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RESEARCH ARTICLE

On the effectiveness of passive controls for summer thermal comfort in highly insulated dwellings

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ABSTRACT
Among environmental controls, solar shading and ventilative cooling are widely considered as key passive strategies for limiting the overheating risks in buildings. While their application is encouraged through Energy Performance of Buildings Directive regulations, several studies have shown that summer thermal comfort in heating-dominate temperate climates still requires deeper investigation, particularly in low-energy residential buildings. Based on qualitative and quantitative data collected through surveys and monitoring in 147 highly insulated houses in Wallonia (Belgium), this paper gives an overview of the implemented passive strategies and discusses their effectiveness. Statistical tests are conducted to evaluate their impact on both perceived and measured indoor conditions. In general, the results highlight a limited impact of the implemented strategies, questioning their proper operation. Operational modes for environmental controls thus appear crucial, and should better respond to occupants' needs, preferences and control opportunities. At a more general level, the study calls for a better understanding of the barriers inhibiting successful integration and operation of environmental controls, in order to effectively reduce overheating risks in residential buildings and limit future diffusion of active cooling systems with their induced environmental impacts.

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Solar shading; ventilative cooling; passive strategies; summer thermal comfort; overheating; highly insulated buildings

Introduction and background

The concern for summer thermal comfort in buildings has also increased for temperate climates over the recent years (Beizaee et al., 2013; Lomas & Kane, 2013; Pathan et al., 2017; Yannas & Rodríguez-Álvarez, 2020). While heatwaves are expected to become more intense and frequent (Ouzeau et al., 2016), it is recognized that excessive exposure to such conditions can negatively impact the comfort, well-being and health of people (World Health Organization, 2004). Various studies (Jones et al., 2016; Yannas & Rodríguez-Álvarez, 2020) have shown that highly insulated and airtight dwellings, which are increasingly encouraged by the general application of the nearly Zero Energy Buildings (nZEB) framework (European Parliament, 2018; European Commission, Directorate-General for Energy, 2021) in heating-dominated temperate climates, are particularly subject to overheating risks. In response, there is a need for the building sector to target achieving comfortable and healthy indoor thermal conditions during summers (Ortiz et al., 2020), yet also limiting the diffusion of active cooling systems (Yang et al., 2021) owing to their energy use and induced environmental impacts (Ademe & Coda-strategies, 2021).

For summer periods in temperate climates, the most effective combination of passive strategies – that is, strategies requiring none to very little energy for their operations (Chan et al., 2010) – is based on the use of solar shading and ventilative cooling (Encinas & De Herde, 2013; Porritt et al., 2012; van Hooff et al., 2015). Various studies have found these techniques capable of maintaining summer thermal comfort (Figueiredo et al., 2016; Tink et al., 2018; van Hooff et al., 2015; Yannas & Rodríguez-Álvarez, 2020).

By absorbing or reflecting solar radiation, solar shading devices can limit the portion of solar radiation that reaches interior spaces in buildings. According to the Technology Readiness Level (TRL) metric, a metric used for assessing the maturity of various technologies (European Commission, 2014), solar shading devices are proven in operational environments (TRL 9 [Zhang et al., 2021]). Different types of solar shadings are available in the market: interior or exterior, fixed or mobile, automated or manual, etc. In general, external solar protections are considered as one of the most effective means for preventing overheating (Mlakar & Štrancar, 2011; Porritt et al., 2012; van Hooff et al., 2015), and their usefulness is recognized in many

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climates (Gamero-Salinas et al., 2020; Harkouss et al., 2018; Zhang et al., 2021). Internal solar shading devices, generally being less expensive than the external ones, are also less efficient in limiting solar radiations – since part of the heat transmitted through glazing remains trapped inside the room. However, the use of light colours or reflective material can improve their efficiency by increasing the reflection of solar radiation towards the outside (yet, without reaching the performance of an external protection). In the Belgian temperate climate, it has been shown that cooling needs could be reduced by 37% using internal light-coloured solar shading devices, and by 70% using external solar shading with low openness factor (Dartevelle et al., 2015).

