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Street temperature and building characteristics as determinants of indoor heat exposure

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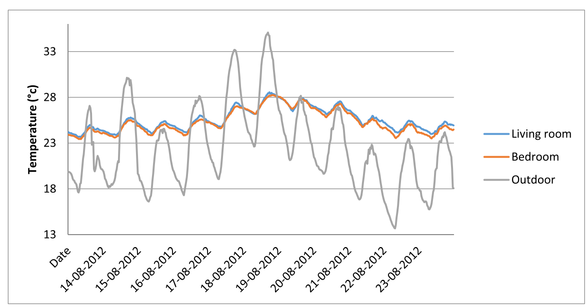
HIGHLIGHTS

- We assessed indoor temperatures, behaviour, and home characteristics in 113 houses.
- Indoor and outdoor temperatures were moderately correlated (R = 0.6).
- Indoor temperatures were much more variable than outdoor temperatures.
- Adapting building characteristics can help in reducing indoor heat.
- In epidemiological studies more consideration of indoor temperatures is needed.

GRAPHICAL ABSTRACT



Variation of half-hourly average temperatures living rooms, bedrooms and outdoor temperature in °C in Arnhem, 14-24 August 2012 (mean of all dwellings)

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ABSTRACT

Higher temperatures are associated with morbidity and mortality. Most epidemiological studies use outdoor temperature data, however, people spend most of their time indoors. Indoor temperatures and determinants of indoor temperatures have rarely been studied on a large scale.

We measured living room and bedroom temperature in 113 homes of elderly subjects, as well as outdoor temperatures, in two cities in the Netherlands. Linear regression was used to determine the influence of building characteristics on indoor living room and bedroom temperatures in the warm episode.

During the warm episode, indoor temperatures were higher during the night and lower during the day than outdoor temperatures. Indoor temperatures on average exceeded outdoor temperatures. The weekly average indoor temperature in living rooms varied between 23.1 and 30.2 °C. Dwellings that warmed up easily, also cooled down more easily.

Outdoor and indoor temperatures were moderately correlated (R^2 = 0.36 and 0.34 for living rooms and bedrooms, respectively). Building year before 1930 and rooms being located on the top floor were associated with higher indoor temperatures. Green in the vicinity was associated with lower temperatures in bedrooms.

This study shows that indoor temperatures vary widely between dwellings, and are determined by outdoor temperatures and building characteristics. As most people, especially the elderly, spend most of the time indoor, indoor temperature is a more exact predictor of heat exposure than outdoor temperature. The importance of mitigating high indoor temperatures will be more important in the future because of higher temperatures due to climate change.

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1. Introduction

Elevated ambient temperatures are associated with short-term increases in mortality and morbidity, especially in elderly (Baccini et al., 2008; Basu, 2009; Bunker et al., 2016; Gasparrini et al., 2015; Ragettli et al., 2019; Tham et al., 2020; van Loenhout et al., 2018; Yu et al., 2012). Climate change is expected to increase temperatures and heat-related health problems (Watts et al., 2018). Epidemiological time series studies generally make use of outdoor temperatures. These temperatures are often measured at regional weather stations in the open field to eliminate influences of coincidental surroundings. These temperatures are only a surrogate for personal exposure to heat (Basu and Samet, 2002; Smargiassi et al., 2008). Outdoor temperatures in cities often surpass those in the surrounding rural areas. This so called 'urban heat island effect' has received increasing attention during the last decades (Ren et al., 2011; Ward et al., 2016). Measurements show that in the Netherlands the heat island effect may rise to 7 °C at night in larger cities (Heusinkveld et al., 2014) and that the heat island effect even exists in small towns (Terpstra et al., 2019).

Measured temperatures at regional weather stations differ not only from urban outdoor temperatures but also from indoor temperatures (Smargiassi et al., 2008). Several studies compared indoor with outdoor air temperatures measured nearby the investigated homes. In the warm season indoor and outdoor temperatures are correlated, but variation between homes is considerable (Franck et al., 2013; Nguyen et al., 2014; Quinn et al., 2014; White-Newsome et al., 2012). Outdoor temperatures explained only a small proportion of the variance of indoor temperature (Smargiassi et al., 2008).

People in temperate climates, especially elderly, typically spend about 90% of their time indoors, mostly at home (Basu and Samet, 2002; Brasche and Bischof, 2005). This makes indoor temperatures an even more important exposure indicator than outdoor temperatures for human health.

A few epidemiological studies have found that morbidity and mortality during heat waves were related to building characteristics such as building year, lack of thermal insulation, dark walls and roofing, absence of air-conditioning, living on higher floors of multi-story buildings, and sleeping on the top floor right under the roof (Basu and Samet, 2002; Vandentorren et al., 2006), suggesting the importance of indoor temperatures. A study showed that heat perception of adults was more related to indoor temperature than to urban structure and outdoor temperatures (Franck et al., 2013). Indoor exposure studies showed significant correlations between indoor heat and health outcomes (Anderson et al., 2013; Van Loenhout et al., 2016). Cooling systems, building materials, night-time ventilation and shading from direct sunlight are important factors influencing indoor temperature (World Health Organization, 2018).

