelling characteristic	**Whether significantly associated with greater threshold exceedance (p<0.05)**							
	Houses				**Flats**			
	Living rooms		**Bedrooms**		**Living rooms**		**Bedrooms**	
	F	**I**	**F**	**I**	**F**	**I**	**F**	**I**
Energy efficiency rating A/B/C (cf. D/E/F/G)	●	●	●	●	●			
Fully double-glazed (cf. partially or fully single-glazed)	●	●	●		●	●	●	
Insulated walls (cf. uninsulated)					●			
150+ mm loft insulation (cf. <150 mm)								
Cavity walls (cf. solid or other)	●		●	●				
Top floor flat (cf. lower floor)	—	—	—	—	●	●		
Flat entry above ground floor (cf. ground or basement)	—	—	—	—	●	●	●	●

● indicates a difference significant at the p<0.05 level for at least one threshold: Cat.−I, Cat.−II, or Cat.−III for living rooms; T = 20°C, 21°C, 22°C for bedrooms.
Significance of differences in prevalence was assessed via chi-square tests applied to nationally weighted proportions; significance in differences in frequency and intensity were assessed via independent t-tests applied to mean Box Cox transformed frequency and intensity metrics for rooms with non-zero hours of exceedance.

Limitations

The present analysis of effects of energy efficiency measures on indoor temperatures is based on a sample representing the existing English housing stock, in which there are very few dwellings that have high levels of insulation, such as those found in homes built to Passivhaus standards[18]. It may be that homes built to higher energy efficiency standards would display different responses to those observed here, being either more, or less likely to overheat. An

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[18] 72% of the 750 EFUS 2017 sample dwellings (representing 74% of the English stock) had an energy efficiency rating (EER) in band D or lower, while the 2016/17 English Housing Survey reported that 70% of the English stock had an EER in band D or below (MHCLG, 2018). By 2020, this figure had fallen to 46%, with 54% having an EER in band C or above (DLUHC, 2022).

analysis of a representative sample of such homes analysed using statistical methods such as those described in this report would be illuminating.

As with any approach relying on statistical inference, it is important to note that any observation of statistically significant effect does not necessarily imply a causal effect. In particular, the analysis reported here has not controlled for the influence of potential confounding factors when comparing dwellings with differing energy efficiency levels. For example, the observation of significantly greater overheating in bedrooms in houses with lower levels of loft insulation may be a consequence of those houses being in warmer regions, or their being less thermally massive, rather than the thermal performance of the roof. Similarly, significant increases in frequency of exceedance of sub-overheating temperatures in fully double-glazed dwellings may be due, partly or in whole, to superior airtightness following an efficiency-driven building retrofit, rather than the glazing alone.

The reported analysis of frequency and intensity of threshold exceedance was conducted using data gathered between May and September in a hot English summer[19]. Consequently, analysis of exceedance at sub-overheating threshold temperatures does not capture the effects of energy efficiency measures and flat floor levels on indoor temperatures during the heating season. Further analysis of winter data could be valuable in determining whether the temperature-elevating effects identified here are maintained; however, care would need to be exercised to avoid conflating effects associated with dwelling characteristics with those informed by heating behaviours.

This analysis does not examine the effects of outdoor ambient temperature in any detail. Understanding how indoor air temperature responds to outdoor temperature would provide further understanding of the extent to which energy efficiency measures protect against the heating up of indoor spaces. Characterisation of the relationship between indoor and outdoor temperatures in the EFUS 2017 dataset would be particularly meaningful in the context of predicting overheating patterns in dwellings exposed to future higher temperatures. Analysis of this relationship using the recently developed concept of a dwelling ‘temperature signature’ (Drury, 2023) is presented in a subsequent report, ‘The effect of energy efficiency measures on summertime overheating in UK dwellings: temperature sensitivity analysis’ (Li, 2024).

There may be co-incidence between the potential for flats to overheat compared to houses and the area of glazing, with flats having more glazing for a given floor area than houses. It would be useful to investigate the relationship between glazed area and overheating.

The use of Box Cox transformations on non-normally distributed frequency and intensity metrics necessitated restriction of samples to those with non-zero hours of exceedance. As thresholds increased, therefore, sample sizes became smaller as fewer dwellings experienced higher temperatures. Although there is no strict minimum sample size for validity of independent t-tests, it is recognised that statistical power diminishes as sample sizes get

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[19] Summer 2018 was the joint hottest summer season (June, July, August) in the Met Office UK national temperature series dating from 1884, and the warmest on record for England as of 2018 (McCarthy et al., 2019). Summer average temperatures were close to +2.0°C above the 1981–2010 average for much of southern and central England and Wales (ibid.).

smaller. Thus, in the reported analysis of factors influencing frequency and intensity of thresholds exceedance, the likelihood of a false negative — failing to identify an extant significant effect — was greater for the higher temperature thresholds, which may have contributed to the lack of significant effects[20].