Ventilative cooling is also considered as a very efficient passive strategy (Hamdy et al., 2017; Mlakar & Štrancar, 2011; van Hooff et al., 2015). Aiming to remove sensible heat from the inside (Zhang et al., 2021), ventilative cooling can be achieved naturally in residential buildings by simply opening windows when the outdoor temperature is lower than the indoor temperature. At TRL 9 (Zhang et al., 2021), it does not require any additional technology. The effectiveness of the technique will depend on the position, size and characteristics of the openings, the presence of wind, but also the difference between outdoor and indoor temperatures (Bernard et al., 2018). The efficiency of ventilative cooling increases with the difference between the outside and the inside temperature, outside being lower. Night time is therefore ideal for this type of ventilation, and is recommended in the literature (Heracleous & Michael, 2018; Weng, 2017).

The thermal mass (concrete, masonry, stone, etc.) of a building and its accessibility i.e. contact with the indoor environment, can also influence indoor summer thermal conditions (Kisilewicz, 2015; Mlakar & Štrancar, 2011). When in contact with the indoor environment, thermal mass can absorb, store and release thermal energy to regulate the indoor temperature on a cyclical basis (Zhang et al., 2021). It has been shown that accessible thermal mass does not lower indoor daily mean temperature compared to lightweight buildings, but has the capacity to limit indoor temperature extremes (Staepels et al., 2013). Consequentially, many authors recommend the use of high thermal mass in residential buildings (Kuczyński et al., 2021; Verbeke & Audenaert, 2018). However, the efficiency of this strategy depends on many other factors: climatic conditions, exposure to heat sources, characteristics of the envelope, time when it is desirable to limit the interior temperatures (depending on the presence of the occupants), ventilation schedule, etc. (McLeod et al., 2013; van Hooff et al., 2015). It is recognized that the potential of thermal mass to prevent overheating is greater when combined with an effective ventilative strategy, such as night cooling (Kuczyński et al., 2021; Mhuireach et al., 2020; Pomfret & Hashemi, 2017; Yannas & Rodríguez-Álvarez, 2020).

Many authors have shown, based on simulation (Figueiredo et al., 2016; van Hooff et al., 2015; Zinzi et al., 2017) and/or monitoring studies (Tabatabaei Sameni et al., 2015; Tink et al., 2018; Yannas & Rodríguez-Álvarez, 2020), that it is often possible to reach acceptable indoor summer thermal conditions using passive strategies only, and without any active cooling system. For future climate scenarios, however, the debate is still open, with some authors warning that these measures could indeed be insufficient (Dodoo & Gustavsson, 2016; Ortiz et al., 2020). In any case, it is well ascertained that the implementation of passive techniques may limit the environmental impacts related to the use of air-conditioning by reducing buildings' cooling needs (Yang et al., 2021) and facilitating the adoption of low enthalpy systems (De Pauw & Jeroen., 2022).

Occupant behaviour could however be a key factor affecting the efficiency of these strategies, especially when manual interventions are required for their operation (i.e. for windows opening, solar shading closure) (Mavrogianni et al., 2017). As a consequence, the definition and simulation of occupant behaviour have gain of interest this last decade (Yan & Hong, 2018). In this way, it is recognized that occupants could play a considerable role in controlling summer thermal conditions (Mavrogianni et al., 2017; Ozarisoy & Elsharkawy, 2019). Authors have thus warned about the importance of properly disseminating information to the occupants (Mlakar & Štrancar, 2011; Tabatabaei Sameni et al., 2015) and have identified factors such as security, noise, pollution, etc. that could limit their actions (Tillson et al., 2013).