Reducing indoor temperatures are now part of overall public health recommendations during heat waves. These recommendations are based on extensive modelling and experimental studies of building indoor climates (e.g. Porritt et al., 2012). Important established determinants include architectural, structural, material and installation solutions. Specific factors include protection against sunlight by window size and orientation, use of outdoor and indoor sunscreens, night time ventilation and cooling systems.

Several studies recently explored indoor temperatures and overheating (Mavrogianni et al., 2017; Morey et al., 2020; Morgan et al., 2017; Pathan et al., 2017). Few studies measured indoor temperature and its determinants in residences occupied by vulnerable populations (Tsoulou et al., 2020; Vellei et al., 2017; White-Newsome et al., 2012; White-Newsome et al., 2011).To expand the knowledge on determinants of indoor heat exposure of the elderly, we studied the contribution to indoor temperature of (1) outdoor temperature in urban areas, (2) housing characteristics and (3) occupant behaviour.

2. Material and methods

2.1. Study design

We measured indoor and outdoor temperature in 113 homes of elderly subjects in two medium sized cities in the Netherlands. Half-hourly average temperatures were measured in the bedroom, living-room and outside the home for four summer months. A baseline questionnaire was used to determine home characteristics potentially affecting indoor summer temperatures. During a baseline week and two relatively warm weeks, a diary was used to record time-varying occupant behaviour such as use of window coverage and ventilation facilities. We compared temporal patterns of indoor and outdoor temperature in the warmest week. We used linear regression to determine the influence of outdoor temperature, home characteristics and occupant behaviour on indoor temperatures in the warmest week.

2.2. Study population

The study was performed in Arnhem and Groningen, two cities in the Netherlands with 150,000–200,000 inhabitants each. In and around the centres, four study areas were identified in each city with a high building density and a low vegetation density. The identification was based upon local urban climate maps (ERDF 2009; Klok et al., 2012), see Figs. S1 and S2. Home addresses of adults >65 years of age were obtained through the population registers of the two cities. We invited 500 and 572 individuals randomly to participate in Arnhem and Groningen, respectively. From the 70 and 100 responders, we randomly selected 56 homes in Arnhem and 57 homes in Groningen to participate in the study. Restriction was needed because of availability of measuring equipment. All participants provided written informed consent. Figs. S3 and S4 show maps of the residential locations of the two cities. More details on recruitment of participants are given in the first publication of this study (Van Loenhout et al., 2016).

2.3. Measurements

From May through August 2012, indoor air temperatures were continuously measured in the living room and bedroom using iButtons Hygrochron temperature/humidity loggers (type DS1923, Maxim Integrated, San Jose, CA, USA). The iButtons were placed on a small standard (Fig. S5), at living height (living room) or sleeping height (bedroom), away from any heat, solar and ventilation sources to decrease the risk of other factors influencing temperature readings. Temperature was measured every 30 min, with an accuracy of 0.5 °C. In week-long performed before and after the study in a wide range of temperature (including high temperatures), the maximum deviation of the loggers was 0.6 °C.

For street measurements, the iButtons were protected from precipitation and solar radiation using radiation shields (Fig. S6) (Davis Instruments Corp., Hayward, CA, USA). These shields were attached to traffic signs, lampposts or balconies at a height of 2.5 m or more. The location was chosen near the investigated addresses. The horizontal distance to the houses varied from 1 to 15 m. Because of close proximity, some dwellings shared the same outdoor measurement station. In total 86 outdoor temperature measurement stations were used for the 113 dwellings. Data of 7 outdoor iButtons were missing because they were taken away. Thus outdoor measurements from 79 stations were analysed and matched with indoor temperatures. In addition, we used temperature recordings of the Royal Netherlands Meteorological Institute in the locations Deelen and Eelde, official (regional, rural) weather stations closest to Arnhem and Groningen, respectively.

2.4. Checklist, questionnaires and diaries

First home visits to the respondents were in April 2012. Prestructured checklists were used to characterise dwellings and the nearby outdoor environment, including information on window pane areas and orientation, window coverage, content of rooms, type of building, proximity of outdoor vegetation. At the start of the study, investigators of both towns jointly paid several home visits to minimise inter-observer differences. During one baseline week in spring 2012 and two warm weeks in summer 2012, the participants kept a diary on their presence at home, ventilation (opening of windows and doors), use of window coverage indoors (using curtains, horizontal and vertical blinds) and outdoors (using sunscreens), indoor thermal perception and heat-related health problems. Questionnaires and diaries are described in more detail in a previous publication (Van Loenhout et al., 2016). The warm weeks were selected based upon the weather forecast, as weeks with three consecutive days with a maximum temperature above 25 °C.

