Title: Determinants of winter indoor temperatures below the threshold for healthy living in England

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Abstract:

This study investigated the determinants of the proportion of hours a dwelling meets the indoor temperature threshold for healthy living of at least 18°C in winter, as recommended in a recent review. Secondary data analysis of a nationally representative survey of English homes (N = 635) showed that older dwellings, detached homes, single occupancy and living in the North of England are associated with the lowest share of hours at the recommended temperature threshold in bedroom, living room, and hallway. These identified determinants could be used to target households at greatest risk of 'unhealthy' temperatures. Being aged above 64 and having a disability is linked to more hours at the criterion; an encouraging finding that the most vulnerable experience low temperatures to a lesser extent. This study also highlights the need for further research particularly in relation to those variables where results were equivocal and / or there was weak supporting evidence, such as tenure, wall type, and EPC rating.

Keywords: temperatures, homes, health, threshold, beta regression

1. Introduction

Temperatures in homes receive attention in research for two main reasons: (1) Their link to energy consumption. Energy consumption increases with a higher demand temperature and more hours of heating. (2) Their link to health. In England and Wales, about 30% more deaths occurred in the winter months of 2017/18 than non-winter months, corresponding to about 50,000 extra deaths (Office for National Statistics, 2019). Housing is thought to play a critical contributing role in these extra deaths: Cold related deaths increase with older age of the property, poorer thermal efficiency ratings, older age of occupants and also with lower indoor temperatures (NICE, 2015; Wilkinson et al., 2001). Implementing energy efficiency measures that make it easier and cheaper to achieve higher indoor temperatures, has a significant positive effect on health (Maidment, Jones, Webb, Hathway, & Gilbertson, 2014). Improving council housing in Wales to national standards reduced the number of emergency hospital admissions for residents aged 60 or above (Rodgers et al., 2016).

This paper investigates temperatures in homes from a health-related perspective. Two recent publications advocate setting an indoor temperature threshold for healthy living: The 2016 Cold Weather Plan for England advised to maintain 18°C as day- and night minimum temperature for those aged above 64 years or with pre-existing medical conditions (Public Health England, 2015). A recent systematic review studied the link between health and temperatures in homes and concluded that there was a strong enough link to recommend a minimum internal temperature of 18°C for everyone in the population at all times (Jevons, Carmichael, Crossley, & Bone, 2016). A recent paper (Huebner, Hamilton, Chalabi, Shipworth, & Oreszczyn, 2018) examined to what extent 645 homes that were approximately representative for the housing stock in England met this criterion, and concluded that the majority of homes do not. The analysis showed that in the bedroom, 11% of homes met the criterion on all days, and 17% on more than 90% of days; in the living room, the numbers are

15% and 24%, respectively, and for the hallway 12% and 17%. In the living room, estimates were somewhat higher for households in which a person aged above 64 65 or with a long-term disability was present. The authors also calculated the number of hours per day temperatures were at least at 18°C in the various rooms. The median number of hours at / above 18°C was about 14 hours per day in the bedroom, 17 hours in the living room, and 13 hours in the hallway, with estimates slightly higher in the living room for old age householders and those with disability, and in the hallway for those with disability. However, the paper did not report which factors (beyond age and disability status) impacted on either outcome variable. The identification of predictors is of paramount importance as it would allow targeting those households most at risk for health-threatening cold exposure. This paper will identify factors related to meeting the recommended temperature.

The remainder of the introduction summarizes existing research on prevailing indoor air temperatures and their predictors in homes[1]. It will not report individual studies investigating health impacts of temperatures given the recent systematic review on this topic (Jevons et al., 2016) that summarized existing evidence. In general, exposure to cold negatively impacts cardiovascular and respiratory health. Specifically regarding the threshold, temperatures below 18°C have been shown to increase blood pressure and higher temperatures to relieve respiratory symptoms (Jevons et al., 2016).

1.1. Temperatures and their determinants in English homes – a literature review

In general, internal temperatures vary significantly between homes (Huebner et al., 2013), and there are distinct observed profiles of how they vary over the course of a day (Huebner et al., 2015) which already indicates that it is unlikely that indoor temperatures are all above 18°C at all times. In fact, whilst average winter indoor temperatures in the same broadly

[1] The focus is on temperatures in English homes, given the variability in climate and housing stock qualities across countries. In addition, the analysis carried out subsequently focuses on English homes only.

nationally representative sample as analysed subsequently were shown to be slightly above 18°C, the standard deviation of the (approximately) normally distributed data was at least 2.4°C (Huebner et al., 2018). Hence, many households had average winter internal temperatures below the recommended threshold. Similarly, a review paper showed that average winter air temperatures in living rooms as measured in different studies were often around 18°C (Vadodaria, Loveday, & Haines, 2014) which again means that a number of homes will have had lower temperatures.

Indoor air temperatures were measured differently in different studies, partly in different seasons, and analysed differently using different predictors which makes comparison across studies difficult. It should be noted that none of the studies below-mentioned measured the temperatures people were exposed to; experienced temperature, i.e. a measure of the temperature people have actually been exposed to, measured for example with a body-worn temperature sensor, is a relatively novel and under-researched topic (for exceptions, see Kennard, Huebner, & Shipworth, 2019; Kuras, Hondula, & Brown-Saracino, 2015).

In this review, we only included studies in which the effect of one predictor was reported whilst controlling for other predictors. This is because determinants of temperatures are often correlated, hence results are hard to interpret if not holding the effect of other predictors constant. Hamilton et al. examined determinants of average indoor air temperatures standardised[2] to outdoor air temperatures of 0 °C, 5 °C and 10 °C during wintertime conditions in 821 English homes (Hamilton, O'Sullivan, Huebner, Oreszczyn, Shipworth, Summerfield, & Davies, 2017). Focusing on low-income households who were recipients of a government programme to improve energy efficiency (the Warm Front Programme), Oreszczyn et al. analysed predictors of daytime internal living room temperatures in winter

[2] Standardising the indoor temperature to an outdoor air temperature allows for comparison over time and for different locations that may be warmer/colder.

standardized to 5°C (Oreszczyn, Hong, Ridley, & Wilkinson, 2006). Kelly et al. examined the determinants of indoor temperatures in 347 English homes over half a year, i.e. including summer and winter temperatures (Kelly et al., 2013). A significantly older study by Wilkinson et al. based on data from 1991 analysed the association of internal hall temperatures standardized to an outdoor temperature of 5°C after four hours of central heating to a range of predictors (Wilkinson et al., 2001).