Overall conclusions

The results of the present work indicate that there are very few significant effects of dwelling energy efficiency measures on propensity to overheat in the living rooms and main bedrooms of houses and flats. Moreover, where significant effects were observed, they suggested preventative effects against overheating, with the presence of thicker loft insulation in particular associated with significantly lower prevalence, frequency and intensity of overheating in bedrooms in houses.

At lower, sub-overheating thresholds, a number of energy efficiency measures — higher energy efficiency rating band, full double-glazing, insulated walls, cavity walls — were found to significantly increase internal temperatures in houses and/or flats, which is the intended purpose of energy efficiency measures.

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[20] As noted in the report section *Testing for between-categories differences in frequency and intensity of threshold exceedance*, unweighted sample sizes were at least 30 in most cases. Sample sizes were reduced to fewer than 30 on three occasions only, all when assessing the influence of loft insulation thickness: for living rooms in flats using the Cat.III adaptive threshold (N=24); and for bedrooms in flats using the $\boldsymbol{T}$=28°C and $\boldsymbol{T}$=29°C nightly mean temperature thresholds (N=27 and N=20).

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Appendix A

Statistical tables

Table A1: Box Cox transformation parameters for frequency of exceedance of adaptive thresholds in living rooms

Threshold	**Houses**				**Flats**							
	All with nonzero exceedance				**All with nonzero exceedance**				**With loft insulation data**			
	N	**λ**	**Sk**	**Kt**	**N**	**λ**	**Sk**	**Kt**	**N**	**λ**	**Sk**	**Kt**
Cat.−III	506	3.138	-0.43	-1.05	110	6.471	-0.99	-0.47	46	9.531	-0.71	-0.84
Cat.−II	506	1.205	-0.24	-0.98	110	2.238	-0.56	-0.89	46	3.359	-0.41	-1.20
Cat.−I	504	0.578	-0.12	-0.75	110	0.912	-0.35	-0.89	46	1.403	-0.28	-1.27
Cat.0-2	501	0.392	-0.08	-0.42	107	0.502	-0.13	-0.85	46	0.583	-0.15	-1.15
Cat.0-1	475	0.263	-0.07	-0.47	105	0.336	-0.07	-0.38	46	0.255	-0.07	-0.87
Cat.0	432	0.195	-0.10	-0.70	101	0.207	-0.06	-0.43	46	0.218	-0.05	-0.46
Cat.0+1	339	0.109	-0.03	-0.52	89	0.124	-0.05	-0.60	43	0.220	-0.02	0.00
Cat.I	234	0.026	-0.01	-0.73	73	0.061	-0.03	-0.63	38	-0.001	0.00	-0.43
Cat.II	138	-0.077	0.02	-0.41	54	0.065	-0.02	-0.42	34	0.072	-0.01	-0.28
Cat.III	74	-0.074	0.02	-0.51	41	0.014	-0.01	-0.77	24	-0.075	0.05	-1.11

N = unweighted sample size
λ = lambda value used in Box Cox power transform
Sk, Kt = skewness and kurtosis statistics for transformed sample data after weighting to national stock

Table A2: Box Cox transformation parameters for frequency of exceedance of mean night-time temperature thresholds in main bedrooms

Threshold	Houses				Flats							
	All with nonzero exceedance				All with nonzero exceedance				With loft insulation data			
	N	λ	Sk	Kt	N	λ	Sk	Kt	N	λ	Sk	Kt
T=20°C	496	2.812	-0.29	-1.00	95	3.344	-0.54	-0.78	38	3.102	-0.16	-1.06
T=21°C	496	1.406	-0.15	-0.75	93	1.633	-0.24	-0.98	38	1.152	-0.11	-1.04
T=22°C	495	0.820	-0.05	-0.37	93	0.821	-0.10	-0.61	38	0.311	-0.05	-1.09
T=23°C	493	0.596	0.02	0.23	93	0.530	-0.02	-0.06	38	0.147	-0.03	-0.86
T=24°C	488	0.435	0.02	0.39	91	0.406	0.02	0.45	38	0.277	-0.02	-0.29
T=25°C	477	0.385	-0.03	0.11	84	0.148	0.00	0.03	37	0.079	-0.02	-0.59
T=26°C	451	0.328	-0.08	-0.25	77	0.136	-0.03	-0.32	36	0.137	-0.04	-0.47
T=27°C	387	0.259	-0.07	-0.39	63	0.114	-0.01	-0.21	33	0.151	-0.04	-0.41
T=28°C	272	0.136	-0.03	-0.53	48	0.059	-0.03	-0.72	27	0.138	-0.04	-0.57
T=29°C	176	0.074	-0.02	-0.65	30	0.132	-0.08	-0.93	20	0.128	-0.08	-1.01