2.5. Data analysis

We first compared diurnal patterns of indoor (living room as well as bedroom) and residential outdoor hourly temperatures focusing on the warmest 7-day period in the summer (Aug 14–20). We then assessed the relation between the average outdoor and indoor temperature per home for this warm period, focusing on between home temperature variability. Simple linear regression was used to analyse relation between building characteristics as predictors for the difference in average weekly indoor and average weekly outdoor temperature. We used the difference in indoor and outdoor temperature as the dependent variable to correct for differences in outdoor temperature between dwellings. Predictor variables were derived from the questionnaires (fixed characteristics). Additionally, we looked at occupant behaviour as predictor of indoor temperature, making use of data from diaries (temporally varying use of facilities). Ventilation during day (11–23h) and night (23–11 h) were included separately, cut-off points of 11 and 23 h were selected by looking at what time the outdoor temperature exceeded the indoor temperature. These results are reported in the Supplementary material, because we cannot determine whether occupant behaviour (such as opening windows) is a cause or a result of high indoor temperatures (independent or dependent variable).

All building characteristics with a significant relation in the single regression models were added in a multiple regression model. Subsequently, factors with $p > 0.20$ in the multiple regression were removed from the model. Next the remaining non-significant factors in single regression models were added one by one to the model to evaluate whether they contributed in a multiple regression models, Variables were retained if $p \leq 0.20$. Strongly interdependent factors were detected by calculation of the Variance Inflation Factor (VIF), and subsequently one of the interdependent variables was removed.

Data were analysed using the software SPSS for Windows (version 21).

3. Results

3.1. Description of the study variables

The 113 participants lived in apartment buildings and terraced houses in and around the city centres of Arnhem and Groningen. Out of the 113 study participants, 15 (14%) were on holidays during the warm week in August and were therefore not included in the analyses. Tables 1 and 2 show the characteristics of the participants and dwellings. Table S1 shows characteristics of the outdoor environment around the dwellings. We excluded three dwellings with air-conditioning from the analysis.

Table 1
Characteristics of the study population and dwellings (in %) (N = 113).

	%
Participants	
Male sex	51
Age (mean, SD)	74 (7.5)
Living alone	55
Good self-sufficiency	96
Good self-perceived health	82
Dwellings	
Year built	
- ≤1930	15
- 1930 ≤ 1969	17
- 1970 ≤ 1984	20
- ≥1985	48
Type of dwelling	
- Apartment building	73
- Terraced houses	27
Outdoor window coverage present	
- In living room	34
- In bedroom	10
Position of dwelling: not directly under the roof	55

3.2. Indoor and outdoor temperatures

We visually checked time plots of measured temperatures and found no anomalies (e.g. extreme values, flat pattern) within the measured indoor and outdoor temperatures. Therefore no measurements were excluded from the study. Indoor temperatures in the warm week in August were 4.6 and 5.5 °C higher than in the baseline week in May, in living rooms and bedrooms respectively. Table 3 shows the mean weekly outdoor and indoor temperatures in the warm week in August. Indoor and outdoor temperatures were slightly higher in Arnhem than in Groningen. The weekly average indoor temperature in living rooms varied widely between 23.1 and 30.2 °C. The highest average bedroom temperature was 29.3 °C. Indoor temperatures on average exceeded outdoor temperatures. Street temperatures exceeded the rural temperatures with on average 1.7 °C for the warm week in August. Differences between both mean minimum temperatures and mean maximum temperatures were larger than that (Tables S2 and S3).

Table 2
Characteristics of living rooms and bedrooms (N = 113) in % or average ± SD.

	Living room	Bedroom
Volume (m^3)	94 (52)	39 (19)
Surface area (m^2)	35 (16)	15 (5)
Height (m)	2.6 (0.4)	2.6 (0.4)
Floor		
0	33	28
1	26	27
2	14	7
3	15	15
4	10	11
5	1	1
6	0	1
Position[a]		
- Ground floor	33	27
- Between ground floor and floor below roof	58	58
- Floor below roof	10	16
Outdoor window coverage present	34	11
Mobile air condition present	3	3
Fan present	12	2
No cooling present	85	96
Green area present outdoor near room	27	34
Window pane area facing East/South/West (m^2)	6.7 (5.5)	2.1 (2.3)
Window pane area facing North (m^2)	2.1 (3.3)	1.5 (3.3)

[a] Two bedrooms were both located at the ground floor as well as just below the roof. In the analyses these were included as 'just below the roof'.

Table 3
Average weekly temperature 14–20 August 2012 in °C.

	City/location	Mean (min–max)[b]
Indoor temperature	Arnhem - living room	25.7 (23.1, 30.2)
	Groningen - living room	25.1 (22.3, 27.1)
	Arnhem - bedroom	25.5 (20.8, 29.3)
	Groningen - bedroom	24.7 (21.7, 28.0)
Outdoor temperature	Arnhem	23.9 (23.1, 24.7)
	Groningen	23.2 (22.7, 24.0)
Rural weather station[a]	Deelen (near Arnhem)	22.3
	Eelde (near Groningen)	21.5

[a] Weather station of the Royal Netherlands Meteorological Institute.
[b] Min and max value of weekly average of dwellings or outdoor locations.