Table 1 summarizes the results from those studies; however, it needs to be repeated that the studies different in important aspects regarding the measured temperatures.

Table 1.

Variable	Findings
Income / ability to pay bill	Clear evidence that higher income / ease to pay bill associated with warmer temperatures (Kelly et al., 2013; Oreszczyn et al., 2006; Wilkinson et al., 2001) but no clear evidence of linear relationship
Energy efficiency	Clear evidence that higher energy efficiency associated with higher temperatures (Hamilton et al., 2017; Kelly et al., 2013; Oreszczyn et al., 2006)
Household size	Clear evidence of higher temperatures in larger households / non-single households (Hamilton et al., 2017; Kelly et al, 2013, Wilkinson et al., 2011).
Dwelling age	Some evidence for lowest temperatures in the oldest dwellings (Hamilton et al., 2017; Kelly et al., 2013) but no evidence of a linear increase of indoor temperatures from oldest to newest dwellings.
Employment status	Some evidence of retired households having the warmest temperatures (Hamilton et al., 2017)
Dwelling type	Some evidence of warmer temperature in flats / in non-detached homes (Hamilton et al., 2017; Kelly et al., 2013)
Tenure	Some evidence that temperatures were higher in socially rented dwellings (Hamilton et al., 2017), in socially and privately rented dwellings (Kelly et al.,

	2013) but not in all studies (Wilkinson et al., 2011)
Age of household	Some evidence that dwellings are warmer if inhabited by older householders (Hamilton, O'Sullivan, Huebner, Oreszczyn, Shipworth, Summerfield, & Davies, 2017; Kelly et al., 2013; Oreszczyn et al., 2006), but not in all studies (Wilkinson et al., 2001).
Central heating	Unclear: Some evidence of colder temperatures in the absence of central heating (Wilkinson et al., 2011); but gas central heating associated with lower temperatures compared to no gas central heating (Kelly et al., 2013)

Kelly et al. (2013) additionally reported higher temperatures in dwellings with less heat loss, more roof insulation, and more double glazing, and lower temperatures in homes with heating controls.

In summary, there was most evidence that income, efficiency, household size, and dwelling age were consistently associated with temperatures in homes. There was also evidence from some studies that dwelling type, and employment status played a role. For tenure and age of households, two studies found an effect and one did not; for central heating, only two studies reported results that were somewhat contradictory but also hard to compare as they differed in their operationalization. The literature review indicated some important variables to include in our planned analyses to add evidence on which factors impact indoor temperatures.

1.2. Aim of this paper

A recent study by the authors of this paper analysed average indoor temperatures in winter, recorded in 645 English homes, to see to what extent they met the threshold criterion of being continuously at 18°C (Huebner et al., 2018). However, apart from age of householders and disability status, the study did not analyse the factors which predict the extent to which houses attain a temperature at or above 18°C.

This paper has one central aim: to identify the determinants of compliance with an indoor temperature threshold defined from a public health perspective. The outcome variable of interest is the average number of hours per day a dwelling is heated to the criterion rather than the number of days for which a dwelling was continuously heated to at least 18°C.The rationale for this was that the latter measure is to some extent contained in the former measure: i.e. if a home was heated to 18°C for 24 hours per day on average across winter, it means that all days will have had continuous temperatures of at least 18°C. Similarly, a very low average of the number of hours a dwelling is heated (e.g. less than one hour per day) would indicate that basically no days would be continuously at 18°C. This paper does not discuss whether a generic temperature recommendation is the best approach, but it identifies determinants of compliance with a publicly defined threshold temperature.

2. Methods

The planned analysis was prespecified and uploaded on the Open Science Framework webpage[3]. Any deviations from the plan are noted in this manuscript.

2.1. Data

The data analysed for this paper formed part of the Energy Follow-Up Survey (EFUS), commissioned by the then Department of Energy and Climate Change, linked to the English Housing Survey (EHS). The EFUS study consisted of an interview survey of a sub-set of households (N = 2,616) that had been first visited as part of the 2010/2011 EHS. The interviewers who performed the Energy Follow-Up Survey asked householders if they would consent to temperature loggers and installed them in case of a positive response (until the interviewer had exhausted their allocation of loggers). N=943 households had temperature loggers placed in up to three rooms (living room, bedroom, and hallway) of the home which were set to record temperatures from about February 2011 to January 2012. Temperatures

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[3] https://osf.io/5x3qm/register/564d31db8c5e4a7c9694b2be

were recorded every 20 minutes using modified TinyTag Transit 2 data loggers, that have an accuracy of +/-0.2°C, and a resolution of 0.01°C (BRE, 2013). The temperature loggers were usually installed by the interviewer at the end of the EFUS interview, on an internal wall, away from heat sources and direct sunlight, at a height accessible by the householder but out of reach of small children. Valid temperature data were obtained from N = 823 households. N = 760 households had temperatures monitored in all three rooms (bedroom, living room, hallway). Of those, N = 105 households were excluded because of changes made to the household or home since the last physical and social survey of the house which had not been recorded in detail. Hence, the final sample size was N = 635 homes that were considered to be approximately nationally representative by location, tenure and dwelling type (see Table 1 in (Huebner et al., 2018), reproduced here in the Appendix as Table A.1), though with privately rented accommodation slightly underrepresented and socially rented overrepresented.

The data cannot be made publicly available. The linked data sets were explicitly made available for this research project by a UK Government Department, the Department for Business, Energy & Industrial Strategy. The high-resolution temperature data and the connection identifier between the EFUS and EHS (to link dwelling and household features) is private. The individual, non-linked data sets and the summarised temperature data are however available on UK Data Archive[4]

2.1.1. Outcome variables

The outcome variable chosen for this analysis was the number of hours per day the temperature is at least 18°C. The data were based on temperature recordings for February 2011, December 2011, and January 2012, i.e. those months considered as winter by the Office for National Statistics (MetOffice, 2013). For every dwelling, extreme value

[4] https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=7471

corrections were performed on the combined temperature data from the three months where any data point which was more than 1.5 interquartile ranges (IQRs) below the first quartile was removed as extremely low temperatures might indicate that the house was unoccupied. The median number of values indicating extremely low temperatures and hence removed were 13, 2, and 8, for bedroom, living room, and hallway, respectively ((Huebner et al., 2018).