While the potential of these techniques is widely recognized, their practical efficiency needs to be questioned, especially in temperate climates without a tradition for implementing such techniques. In fact, while the application of these techniques is encouraged by building energy codes for new buildings, for example, the Energy Performance of Buildings Directive (EPBD) (European Parliament, 2018), it has been shown in heating-dominated regions such as Wallonia, Belgium, that overheating is still an important cause of discomfort in recently-built highly insulated houses (Jones et al., 2016; Ortiz et al., 2020; Rohdin et al., 2014; Toledo et al., 2016). This is also the case when renovations are conducted (Singh et al., 2014). The reasons behind this situation need to be explored. In this context, this paper gives an overview of implemented summer passive strategies in recently-built highly insulated houses, and discusses their practical impact on the perceived and measured indoor thermal conditions. The main novelty of the paper is thus to question, evaluate and discuss the effectiveness of these passive controls in actual situations.

Method

Data regarding implemented passive summer strategies, and the perceived and measured summer thermal conditions for this study, were primarily extracted from previously conducted Post Occupancy Evaluations (POEs) (Dartevelle & Vanwelde, 2018). These POEs had collected data via survey and measurement campaigns in highly insulated houses in Wallonia between 2015 and 2018. On the extracted data, statistical tests were performed to evaluate how the implemented strategies effectively improved summer thermal conditions. The set-up of this method is illustrated in Figure 1.

The analysed buildings were part of a public action accompanying the first steps of the EPBD implementation (European Parliament, 2018). Their main characteristics (geometry, constructions characteristics and estimated energy performance according to EPBD calculation) were available in a dedicated database. All selected dwellings had been occupied for a minimum of 3 years in order to guarantee a sufficient living experience of the users (Li et al., 2018).

The methods used for the survey and measurement campaigns, described in the following subsections, were submitted for approval to the Belgian Data Protection Authority (number VT005055129) and, in this context, an informed consent was obtained from all participants.

Survey

Data regarding implemented passive summer strategies and perceived summer thermal conditions were derived from the results of the survey conducted on the initial sample of 453 houses by means of an online questionnaire using Limesurvey (Limesurvey GmbH, 2006–2023).

The questionnaire was launched at the end of 2015. It was compound of 59 questions and included three parts. The first part focused on occupants' appraisal of the Indoor Environmental Quality (IEQ) of the building (25 questions), the second aimed to verify and complete the known buildings' characteristics (10 questions) and the third was dedicated to ascertaining the profiles and the habits of the occupants (24 questions). The occupants were asked to give a general appreciation or description, not particularly relating to the moment when the questionnaire was completed. A total of 147 complete responses (one per house) were received, representing a response rate of 32.5% (incomplete or judged unreliable data were first removed). In the following, this sample is defined as S1 ($n = 147$).

For the present study, the answers to the following questions were specifically analysed and discussed:

> Q1. Do you experience overheating situations in your dwelling? In which room and season?
>
> Q2. Do you use solar shading to protect against the heat of the sun? (Examples of solar shading were given, including both external and light-coloured reflective internal devices)
>
> Q3. Were these solar shading devices present at the end of the construction stage?
>
> Q4. Are they automatized? (automatic closing and opening)
>
> Q5. Do you open the windows in order to cool down the rooms? In which room, season and moment of the day (day and/or sleeping time)?

After conducting a pilot test, which involved a focus group with an independent group, and considering that evaluating the frequency of discomfort episodes was the main objective of the measurements campaign (see next section), discrete answer options (i.e. yes or no) were preferred. This choice aimed to facilitate and speed-up questionnaire responses, as well as enhance user acceptability of the survey. The authors, however, acknowledge that using Likert scales would have allowed the introduction of 'quantitative' aspects and more nuanced analysis.

These questions were intended to give an overview of the implemented strategies. In order to get the full picture of their implementation by the occupants, capturing the moment, the frequency and duration of actions (opening/closure) and/or episodes of discomfort would have been necessary, which was out of the scope of the survey.

Measurements and on-site verifications

Data regarding measured summer thermal conditions were derived from measurements conducted just after the survey campaign, on a subsample of 23 buildings (S2, $n = 23$). This subsample was selected from the first sample (S1, $n = 147$) based on the agreement of the occupants and on the feedback received in terms of overheating complaints. The aim of this purposive sampling was to have a similar overheating complaints rate in subsample S2 compared to sample S1. Key indicators of Indoor Environmental Quality (air temperature, relative humidity, CO_2, sound level) were measured during one entire year with a 10 min time step. Two initially participating houses had to be removed since the participants dropped out, and have thus not been included in S2.