Fig. 1 shows the average diurnal pattern of outdoor and indoor temperatures in ten days of August of all dwellings in Arnhem combined and of all dwelling in Groningen combined: the warm week of the study period when people completed the diaries and the three following days. Diurnal variations in hourly average outdoor temperatures are much larger than variations in indoor temperatures. On warm days, average outdoor temperatures exceed average indoor temperatures between about 11 and 23 h. Indoor temperatures increased in the first five days. When outdoor temperatures decreased after these five days, indoor temperatures also decreased, but more gradually than outdoor temperatures. There was a strong correlation between the increase between Aug 14 and Aug 20 and decrease from Aug 20 to Aug 23 of indoor temperatures in dwellings living room temperatures (Pearson's R^2: 0.83, $p < 0.01$), meaning that dwellings that warm up easily, also tend to cool down more easily (Fig. S7).

3.3. Relation outdoor - indoor temperature

During the warm week in August, the weekly mean indoor temperatures of dwellings were significantly associated with temperatures measured outdoors of the dwellings. Homes with a 1 °C higher outdoor temperature had a 0.9 °C (SD = 0.23; $p < 0.01$) and 1.1 °C (SD = 0.3; $p < 0.01$) higher temperature in the living rooms and bedrooms respectively. Scatterplots of weekly average outdoor temperatures versus weekly average indoor living room and bedroom temperatures are shown in Fig. 2. Indoor temperatures varied more widely than outdoor temperatures between the dwellings. Homes with a higher outdoor temperature also had higher indoor temperatures, but the correlation was moderate ($R^2 = 0.36$ and 0.34 for living rooms and bedrooms, respectively) and the variation in indoor temperatures was much higher than in outdoor temperatures, suggesting that other (building and behavioural) characteristics affect indoor temperatures.

3.4. Building and outdoor characteristics and indoor temperature

Table 4 shows the results of univariate regression analyses of the relation between building characteristics and indoor temperatures in living rooms and bedrooms.

Dwellings built before 1930 had 0.6 °C lower temperatures in the living rooms and bedrooms than those built from 1985 onwards. There were no significant differences between houses built between 1931–1969 and 1970–1984 versus the reference category of houses built after 1984. Dwellings with attached houses on one or both sides had borderline significant lower temperatures in living rooms (−0.4 °C) and bedrooms (−0.6°) compared to apartment buildings. A

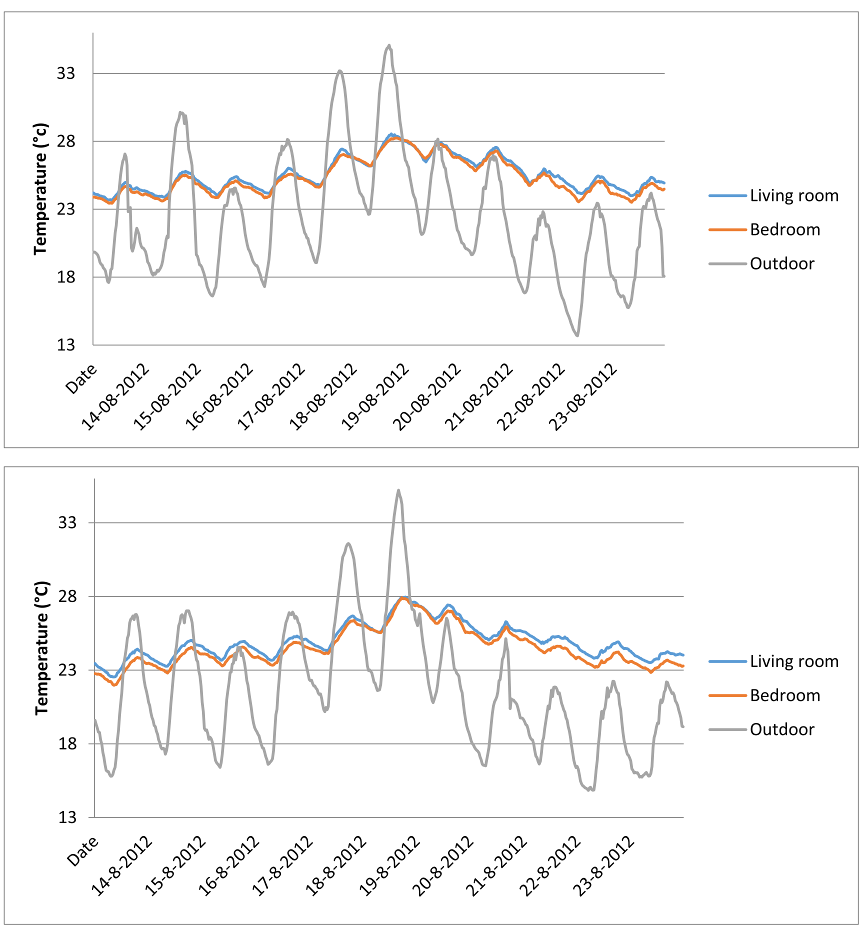

Fig. 1. Variation of half-hourly average temperatures living rooms, bedrooms and outdoor temperature in °C in Arnhem (upper) and Groningen (lower), 14–24 August (mean of all dwellings).