For each home, on each day, and in each room, the average number of hours for which the temperature was at least 18°C per a 24-hour period was calculated. That meant checking if three consecutive measurements, i.e. 20-minute segments, were all at least 18°C, where each day lasted from midnight in one day to midnight the next day. Two days (30th of January 2012, 28th of February 2011) were excluded from analysis as there was no subsequent day. For each home, the estimated number of daily hours was averaged across all days, separately for bedroom, living room, and hallway. Hence, three outcome variables were used subsequently.

2.1.2. Predictor variables

To decide which variables to use as predictors for the chosen outcome variables, we based the selection on previous evidence (see 1.1). .

Table 2 and 3, respectively, summarize the household related (Table 2) and building related (Table 3) predictors, their categories and frequencies. The first category of each variable listed in the tables represents the reference category used in the subsequent regression analysis.

For all categorical variables apart from two, a normative strategy was employed to choose the reference category, i.e. the most common group was the reference category. For two categorical variables, a theoretical approach was chosen to identify the reference category by considering an ordinal feature of them. The first categorical variable was dwelling type –

detached dwellings have the largest surface area on average and hence greatest heat loss (and conversely flats have the least heat loss). The second categorical variable was region – here, the South-East was chosen as reference category as it was one of the warmest regions and had a relatively large sample size N (London and South-West were warmer but had a much lower N). Figure 1 shows the average temperatures in the three winter months under consideration in each region. For each dwelling in the study, hourly weather data from the nearest Met Office weather station system (MIDAS) was gathered, and then averaged across all dwellings in one region.

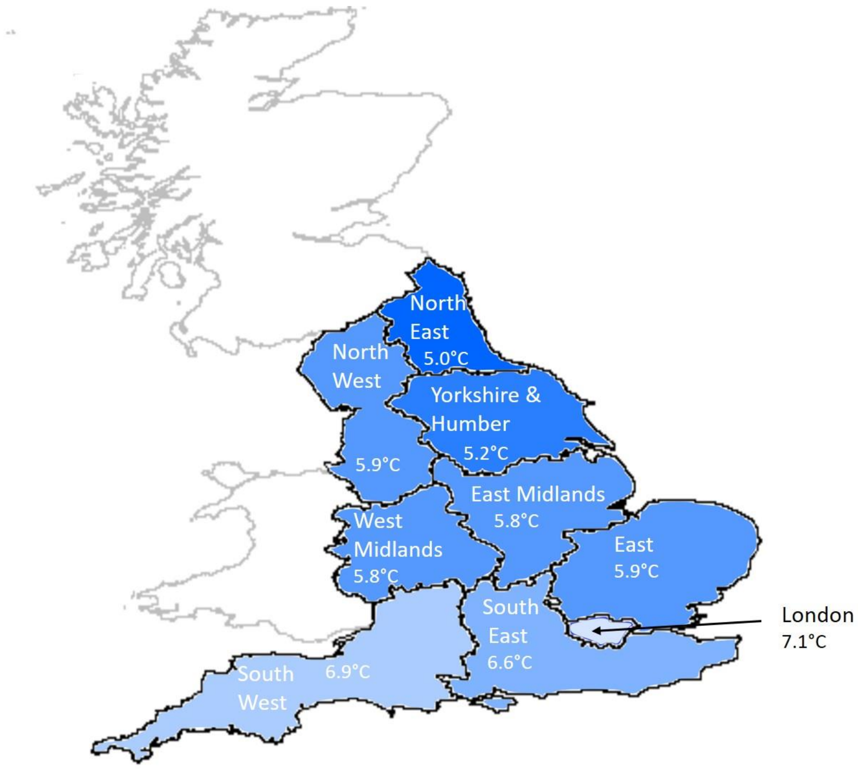

Figure 1. Average winter outdoor temperatures for the different regions, and their location in Great Britain. [5]

[5] Coordinates for the map derived from https://borders.ukdataservice.ac.uk

The North East and Yorkshire & Humber were the coldest, London the warmest region. East, East Midlands, West Midlands, and North West had about the same mean temperature. For an analysis of significant differences, see Appendix Table A.2.

For ordinal variables, the endpoint category with the larger N was chosen as reference category.

Note that the disability variable indicated anyone in the household having a long-term disability, defined as long-lasting impairment in the categories of vision, hearing, mobility, breathing, learning, heart, mental, other, and "don't know"; it did not necessary mean that the individual was registered as disabled. Some households had one member with multiple disabilities or multiple members with one or more disabilities. Here, as in the paper by Huebner et al. (2018), only a dichotomous status of any disability in the household was recorded.

Table 2. Household related predictors.

Variable and categories	Frequency
Disability status	
No	266
Yes	369
Income[6] *(equivalized)*	
1st quintile (lowest)	112
2nd quintile	145
3rd quintile	143
4th quintile	128
5th quintile	107
Tenure	
Own	403
Rented from local authority	82
Privately rented	56
Rented from Registered Social Landlord	94
Household composition	
Couple, no dependent(s)	248
Couple with dependent(s)	142
Single with dependent(s)	34
Single person, >=60 years	108

[6] AHC (After-Housing-Costs) equivalised income; i.e. household income with housing costs removed that has been recalculated to take into account differences in household size and composition

Single person, <60 years	75
Other (multi-person)	28
Employment status of Household Reference Person (HRP)	
Full-time work	279
Not working[7]	91
Part-time work	55
Retired	210
Household vulnerable	
No	428
Yes – on means tested / disability benefits	207
Fuel poverty – Low income, high cost definition	
Not in fuel poverty	565
In fuel poverty	70
Anyone 65 years or older?	
No	429
Yes	206

Table 3. Building related predictors.

Variables and categories	Frequency
Dwelling age	
Pre-1919	98
1919-44	102
1945-64	154
1965-80	161
1981-90	61
Post-1990	59
Dwelling type	
Detached	153
Semi-detached	204
Mid terrace	107
End terrace	71
Flat (converted / purpose-built)[8]	100
Floor area	
110 m^2 or more	158
90- 109 m^2	93
70 – 89 m^2	163
50 – 69 m^2	156
Less than 50 m^2	68
Region	

[7] Comprising unemployed (N=16), full-time education (N=3), and other inactive (N = 72). This combination was not pre-specified but became necessary to avoid too small categories.