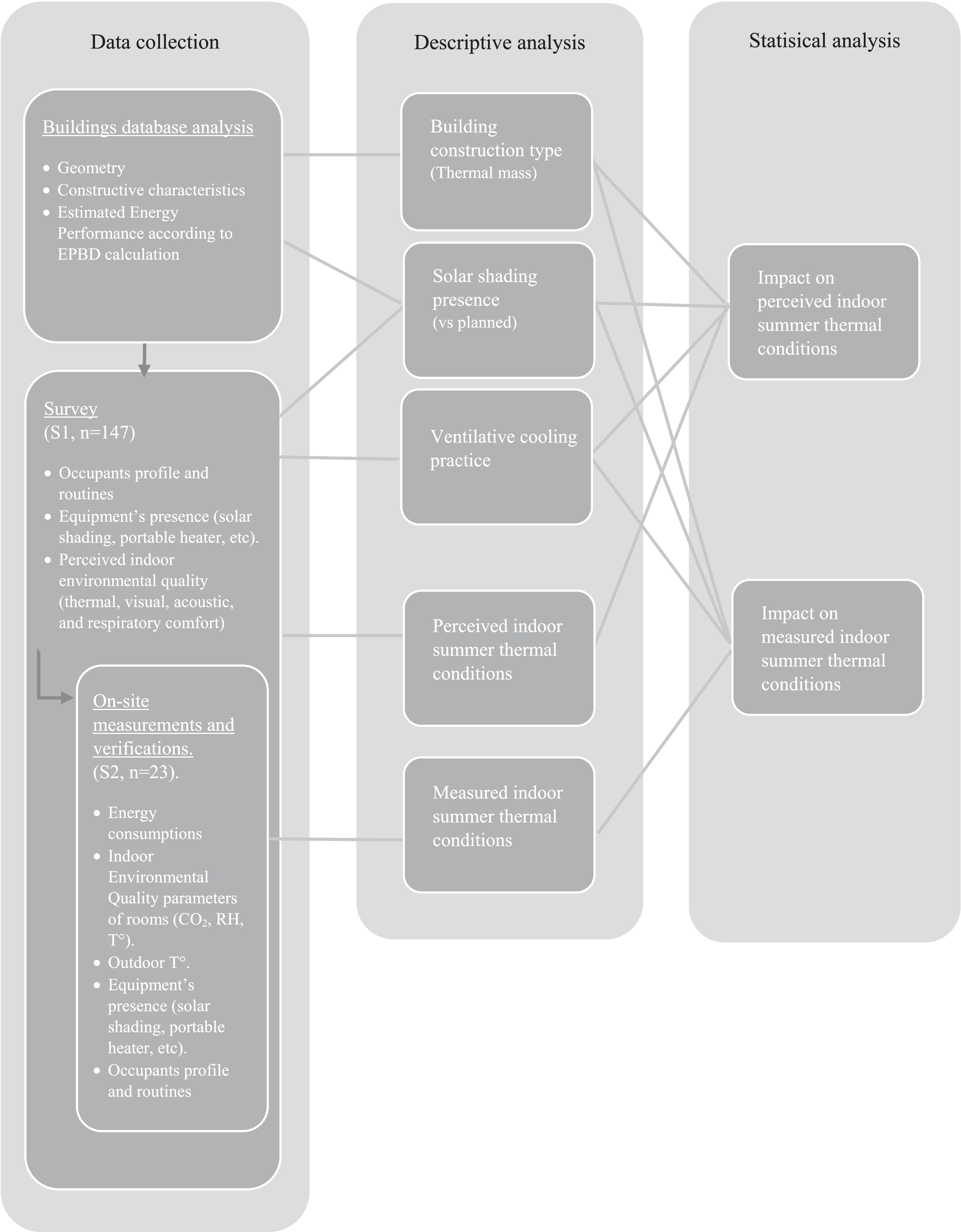

Figure 1. Workflow of the study.