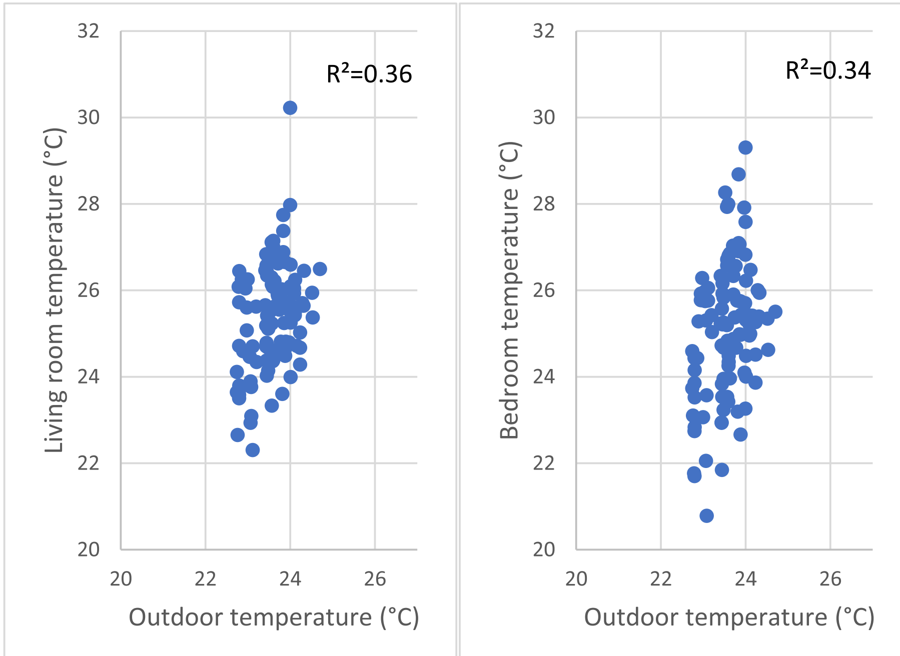

Fig. 2. Weekly average temperature outdoors and weekly average temperature in living rooms (left) and bedrooms (right), 14–20 August 2012 (in °C).

room located on the ground floor resulted in 1.6 °C lower living room temperature and 2.2 °C lower bedroom temperature compared to a room directly below the roof. The bedroom temperature was 0.6 °C higher when there was no vegetation outdoors near the bedroom. All other building characteristics were not significantly associated with living room or bedroom temperature respectively. There was no statistical interaction between building characteristics and city (Arnhem or Groningen) in the models.

Table 4
Univariate analyses of building characteristics and difference in mean six-day outdoor and indoor temperature in °C (14–19 August 2012).

Building characteristics	Living room β (95% CI)	Bedroom β (95% CI)
Year of construction		
- ≤1930	−0.6 (−1.2;0.0)*	−0.6 (−1.4;0.21)#
- 1931 ≤ 1969	−0.1 (−0.7;0.6)	0.1 (−0.7;0.8)
- 1970 ≤ 1984 (reference: >1984)	−0.2 (−0.8;0.4)	0.1 (−0.8;0.7)
Terraced house (reference: apartment building)	−0.4 (−0.9;0.0)#	−0.6 (−1.2;0.1)#
Size (per 1 m^3)	0.00 (0.00;0.00)	−0.01 (−0.02:0.01)
Height (per m)	−0.45 (−1.01;0.10)#	0.02 (−0.82;0.86)
Floor level	0.3 (0.2;0.4)*	0.4 (0.2;0.6)*
Location		
- Intermediate level	−0.5 (−1.2;0.14)#	−0.3 (−0.9;0.4)
- Ground floor (reference: just below roof)	−1.6 (−2.3;−0.9)*	-2.2 (−2.9;−1.5)*
No outside vegetation nearby	0.3 (−0.2;0.8)	0.6 (0.0;1.2)*
Windowpane area oriented at East. South and/or West (per m^2, median (min–max))	−0.01 (−0.05;0.03)	0.13 (0.02;0.25)*
Windowpane area oriented at North (per m^2, median (min–max))	0.01 (−0.06;0.07)	−0.04 (−0.12;0.04)

* $p < 0.05$.
\# $p < 0.20$.