[8] Purpose-built and converted flats combined as there were only 14 converted flats in the sample, i.e. too few for a category. This was not prespecified but became necessary because of the small sample size for converted flats.

South East	101
London	46
South West	59
East	88
North East	44
East Midlands	53
North West	103
West Midlands	58
Yorkshire & The Humber	83
Wall type	
Cavity insulated	293
Cavity uninsulated	193
Other	149
Heating system	
Central heating	578
No central heating	57
Double glazing of windows	
More than 80%	544
Less than 80%	91
EPC rating	
F&G	88
E	259
D	277
A-C	61

2.2. Statistical analysis

Data were analysed using beta regression. This was necessary given that the dependent variable of number of hours at a minimum of 18°C per day was bounded by 0 and 24, respectively the minimum and maximum number of hours in the day at which the temperature could have been at 18°C. Using ordinary regression analysis could result in predicted values outside those bounds. Hence, the outcome variables were transformed to reflect the proportion of hours meeting the criterion by dividing each value by 24, resulting in values between 0 and 1 as required as input for beta regression.

Beta regression assumes that the dependent variable y is beta-distributed and that its mean is related to the regressors through a linear predictor with unknown coefficients and a link function. The purpose of the link function - which should be strictly monotonically increasing and differentiable- is to map the (0,1) range of the outcome variable into the range of real numbers (Cribari-Neto & Zeileis, 2010; Ferrari & Cribari-Neto, 2004). There are a few candidate link functions to choose from and the logit function was chosen for this analysis because of its ease of interpretation. The beta regression model also includes a precision parameter (PHI) which was kept constant in these analyses (for details, see (Cribari-Neto & Zeileis, 2010)).

Beta regression naturally incorporates features such as heteroskedasticity or skewness which are common in rates or proportions, as in our case.

Since the dependent variable y also assumed the extreme values of 0 and 1 (which the analysis method cannot process), each y was further transformed, following (Smithson & Verkuilen, 2006) through application of the following formula (where n is the sample size)[9]:

$$y_{new} = \frac{\left(y \times (n-1) + \frac{1}{2}\right)}{n}$$

The beta regression analysis was carried out in the R system for statistical computing using the package 'betareg' (Zeileis et al., 2016). The interpretation of the beta regression of the kth regression coefficient β_k is as follows: if the value of the kth regression coefficient is increased by one unit then the odds ratio relative to the original value of the kth covariate is e^{β_k}.

The significance level was set as < 0.1. The p value indicates the probability of observing a difference as large or larger than what was observed, if the null hypothesis is true. Choosing a larger cut-off for statistical significance than the conventional cut-off of 0.05, results in a larger Type 1 error , i.e. a higher risk of rejecting the null hypothesis when it is true (Kirkwood & Sterne, 2003). Given the nature of the analysis done in this paper, i.e. to highlight potentially important factors in determining 'healthy' temperatures, it was judged to

[9] This manipulation was not prespecified in the pre-analysis plan, as the authors had been unaware of this issue.

be worth taking the small risk of classifying a factor as significant when it is not than to miss a factor that could play an important role. However, we interpreted a p value from close to 0.05 to 0.1 as indicating a variable that was potentially of interest, without being able to draw strong conclusions based on the current data and analysis.

3. Results

3.1. Descriptives of the outcome variables

The outcome variables of interest were the average number of hours a specific room in the house - bedroom, living room, and hallway – attained a minimum temperature of 18°C. The outcome variables were non-normally distributed with peaks at either extreme of 0 and 24 hours (Huebner et al., 2018). For the three rooms, the median (Md) number of hours at a minimum of 18°C were approximately Md_{BR} = 14 hours per day (bedroom), Md_{LR} = 17 hours (living room), and Md_{Hall} = 13 ½ hours (hallway). As outlined above, we transformed the outcome variable into a proportion by dividing each estimate by 24, the number of hours in a day.

Figure 2 below shows the frequency histogram of the proportion of hours at which temperatures are at least 18°C in each of the three rooms. The outermost bar on the right shows how many homes out of the 635 homes met the criterion for at least 21 hours, 36 minutes (90% of 24 hours), and the outermost bar on the left for less than 2 hours, 24 minutes

(10% of 24 hours).

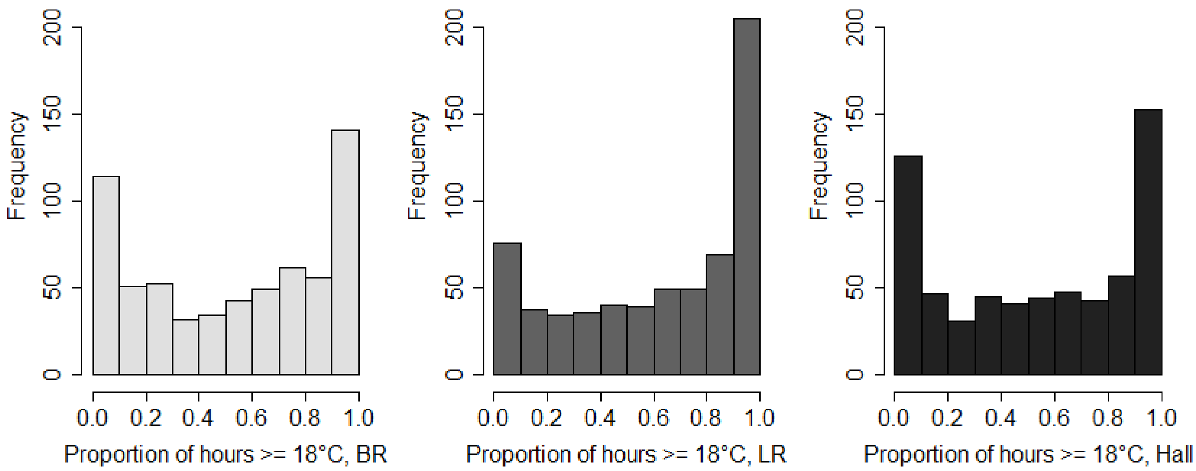

Figure 2. Frequency of homes (out of 635) at the various proportions of hours per day meeting the criterion in the three rooms analysed.