The campaign took place in 2016, a year that can be considered broadly an average of the last 30 years for solar radiation and temperature (Royal Meteorological Institute of Belgium, 2017). Six days exceeded the maximum temperature of 30°C, 25 days exceeded 25°C and 97 days exceeded 20°C.

The measuring devices (Netatmo sensors with verified tolerance of ±0.3°C) were all calibrated by the Belgian Building Research Institute (BBRI) before the measurement campaign. Sensors were placed on top of existing furniture at a minimal height of 80 cm by the research team, and were placed away from other internal heat sources and windows to avoid direct solar radiation.

For the present analysis, the percentage of occupancy time when indoor air temperature exceeded 25°C was used to describe indoor summer thermal conditions.

This indicator differs from common overheating criteria since it is based on air temperature and not operative temperature; although these two values are frequently considered equivalent in highly insulated building (Fletcher et al., 2017; Gamero-Salinas et al., 2020). As most common time-integrated indices used to describe overheating in buildings (Rahif et al., 2021) the other environmental parameters such as air velocity and relative humidity, and personal factors such as clothing factor and metabolic rate, which affect thermal comfort, are neglected. It is also acknowledged that a criterion exclusively based on the percentage of time exceeding a specific indoor air temperature, might not be directly representative of thermal comfort – as it does not consider the adaptive capacity that occupants could have in certain rooms (de Dear et al., 2020; NBN, 2019). There is still however discussion on the applicability of this adaptive capacity in residential contexts, especially in sleeping area where the adaptive capacity of occupants may be reduced (Peeters et al., 2009). Some authors have thus proposed new limits, specifically dedicated to residential buildings (de Dear et al., 2018; Peeters et al., 2009). As the focus of this study was to illustrate the impact of summer passive strategies on indoor conditions, rather than their implication on thermal comfort, a static threshold based on air temperature was preferred. This criterion has the advantage of offering a shared basis for the description of indoor conditions (Fletcher et al., 2017; Fokaides et al., 2016; Lomas & Kane, 2013; McLeod & Swainson, 2017). This can facilitate the comparison between different rooms and buildings, which were all exposed to the same climate. Also, using a relatively low threshold, such as 25°C, gave a specific value for all rooms of all buildings, differing from 0 and improving the statistical power of the conducted analysis.

As room occupancy was found to considerably vary across days and houses, and in the absence of continuous high-resolution spatio-temporal models of occupants' location, realistic assumptions had to be made. Based on feedback from households, and in line with similar studies (Adekunle & Nikolopoulou, 2016; Fletcher et al., 2017; Lomas & Kane, 2013), assumptions were made for general occupancy. For living room, general occupancy was assumed between 7 am and 10 pm, and for bedrooms between 10 pm and 7 am, for cases that were occupied during working hours ($n = 7$). Conversely, for houses that were unoccupied during the day (n = 16), occupancy of the living room was considered only from 7 am to 9 am and from 5 pm to 10 pm on business days. Known periods of prolonged absence (e.g. vacations) were excluded from the analysis, in order to limit bias that could be induced by uncontrolled situations (i.e. no action undertaken by the occupants to control solar radiation or to dissipate the heat accumulated in the building).

While installing the measuring devices, the research team visited the houses and conducted semi-structured interviews with occupants in order to verify the data collected by means of the survey, e.g. routines, satisfaction and buildings characteristics. No substantial discrepancies were found especially in the reported actions. Nevertheless, some informal discussion with the occupants regarding their ventilative cooling practice suggested that improvements were possible, especially regarding the duration and moment of openings. Additionally, a grey coloured internal solar shading device, which did not demonstrate high reflective properties, was not considered in the analysis.

In a few cases, discrepancies were also found between perceived discomfort reported during the initial survey and measured data. Despite this subject being relevant in thermal comfort domain, the analysis was out of the scope of the present paper aimed at questioning the effectiveness of passive controls. It was thus not analysed in this paper, since this would necessitate specific approaches such as considering perceived comfort directly related to the measured period.