3.5. Occupant behaviour and indoor temperature

Participants listed the hours they used indoor ventilation (opening of windows and doors), window coverage, including curtains, horizontal and vertical blinds, and outdoor window coverage (sunscreens). The use of ventilation and window coverage can be both a result and a cause of changes in temperature. The analysis on behaviour treated as independent variable is presented in the Supplementary material.

3.6. Multiple regression analyses on building characteristics

The results of the multiple regression analyses are presented in Table 5. Living rooms at the ground floors were on average 1.6 °C cooler than living rooms directly under the roof. Also bedrooms at the ground floor were coolest compared to bedrooms on other floors. Per m^2 of windows at the east, south or west side temperature in bedroom was 0.2 °C higher. Per m^2 of windows facing north bedroom temperature was 0.07 °C higher. Per 1 m^3 increase in size of the bedroom,

Table 5
Multivariate analyses of building characteristics and difference in mean six-day outdoor and indoor temperature in °C (14–19 August 2012).

	Living room B (95% CI)	Bedroom B (95% CI)
Location		
- Intermediate level	−0.5 (−1.2;0.1)#	−0.2 (−0.8;0.4)
- Ground floor (reference: just below roof)	−1.6 (−2.3;−0.9)#	−2.2 (−2.8;−1.5)*
Size (per 1 m^3)	Not included in multivariate model	−0.01 (−0.02;0.00)#
Window area facing East, South and West (per m^2)	Not included in multivariate model	0.21 (0.10;0.31)*
Window area facing North (per m^2)	Not included in multivariate model	0.07 (−0.01;0.14)#
R^2 of the model	0.24	0.43

* $p < 0.05$.
\# $p < 0.20$.

temperature decreased with 0.01 °C. Other outdoor and building factors had no significant contribution to indoor temperatures.

4. Discussion

4.1. Outdoor temperatures

On average, the difference between the urban outdoor measurements and the closest rural meteorological weather station was 1.7 °C in the warm week in August. The urban-rural difference in minimum and maximum temperatures was larger. Cities tend to get warmer during the day and cool down less at night than rural areas, as building materials and man-made surfaces warm up during the day and slowly release the heat during the night. The outdoor measurements were near participants' dwellings and may not be representative for the study areas. Other studies found similar difference in urban and rural temperatures in the Netherlands (Heusinkveld et al., 2014).

4.2. Relation between outdoor and indoor temperature

Our study shows a moderate relationship between outdoor and indoor temperatures during a warm episode. Homes exposed to average outdoor temperatures of 1 °C higher had living rooms and bedrooms that were on average 0.9 and 1.1 °C higher, respectively, as well A linear relation between outdoor and indoor temperature during warm periods was also reported in Montreal (Smargiassi et al., 2008) and Boston, Massachusetts (Nguyen et al., 2014). Indoor temperatures in New York increased 0.43 °C for every 1 °C increase outdoors (Tamerius et al., 2013). This relationship did not exist in Australian air-conditioned houses (Loughnan et al., 2015). In the Netherlands, air-conditioning use in private dwellings is uncommon. We excluded the three dwellings with air-conditioning from the analysis. We note that our analysis was focused on comparing between home variability of indoor and outdoor temperatures.

Indoor temperatures in our study gradually rose with an average 3.5 °C in the five days of the warm period. This steady rise in temperature might partly explain why there are more health effects when warm episodes last longer (D'Ippoliti et al., 2010).

The variation in average indoor temperatures per home was much higher than in residential average outdoor temperatures near the dwellings. Consistently, weekly average indoor and outdoor temperatures were only moderately correlated, indicating a strong impact of other factors, such as building characteristics and behaviour, on indoor temperatures beyond the outdoor temperature.

In addition, we detected a strong association between warming up and cooling down of the dwellings. Dwellings that warm up easily, also cool down easily. This observation is consistent with building characteristics such as insulation and thermal mass and occupant behaviour being important determinants of indoor temperatures. Many buildings fail in controlling temperatures (Coley and Kershaw, 2009). The more effective the housing structure, the less additional measures will be necessary to keep internal conditions at least tolerable. Control of the personal thermal environment is an essential goal of housing and should start with a preventive design (Lee, 1975).

4.3. Building characteristics and indoor temperature

Several building characteristics were associated with the indoor temperature in our study. Living rooms and bedrooms on the ground floor were associated with a 1.6 and 2.2 °C lower temperature compared to the rooms being located on the top floor. In Montreal, Canada, Smargiassi et al. reported a 1.0 °C and 2.5 °C increase in indoor temperature on the first and third floor compared to the ground floor, respectively (Smargiassi et al., 2008). In France, a dwelling located directly under the roof was the most important risk factor of the building for mortality during a heat wave (Vandentorren et al., 2006). Also Beizaee et al. showed that more top-floor living rooms than lower levels rooms tended to exceed indoor temperature thresholds in the UK (Beizaee et al., 2013). The results of these studies are in line with our findings.