As discussed in detail in (Huebner et al., 2018), the majority of homes do not meet the criterion of having a minimum temperature of 18°C at all hours of the day. This finding is also consistent with previous work (Huebner et al., 2013; Vadodaria et al., 2014) which indicated large variability between homes and temperatures below 18°C. Such low temperatures can indicate occupant absence, insufficient capacity of the heating system to deliver higher temperatures, a preference for lower temperature, and many other factors that cannot be differentiated in this study.

3.2. Predicting hours above 18°C

This section reports the output of the beta regression analysis for the three different rooms. The tables show only variables that were statistically significant at $p < 0.1$. The first column labelled 'estimate' gives the regression coefficient estimate; the third column the exponential of the regression coefficient, i.e. the Odds ratio (OR). To recap, the outcome variable is the proportion of hours a room is heated to the recommended temperature in 24 hours. If the value is zero, the probability of reaching the recommended temperature is zero (i.e. the proportion of hours is zero; the recommended temperature is never reached); if the value is one the probability is one (i.e. the proportion of hours is 1; the recommended temperature is reached for all 24 hours). The odds is the ratio of the probability of reaching the recommended temperature (all the time over 24 hours) over the probability of not reaching it (i.e. probability of "success" over probability of "failure", where success corresponds to 24 hours and failure to 0 hours). The OR corresponds to the ratio of the odds for one category of a predictor to the odds for the reference category for that predictor. An OR of 1 means that there is no difference in the odds for both categories. For more details, see e.g. (Szumilas, 2010)

3.2.1. Bedroom

The pseudo-R^2 value[10] for this model was 21.1%. Dwelling age was a significant predictor with all homes built past 1945 having significantly more hours at 18°C. Semi-detached, mid-terrace houses, and flats had more hours at the criterion than the reference category of detached dwellings. Those without central heating had fewer hours at the criterion. Regarding floor area, the results were less clear – whilst the second-largest category of homes meet the criterion at more hours than the largest homes, the categories of even smaller dwelling size did not. Regarding location, London, the East and the East Midlands did not differ from the reference category of South-East; the remaining regions had a significantly lower proportion of hours at the criterion than the reference categoriy. All household types except for 'couple with dependents' met the criterion at a lower proportion of hours than the reference category of 'couple no dependent(s)'. Those in fuel poverty met the criterion at a lower proportion of

[10] Defined as the squared correlation of linear predictor and link-transformed response, see (Zeileis et al., 2016)

hours whereas households with ‘anyone aged 65’ met the criterion at higher proportion of hours.

Table 4 shows details of the beta regression for those predictors with at least one significant effect.

Table 4. Results of beta regression, for the bedroom

	Estimate	**Std. Error**	**OR exp(Estimate)**	**Lower 95%**	**Upper 95%**	**P-value**
(Intercept)	-0.917	0.349	0.4	0.202	0.792	0.009
Dwelling age- Ref: Pre-1919						
1919-44	0.317	0.201	1.374	0.926	2.039	0.115
1945-64	0.747	0.214	2.111	1.388	3.21	<0.001***
1965-80	0.785	0.215	2.192	1.437	3.343	<0.001***
1981-90	0.853	0.256	2.346	1.42	3.878	0.001**
Post-1990	0.833	0.275	2.3	1.342	3.944	0.002**
Dwelling type – Ref: Detached						
Semi-detached	0.34	0.163	1.405	1.02	1.936	0.037*
End- terrace	0.252	0.206	1.287	0.86	1.925	0.22
Mid terrace	0.526	0.212	1.693	1.118	2.563	0.013*
Flat	0.901	0.264	2.461	1.468	4.127	0.001**
Central heating – Ref: Yes						
No	-0.377	0.215	0.686	0.45	1.046	0.08.
Floor area – Ref: 110 sqm or more						
90- 109 sqm	0.357	0.17	1.429	1.024	1.995	0.036*
70 – 89 sqm	0.201	0.165	1.223	0.885	1.691	0.223
50 – 69 sqm	0.185	0.187	1.203	0.833	1.736	0.325
Less than 50 sqm	0.297	0.247	1.346	0.83	2.184	0.228
Region- Ref: South East						
London	-0.178	0.229	0.837	0.535	1.31	0.437
South West	-0.453	0.203	0.636	0.427	0.946	0.026*
East	-0.015	0.183	0.985	0.688	1.411	0.936
North East	-0.701	0.227	0.496	0.318	0.774	0.002**
East Midlands	-0.141	0.218	0.868	0.567	1.33	0.517
North West	-0.535	0.176	0.586	0.415	0.826	0.002**
West Midlands	-0.389	0.208	0.678	0.451	1.019	0.061.
Yorkshire & The Humber	-0.506	0.184	0.603	0.42	0.864	0.006**
Household comp. - Ref: couple no dependent						
Couple with dependent	0.207	0.152	1.23	0.914	1.657	0.172
Single with dependent	-0.438	0.251	0.645	0.394	1.056	0.081.

	Estimate	Std. Error	OR exp(Estimate)	Lower 95%	Upper 95%	P-value
Single person, >=60 years	-0.769	0.169	0.464	0.333	0.645	<0.001***
Single person, <60 years	-0.885	0.191	0.413	0.284	0.6	<0.001***
Other (multi-person)	-0.526	0.251	0.591	0.361	0.968	0.036*
Fuel poverty – Ref: No						
Yes	-0.385	0.195	0.68	0.464	0.998	0.049*
Anyone >=65 years or or older? – Ref: No						
Yes	0.306	0.169	1.358	0.976	1.889	0.07.
phi	1.266					
Pseudo R-squared	0.213					

'***' < 0.001 '**' <0.01 '*' <0.05 '.' <0.1

3.2.2. Living room

Living room results were similar to those of the bedroom. Compared to the reference category of pre-1919 dwellings, all other building ages were associated with a larger proportion of hours at the criterion. All dwelling types met the criterion at more hours than detached homes. For floor area, only the second largest size met the criterion at a significantly higher proportion of hours than the largest dwelling size. Opposite to results from the bedroom and surprisingly, dwellings without central heating had more hours at the criterion. Analysis of the geographical regions showed that three regions met the criterion for less time than the reference category of South-East. Households in which an occupant had a disability or was aged above 64 yearsor met the criterion at a higher proportion of hours, as did those living in a property owned by the local authority. All household types except for 'couple with dependents' met the criterion at a lower proportion of hours than the reference category of 'couple no dependent(s)'. Those households with a disability and those aged over 64 years met the criterion at more hours. Table 5 gives details of the regression analysis results.