N = unweighted sample size
λ = lambda value used in Box Cox power transform
Sk, Kt = skewness and kurtosis statistics for transformed sample data after weighting to national stock

Table A3: Box Cox transformation parameters for intensity of exceedance of adaptive thresholds in living rooms

Threshold	Houses				Flats							
	All with nonzero exceedance				All with nonzero exceedance				With loft insulation data			
	N	λ	Sk	Kt	N	λ	Sk	Kt	N	λ	Sk	Kt
Cat.−III	506	0.627	0.00	-0.01	110	0.622	0.07	0.67	46	0.073	0.00	-0.50
Cat.−II	506	0.479	-0.03	-0.21	110	0.536	0.04	0.36	46	0.126	-0.01	-0.61
Cat.−I	504	0.342	-0.03	-0.28	110	0.424	-0.01	0.13	46	0.124	-0.02	-0.72
Cat.0-2	501	0.287	-0.04	-0.19	107	0.240	-0.02	-0.17	46	0.097	-0.02	-0.73
Cat.0-1	475	0.198	-0.05	-0.38	105	0.213	-0.01	-0.04	46	0.096	-0.02	-0.58
Cat.0	432	0.152	-0.08	-0.59	101	0.147	-0.04	-0.34	46	0.151	-0.03	-0.33
Cat.0+1	339	0.070	-0.02	-0.43	89	0.100	-0.05	-0.60	43	0.186	-0.02	-0.03
Cat.I	234	0.008	0.00	-0.66	73	0.051	-0.03	-0.76	38	0.026	-0.01	-0.51
Cat.II	138	-0.078	0.02	-0.43	54	0.057	-0.02	-0.49	34	0.073	-0.02	-0.41
Cat.III	74	-0.061	0.02	-0.58	41	-0.018	0.01	-0.84	24	-0.089	0.07	-1.21

N = unweighted sample size
λ = lambda value used in Box Cox power transform
Sk, Kt = skewness and kurtosis statistics for transformed sample data after weighting to national stock

Table A4: Box Cox transformation parameters for intensity of exceedance of mean night-time temperature thresholds in main bedrooms

Threshold	Houses				Flats							
	All with nonzero exceedance				All with nonzero exceedance				With loft insulation data			
	N	λ	Sk	Kt	N	λ	Sk	Kt	N	λ	Sk	Kt
T=20°C	496	0.607	0.04	0.47	95	0.503	0.12	1.04	38	-0.248	0.03	-0.68
T=21°C	496	0.518	0.05	0.51	93	0.294	0.05	0.60	38	-0.130	0.02	-0.70
T=22°C	495	0.433	0.04	0.54	93	0.272	0.05	0.60	38	-0.049	0.01	-0.67
T=23°C	493	0.386	0.04	0.52	93	0.259	0.04	0.49	38	0.058	-0.01	-0.49
T=24°C	488	0.312	-0.01	0.11	91	0.241	0.01	0.34	38	0.179	-0.02	-0.18
T=25°C	477	0.266	-0.06	-0.23	84	0.094	-0.02	-0.33	37	0.094	-0.04	-0.66
T=26°C	451	0.234	-0.10	-0.35	77	0.134	-0.06	-0.44	36	0.162	-0.07	-0.52
T=27°C	387	0.182	-0.07	-0.37	63	0.112	-0.03	-0.37	33	0.139	-0.08	-0.67
T=28°C	272	0.117	-0.04	-0.40	48	0.077	-0.05	-0.73	27	0.136	-0.07	-0.64
T=29°C	176	0.079	-0.03	-0.56	30	0.133	-0.11	-0.85	20	0.160	-0.13	-0.83

N = unweighted sample size
λ = lambda value used in Box Cox power transform
Sk, Kt = skewness and kurtosis statistics for transformed sample data after weighting to national stock

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