Windows were associated with a 0.1 to 0.2 °C increase in bedroom temperature per m^2 in our study. Green in the vicinity of the bedroom was associated with a lower temperature in the bedroom. In contrast to our findings, Smargiassi et al. did not find associations between indoor temperature and window size or green coverage of the building front (Smargiassi et al., 2008).

We found differences in associations for living rooms and bedrooms, which may be explained by the different use, design and location of the rooms. In bedrooms, the amount of green near the dwelling was associated with a 0.6 °C decrease in temperature in the bedroom, but not in the living room. Windows size facing east/south/west was associated with an increase of 0.1 °C per m^2 in the bedroom, but not in the living room. These differences may partly be explained by the fact that living rooms have a larger volume and more often (34%) outdoor window coverage than bedrooms (6%). Trees outside and larger windows may thus be of more influence in bedrooms.

For reasons of energy saving, many houses are being insulated to decrease energy consumption in winter time. It is important to take effects of indoor heat in summer time into account in insulation measures. Insulation should be combined with ventilation and outdoor window coverage.

4.4. Occupant behaviour and indoor temperature

Homes with a higher use of indoor window coverage had higher indoor temperatures. Window coverage may both be a cause and an effect of changes in temperature. The same applies to ventilation. Ventilation during the day was associated with higher indoor temperatures, as can be expected, since it allows warm air to flow from the warmer (outdoors) to the colder (indoors) environment. However, ventilation during the night was also associated with higher indoor temperatures in the warmest week in August. This may also be because of reverse causation: people who experience higher indoor temperatures may ventilate more, both during daytime and night-time. This is a limitation of our study, which is based upon comparing measured indoor temperatures and specific behaviours between homes. An experimental design with assessment of temporal changes related to interventions – e.g. (proper) use of screens - within the same home would have been more effective to assess the impact of behaviour. Since ventilation behaviour and use of window coverage was stable within a participant, we could not exploit temporal contrasts in determinant and temperature. Tsoulou et al. also found interaction between occupant behaviour (window opening, occupancy and A/C use) and indoor temperature (Tsoulou et al., 2020).

Only 34% of the living rooms and 6% of the bedrooms had outdoor window coverage. And even if present, they were not frequently used, possibly because the elderly participants were not able to use it or because they underestimated the effect on temperature. The very lower number of dwellings having outdoor coverage at bedroom windows might reflect the assumption that outdoor window coverage is less important in the bedroom than in living rooms, this is not the case as not only the bedrooms warm up during the day, but also because the very vulnerable also spend time in their bedrooms during the day. Taylor et al. found external shutters to be effective at reducing indoor temperatures (Taylor et al., 2018).

4.5. Relevance of indoor temperature

Indoor temperatures in the warm week in August were 4.6 and 5.5 °C higher than in the baseline week in May, in living rooms and bedrooms, respectively. In the chilly week in May, some people used their heating to create a comfortable temperature. All Dutch homes have a heating. As such, indoor temperatures in August were 5 °C warmer than the participants normally choose to have in their homes. In a previous publication from the same study, we reported that more than half of the participants found the temperature in August too warm. We found a relation between temperature and heat-related problems such as annoyance to heat and sleep disturbance as reported before (Van Loenhout et al., 2016).

Many studies have investigated the effect of outdoor temperature on morbidity and mortality. This study shows that indoor temperatures vary widely between dwellings, and outdoor temperature is a relatively poor indicator. As most people, especially the elderly, spend most of the time indoor, the indoor temperature is more relevant than the outdoor temperature (Van Loenhout et al., 2016). Indoor temperature is associated with outdoor temperatures, but is additionally influenced by building characteristics and by occupant behaviour.

The importance of mitigating high indoor temperatures will be more important in the future because of higher outdoor temperatures caused by climate change (Watts et al., 2018). But also the ageing population and the tendency of elderly living at home longer instead of living in institutions will contribute to the problem of heat related health effects. Indoor temperatures may rise even more because energy saving building design tends to restrict the removal of heat from houses (Bone et al., 2010; Sharifi et al., 2019). In the Netherlands, in 2021 new legislation will come into force to lower the risk of overheating of new buildings. This legislation does not apply to existing buildings.

4.6. Strengths and limitations

This study is a large observational study investigating indoor temperatures. The study was performed in real-life conditions, giving a realistic view of the quantitative impact of factors influencing indoor temperatures. The study included measurements in as much as 113 dwellings, both bedroom and living room temperature, as well as outdoor temperature close to the dwelling. The dwellings may not by fully representative for dwellings of elderly because of response bias, which could lead to more participants with housing with higher indoor temperatures. Although the sample is not fully random, we believe that the dwellings are broadly representative for the dwellings in the study areas. The building and urban structures resemble those in other Dutch cities. Because of the same response bias, the health of the participants was probably better than average.

In recent years, warmer weeks occurred than in the warmest week in this study. Even in our study, indoor temperatures reached high levels and we found correlations between building characteristics and indoor temperatures. In warmer summers we expect even higher indoor temperatures and stronger relations between building characteristics and indoor temperatures.