Table 5. Results of the beta regression for the living room.

	Estimate	Std. Error	OR exp(Estimate)	Lower 95%	Upper 95%	P-value
(Intercept)	-0.844	0.34	0.43	0.221	0.838	0.013

	Estimate	Std. Error	OR exp(Estimate)	Lower 95%	Upper 95%	P-value
Dwelling age- Ref: Pre-1919						
1919-44	0.457	0.197	1.579	1.074	2.321	0.02*
1945-64	0.527	0.209	1.693	1.125	2.548	0.012*
1965-80	0.555	0.21	1.742	1.155	2.63	0.008**
1981-90	0.489	0.25	1.631	1	2.662	0.05.
Post-1990	0.503	0.268	1.654	0.978	2.798	0.06.
Dwelling type – Ref: Detached						
Semi-detached	0.504	0.16	1.655	1.211	2.262	0.002**
End- terrace	0.378	0.201	1.459	0.984	2.162	0.06.
Mid terrace	0.883	0.207	2.418	1.612	3.625	<0.001***
Flat	0.973	0.257	2.645	1.599	4.377	<0.001***
Central heating – Ref: Yes						
No	0.353	0.209	1.424	0.945	2.144	0.091.
Floor area – Ref: 110 sqm or more						
90- 109 sqm	0.378	0.165	1.459	1.055	2.018	0.022*
70 – 89 sqm	0.089	0.161	1.093	0.797	1.499	0.58
50 – 69 sqm	0.036	0.182	1.036	0.725	1.482	0.845
Less than 50 sqm	0.051	0.239	1.052	0.658	1.682	0.832
Region- Ref: South East						
London	0.03	0.221	1.031	0.668	1.59	0.892
South West	-0.231	0.197	0.793	0.539	1.168	0.241
East	0.257	0.178	1.294	0.913	1.832	0.147
North East	-0.537	0.221	0.584	0.379	0.901	0.015*
East Midlands	-0.106	0.211	0.899	0.594	1.361	0.615
North West	-0.489	0.171	0.613	0.439	0.858	0.004**
West Midlands	-0.33	0.202	0.719	0.484	1.069	0.103
Yorkshire & The Humber	-0.495	0.179	0.609	0.429	0.866	0.006**
Tenure – Ref: Own						
Rented from local authority	0.394	0.184	1.483	1.035	2.126	0.032*
Privately rented	-0.177	0.187	0.838	0.581	1.209	0.344
Rented from RSL	0.102	0.171	1.107	0.792	1.547	0.552
Household comp. - Ref: couple no dependent						
Couple with dependent	0.086	0.148	1.09	0.816	1.455	0.561
Single with dependent	-0.82	0.246	0.441	0.272	0.713	0.001*
Single person, >=60 years	-0.947	0.164	0.388	0.281	0.535	<0.001***
Single person, <60 years	-1.058	0.188	0.347	0.24	0.502	<0.001***
Other (multi-person)	-0.608	0.245	0.544	0.337	0.879	0.013*
Disability status – Ref: No						

	Estimate	Std. Error	OR exp(Estimate)	Lower 95%	Upper 95%	P-value
Yes	0.264	0.106	1.302	1.059	1.602	0.012*
Anyone >=65 years or older? – Ref: No						
Yes	0.379	0.164	1.461	1.06	2.014	0.021*
Phi	1.423					
Pseudo R-squared	0.278					

'***' <0.001 '**'< 0.01 '*' <0.05 '.' <0.1

3.2.3. Hallway

As in in the case of the living room and bedroom, all buildings post 1944 met the criterion at more hours than pre-1919 dwellings. For dwelling type, only the comparison of flats versus detached houses was statistically significant. Again, the second largest dwelling size met the criterion at fewer hours than then reference category of largest homes. Surprisingly, homes without cavity wall insulation and other wall types had met the criterion at more hours than those with cavity wall insulation. Those living in privately rented accommodation met the criterion at a lower proportion of hours. Dwellings with the highest class of EPC ratings encompassing A, B, and C ratings met the criterion at more hours than the category encompassing F&G ratings. London, the East, and East Midlands did not differ from the reference category, the other regions met the criterion at fewer hours. All household types except for 'couple with dependents' met the criterion at a lower proportion of hours than the reference category of 'couple no dependent(s)'. Those households with a disability met the criterion at more hours. Table 6 reports the details.

Table 6. Results of beta regression for the hallway.

	Estimate	Std. Error	OR exp(Estimate)	Lower 95%	Upper 95%	P-value
(Intercept)	0.385	0.417	1.47	0.649	3.332	0.356
Dwelling age- Ref: Pre-1919						
1919-44	0.291	0.204	1.338	0.898	1.994	0.153
1945-64	0.543	0.216	1.722	1.128	2.629	0.012*
1965-80	0.537	0.217	1.712	1.118	2.621	0.013*
1981-90	0.566	0.259	1.762	1.06	2.927	0.029*

	Estimate	**Std. Error**	**OR exp(Estimate)**	**Lower 95%**	**Upper 95%**	**P-value**
Post-1990	0.603	0.278	1.828	1.061	3.151	0.03*
Dwelling type –						
Semi-detached	-0.016	0.165	0.984	0.712	1.359	0.921
End- terrace	0.048	0.208	1.049	0.698	1.577	0.816
Mid terrace	0.326	0.214	1.385	0.911	2.107	0.128
Flat	0.517	0.266	1.677	0.996	2.823	0.052.
Floor area –						
90- 109 sqm	0.334	0.172	1.396	0.997	1.956	0.052.
70 – 89 sqm	0.02	0.167	1.02	0.735	1.415	0.907
50 – 69 sqm	0.279	0.189	1.322	0.912	1.916	0.141
Less than 50 sqm	0.396	0.249	1.485	0.912	2.417	0.112
Wall type – *Ref: Cavity insulated*						
Cavity uninsulated	0.284	0.133	1.328	1.023	1.724	0.033*
Other	0.415	0.178	1.515	1.068	2.149	0.02*
Tenure – *Ref: Own*						
Rented from local authority	0.006	0.191	1.006	0.692	1.464	0.974
Privately rented	-0.342	0.193	0.71	0.486	1.037	0.077.
Rented from RSL	0.065	0.177	1.067	0.754	1.51	0.715
EPC rating – *Ref: F&G*						
E	0.284	0.178	1.328	0.937	1.881	0.111
D	0.258	0.207	1.294	0.862	1.943	0.214
A-C	0.657	0.307	1.928	1.057	3.519	0.032*
Region- *Ref: South East*						
London	0.115	0.229	1.121	0.716	1.757	0.617
South West	-0.351	0.205	0.704	0.471	1.053	0.087.
East	0.143	0.185	1.154	0.803	1.659	0.439
North East	-0.824	0.229	0.439	0.28	0.688	<0.001**
East Midlands	-0.311	0.22	0.733	0.476	1.129	0.158
North West	-0.419	0.178	0.658	0.464	0.931	0.018*
West Midlands	-0.574	0.21	0.563	0.373	0.851	0.006**
Yorkshire & The Humber	-0.45	0.186	0.638	0.443	0.918	0.016*
Disability status – *Ref: No*						
Yes	0.288	0.109	1.333	1.076	1.652	0.009**
Household comp. - Ref: couple no dependent						
Couple with dependent	0.063	0.153	1.065	0.789	1.439	0.681
Single with dependent	-0.555	0.254	0.574	0.349	0.944	0.029*
Single person, >=60 years	-0.695	0.17	0.499	0.358	0.696	<0.001**
Single person, <60 years	-0.881	0.193	0.414	0.284	0.604	<0.001**
Other (multi-person)	-0.526	0.253	0.591	0.36	0.969	0.037*
phi	1.186					
Pseudo R-squared	0.22					

***' <0.001 '**' <0.01 '*' <0.05 ‘.’ <0.1

4. Result summary and discussion

Table 7 summarizes findings from all three rooms. Only significant categories of statistically significant variables are shown. The upward arrow indicates an increase in the proportion of hours heated to the criterion; a downward error a decrease.

Table 7. Summary of results from all three regression analyses.

Variable and category	**BR**	**LR**	**Hall**
Dwelling age- Ref: Pre-1919			
1919-44		↑*	
1945-64	↑***	↑*	↑*
1965-80	↑***	↑**	↑*
1981-90	↑**	↑.	↑*
Post-1990	↑***	↑.	↑*
Dwelling type – Ref: Detached			
Semi-detached	↑*	↑**	
End- terrace		↑.	
Mid terrace	↑*	↑***	
Flat	↑**	↑***	↑.
Central heating – Ref: Yes			
No	↓.	↑.	
Wall type – Ref: Cavity insulated			
Cavity uninsulated			↑*
Other			↑*
Floor area – Ref: 110 sqm or more			
90- 109 sqm	↑*	↑*	↑.
EPC rating – Ref: F&G			
A-C			↑*
Region- Ref: South East			
South West	↓*		↓.
North East	↓**	↓*	↓***
North West	↓**	↓**	↓*
West Midlands	↓.		↓**
Yorkshire & The Humber	↓**	↓**	↓**
Tenure – Ref: Own			
Rented from local authority		↑*	
Privately rented			↓.
Household comp. - Ref: couple no dependent			
Single with dependent	↓.	↓*	↓*
Single person, >=60 years	↓***	↓***	↓***
Single person, <60 years	↓***	↓***	↓***
Other (multi-person)	↓*	↓*	↓*
Fuel poverty – Ref: No			
Yes	↓*		
Disability status – Ref: No			

Yes		↑*	↑**
Anyone >=65 years or older? – Ref: No			
Yes	↑.	↑*	

***' <0.001 '**' <0.01 '*' <0.05 ‘.’ <0.1

The evidence on housing age is relatively consistent across the three rooms: in all analyses, the oldest houses met the criterion at the lowest number of hours, with the difference most pronounced to post-war buildings from 1945 to 1989. This finding on the importance of dwelling age is in line with previous research (Hamilton et al., 2017; Kelly et al., 2013). Findings are also consistent across rooms for region, with the North East, the North West, Yorkshire and the Humber meeting the criterion at fewer hours, with all $p < .05$ (and most $< .01$). These regions were all significantly colder than the reference category of South-East (see Appendix Table A.3 and Figure 1), i.e. this finding of fewer hours at the criterion might indicate an effect of external temperature. Evidence for the South-West and the West Midlands is less clear. Other external temperature variables, such as the spread in temperatures, frequency and duration of cold spells, and minimum temperatures might play an additional role to the mean temperature. Previous studies used standardized temperatures (e.g. (Hamilton et al., 2017; Oreszczyn et al., 2006) and hence did not use location as a predictor.

Analysis by household type shows the same result across the three types of rooms: ‘Single person’ households met the criterion at fewer hours and was most pronounced for ‘singles without dependents’ (all $p < .001$). Hence, those living alone or with only one adult have the highest risk of being exposed to temperatures below the recommended temperatures, in line with the reporting of (Hamilton et al., 2017). ‘Other multi-person’ households met the criterion at fewer hours ($.01<p<.05$) however this is not an informative category.

For other predictor variables, the results differ more across the three rooms. Dwelling type results indicate that flats, semi-detached and terraced houses met the criterion at significantly more hours than detached houses in bed- and living room; however, in the hallway only flats were statistically significantly different from detached houses and only at $p < 0.1$. Detached homes have the largest surface area exposed to the outside and hence lose most heat. Hallways are complex spaces in terms of temperature compared to other rooms; some hallways are very contained like a normal room, others can be spread over several floors resulting in considerable stack driven ventilation exacerbated by entrance doors and loft hatches. Households with uninsulated cavity walls and other walls met the criterion at higher number of hours in the hallway which is counterintuitive – but again, the hallway could be considered a special case because of its location in a dwelling.

For tenure type, weak evidence indicated that those living in dwellings owned by the local authority met the criterion at a higher number of hours, and those in privately rented accommodation at lower number of hours, relative to the reference category; also previous research (see Table 1) was inconclusive on this.

There is some suggestion that being in fuel poverty is linked to being exposed to fewer hours at the criterion, but the evidence is not strong. Being aged 65 and above and having a disability is linked to being exposed to more hours at the criterion which is in line with (Huebner et al., 2018); it has to be considered a positive finding that those most vulnerable to low temperatures do not experience them more than others but if anything they experience them less. The results on householder age are consistent with previous research (Hamilton et al., 2017; Kelly et al., 2013; Oreszczyn et al., 2006; Table 1).