The data on occupant behaviour relied on self-reporting which may have introduced biases. Participants were not instructed to open or close windows or curtains as could be done in an experimental design. Therefore, in our study we cannot tell whether occupant behaviour is a result or a cause of changes in temperature (dependent or independent).

The data of the building and street characteristics are obtained by observation. Most of the data were collected by the two principal investigators, who visited several houses together at the start of the study, to minimise differences in reporting. Our analysis was based on air temperature only. Air temperature has been the focus of epidemiological time series of morbidity and mortality. Because of the big sample size, it was not feasible to include solar radiation measurement in addition to air temperature and relative humidity. In our previous publication in this population, the Heat Index, using both temperature and relative humidity, was not a better indicator than air temperature to assess heat-related health problems (Van Loenhout et al., 2016). We did not use indices for thermal comfort in the study such as CIBSE TM52 (CIBSE, 2013), nor did we use dichotomized metrics indicating whether a specific value was met or not. These metrics are highly relevant in policy applications or building design but less in epidemiological studies. In epidemiological time series studies of mortality and morbidity, temperature is used as a continuous variable as exposure metric. Therefore we think that from a health perspective, it is most important to look at indoor temperature (as a continuous variable) rather than looking at the fulfilment of indoor heat indices. The indoor environment is where people experience of large part of the exposure to heat and the health effects found in time series studies.

4.7. Recommendations

For energy saving, many existing and new buildings are now being highly insulated. Attention should be paid to indoor temperature in renovated and new buildings, by incorporating indoor temperature and ventilation demands in e.g. information campaigns, energy saving grants and requirements for new buildings. Insulating dwellings can increase overheating in buildings with a lack of options for purge ventilation (Fosas et al., 2018). Despite the findings of our study, it is generally acknowledged that well-built houses can reduce heat exposure (Loughnan et al., 2015; Mavrogianni et al., 2014; Nguyen et al., 2014). To realise healthy indoor temperatures, passive design features, such as use of window coverage and natural breeze, are less expensive and more environmentally sustainable than air-conditioning (Loughnan et al., 2015). In the maritime temperate climate of the Netherlands air-conditioning is not abundant but the use of air-conditioning is increasing.

In the Netherlands, heat adaptation focuses mainly on cooling down the outdoor environment. Building cooler buildings is getting increased attention. In addition, it is important to focus on occupant behaviour. Several studies in the UK pointed out that occupant behaviour is of high importance for indoor temperature (Mavrogianni et al., 2017; Morgan et al., 2017).

The new European Climate Law requires Member States to develop and implement climate adaptation strategies. It is important to connect climate adaptation and mitigating with regard to buildings. The energy demand of air-conditioning systems can be substantial in the future (Petrou et al., 2019).

Further research should focus on the effect of occupant behaviour on indoor temperature. In practice, the impact of occupant behaviour and the effect on building's thermal conditions and energy use are often ignored (Tsoulou et al., 2020). Study designs specifically addressing interventions in a semi-experimental design are called for. Specific attention should be paid to the ability of elderly to use certain cooling facilities. For elderly it is sometimes too difficult or too demanding to use window coverage and open windows and doors for ventilation. In addition, also in our study, participants mentioned that they could not always open doors and windows at night to cool their homes because of fear of burglary.

In addition, research should focus on what lessons can be learned from buildings and behaviour in warmer regions that could be adapted for use in countries with a cooler climate.

5. Conclusions

Our study documents substantially increased indoor temperatures during a short period with high outdoor temperatures in a temperate climate. Indoor temperatures show less diurnal variation than outdoor temperatures. In warm episodes, indoor temperatures are higher during the night and lower during the day than outdoor temperatures. During a warm episode, homes with higher outdoor temperatures on average had higher indoor temperatures, but the correlation was moderate ($R = 0.6$). The variability of average indoor temperatures was much larger than the residential outdoor temperature, documenting the important contribution of other factors, such as building characteristics. Several building characteristics were associated with the indoor temperature, Living rooms and bedrooms on the ground floor were associated with a 1.6 and 2.2 °C lower temperature compared to the rooms being located on the top floor. Other factors included building year (0.6 °C lower living and bedroom temperatures in houses built before 1930 compared to built from 1985 onwards), window size and orientation (0.13 °C higher bedroom temperatures per m^2 when windows facing East/South/West) and green in the vicinity of the bedroom (0.6 °C higher indoor bedroom temperature when no vegetation was present in the vicinity of the bedroom).

CRediT authorship contribution statement

Moniek Zuurbier: Methodology, Writing – original draft, Funding acquisition. **Joris Adriaan Frank van Loenhout:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Amanda le Grand:** Methodology, Investigation. **Frans Greven:** Methodology, Writing – review & editing. **Frans Duijm:** Methodology, Funding acquisition. **Gerard Hoek:** Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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