A relatively consistent but puzzling finding is that the second-largest dwelling size met the criterion at a greater number of hours than the largest dwelling size; however, no other dwelling sizes do. No explanation comes to mind, making this a topic that needs further investigation.

Results are not very clear for EPC ratings with only the significant difference is between A-C rated dwellings compared to F&G rated dwellings in the hallway. Previous research had found that higher energy efficiency was consistently associated with higher temperatures (Hamilton et al., 2017; Kelly et al., 2013; Oreszczyn et al., 2006), which might indicate that energy efficiency plays a greater role for continuous temperatures as opposed to the dichotomy of above and below the criterion used here.

Results on central heating are contradictory and only significant at $p < 0.1$. Hence, further research is needed before reaching any conclusion about this predictor. However, it can be said that central heating is not a protective factor against experiencing temperatures that might be too low from a health perspective. Also, two previous studies were inconclusive on the effect of central heating systems (see Table 1).

The following variables did not show any statistical significance: income, household ‘being vulnerable’, double-glazing, and employment status. Income or ‘the ability to pay bills with ease’ has previously been associated with warmer temperatures (Kelly et al., 2013; Oreszczyn et al., 2006; Wilkinson et al., 2001). A possible explanation is the outcome variable used in this analysis was based on the dichotomy of meeting the criterion of 18°C vs. not and it is conceivable that income plays a greater role for reaching higher temperatures.

It is clear from the calculated R^2 values that a large share of variance remains unexplained, indicating that crucial, non-measured predictors might be missing.

The study cannot answer to what extent people were exposed to temperatures below the threshold as no occupancy data was collected. Whilst outlier correction was performed to identify likely periods of unoccupation, this is a relatively crude measure, and hence, values with no occupant are likely retained.

It is outside the scope of this paper to critique the threshold temperature recommendation. The temperature recommendation had been concluded from a systematic review of evidence from a public health perspective (Jevons et al., 2016). Our aim was to identify the determinants which ensure compliance to this threshold.

5. Conclusions

This study was the first to investigate the determinants of the proportion of hours a dwelling meets the recommended indoor temperature threshold for healthy living, i.e. of at least 18°C. Results indicated that older dwellings, detached homes, single occupancy and living in the North of England had the lowest share of hours at the criterion. These characteristics are all relatively easy to observe, e.g. compared to income, and would allow targeting those at most risk of unhealthy temperatures. Hence, any attempt aimed at alleviating low temperatures for healthy living might want to first identify and intervene in dwellings with these characteristics. Conversely, those living in flats, in the Southern regions, in couple households, and newer dwellings experienced more time above the threshold of harmful temperatures.

This study also highlights the need for further research particularly in relation to those variables where results were not clear, such as tenure, wall type, and EPC rating. Future work could also address the question what characteristics are related to being in the category of coldest homes (e.g. such as coldest 20%) as opposed to time above a threshold; and the ideal future study would use data on exposure to specific temperatures.

Declaration of interest: none.

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Appendix 1

Table A1. Comparison of sample characteristics to 2011 Census data.

	N in sample	% in sample	% in 2011 census
Region (ONS, n.d.-a)			
North East	44	6.93	4.90
North West	103	16.22	13.30
Yorkshire & Humber	83	13.07	9.97
East Midlands	53	8.35	8.55
West Midlands	58	9.13	10.57
East	88	13.86	11.03
London	46	7.24	15.42
South East	101	15.91	16.29
South West	59	9.29	9.98
Dwelling type (ONS, n.d.-b)			
Detached	153	24.09	22.30
Semi-detached	204	32.13	30.70
Terraced (including end-terrace)	178	28.03	24.50
Purpose-built flats	86	13.54	16.70
Converted flat	14	2.20	4.30
In commercial building	0	0.00	1.10
Caravan, mobile home etc.	0	0.00	0.40
Tenure (ONS, n.d.-c)			
Owned outright	192	30.24	30.60
Owned with a mortgage / loan	211	33.23	32.80
Shared ownership	na	na	0.80
Rented from council (Local Authority)	82	12.91	9.40
Social rented: Other	94	14.80	8.30
Private rented	56	8.82	16.80
Living rent free	na	na	1.30

Table A.2 shows the mean external temperature, standard deviation, and the number of dwellings for each region of England. The data are derived from the weather station data for the properties included in the study, for February 2011, December 2011, and January 2012.

Table A.2 Mean external temperatures, standard deviation and frequency of dwellings for the nine regions of England.

Region	Mean (°C)	Standard Deviation	N
South East	6.55	0.51	101
East	5.87	0.45	88
East Midlands	5.79	0.46	53
London	7.05	0.50	46
North East	4.97	1.03	44
North West	5.87	0.95	103
South West	6.91	0.75	59
West Midlands	5.80	0.41	58
Yorkshire & Humber	5.18	0.72	83
Total	5.99	0.91	635

A one-way ANOVA showed a significant main effect of Government Office Region, $F(8, 626) = 64.87$, $p < .001$. Pairwise comparisons with Tukey's HSD correction for multiple comparisons were then carried out, see Table A.2 for detailed results.

North East and Yorkshire and the Humber are both significantly colder than any other region, but do not differ significantly from each other. London, the warmest region, is significantly warmer than any other region, apart from the South-West. East, East Midlands, West Midlands, and the North West do not differ significantly from each other.

Table A.3. Mean difference in average external temperature between regions whereby the value for the row region is subtracted from the column region. The second value underneath corresponds to p-value.

	South-East	*East*	*East Midlands*	*London*	*North East*	*North West*	*South West*	*West Midlands*	*Yorkshire & Humber*
South-East	x								
East	.674 <.001	x							
East Midlands	.7534 .001	.079 .999	x						
London	-.506 .001	-1.180 <.001	-1.259 <.001	x					
North East	1.572 <.001	.897 <.001	.818 <.001	2.078 <.001	x				
North West	.681 .001	.007 1.000	-.072 1.000	1.187 <.001	-.890 <.001	x			
South West	-.364 .031	-1.039 <.001	-1.118 <.001	.142 .979	-1.936 <.001	-1.046 <.001	x		
West Midlands	.745 <.001	.071 1.000	-.008 1.000	1.251 <.001	-.826 <.001	.064 1.000	1.110 <.001	x	
Yorkshire & Humber	1.364 <.001	.611 <.001	.611 <.001	1.870 <.001	-.207 .785	.6831 <.001	1.729 <.001	.6190 <.001	x