Statistical analysis

Statistical analysis has been carried out to evaluate whether the presence of solar shading (external or light-coloured/reflective internal devices), ventilative cooling practice and/or high thermal mass of the building significantly reduced the frequency of overheating discomfort reported by occupants (survey data) and the time when temperature exceeded 25°C (measurements).

The influence on perceived discomfort was studied through a chi-squared analysis (Fisher, 1922; Pearson,

1900) to compare the observed frequencies with those expected by-chance in various categories.

Since the data distributions were significantly different from normal (*p*-value of Kolmogorov–Smirnov test <.001(Kolmogorov, 1933; Smirnov, 1939)), a Wilcoxon non-parametric test was used to analyse the influence on temperature exceeding 25°C (Wilcoxon, 1945). This test, based on ranked values, estimates the probability of having the same difference of medians between two samples, if these were part of the same population.

Due to the limited size of the sample, to counteract the risk of not detecting an effect that actually exists (Type II error), the analysis calculated, for each test, both the statistical significance (*p*-value at the alpha level of .05) and the effect size of the detected differences. The effect size offers a standardized method to estimate the magnitude and the substantive relevance of the differences or deviations between groups of data (Field et al., 2012), without being subjected to some of the limitations of null hypothesis significance testing (NHST). Pearson r effect sizes were estimated based on Rosenthal (Rosenthal, 1991). The Cohen interpretation of effect size values was used for this study: $r > 0.1$ small; $r > 0.3$ medium; $r > 0.5$ large (Cohen, 1992).

Building characteristics and occupant profiles

The dwellings that were selected to be part of the samples were mainly energy efficient detached single-family houses, which composed about 90% of the entire sample. This building type represents 79.7% of the Belgian housing stock (Anfrie et al., 2017).

The houses are all located in Wallonia, in the southern part of Belgium, and correspond to a latitude of around 50° North. This falls in a Cfb climatic zone, which is a temperate oceanic climate according to the Köppen–Geiger climate classification system (Peel et al., 2007). The monitored houses of subsample S2 are all located in semi-rural to rural settings, and have little-to-none surrounding obstructions, which potentially allows an optimal facade orientation.

Quantitative and qualitative characteristics of the buildings featured in sample S1 and subsample S2 are presented in Figures 2 and 3. These data were collected from the available Belgian EPBD calculations database (Gouvernement wallon, 2008) and from the conducted survey and on-site measurements/verifications. In Figure 2, quantitative characteristics are presented using boxplots to illustrate the range and distribution of variables: minimum, 25th percentile, median, 75th percentile, maximum. Mean values are also indicated by a circular dot to enhance readability. It must be noted that the presented characteristics of S1 also include the characteristics of its subsample S2.

In general, the buildings present the following characteristics: heated floor area close to 220 m^2, mean U-value of 0.22 $W/m^2\,K$ (ranging from 0.09 to 0.4 $W/m^2\,K$) for walls, mean *U*-value of 0.16 $W/m^2\,K$ (ranging from 0.09 to 0.38 $W/m^2\,K$) for roof, mean *U*-value of around 1.5 $W/m^2\,K$ (ranging from 0.71 to 1.9 $W/m^2\,K$) for windows, and mechanical ventilation with heat recovery (95% of the cases for S1 and 100% for S2) resulting in a mean heating need close to 40 kWh/m^2 year (ranging from 0 to 105 kWh/m^2 year). Around 75% of these houses are constructed using traditional masonry, that is, cavity walls. Following a simplification of the Belgian EPBD classification based on the thermal capacity of building elements, these houses are considered as heavy constructions, even in case of wood structure for the roof. Conversely, the buildings that do not reach 50% of horizontal and vertical elements presenting at least an accessible mass of 100 kg/m^2 are considered as light constructions. In practice, the houses presenting this condition (1 out of 5 in S1, and 1 out of 4 in S2) were found to have a timber frame.

Overall, all these highly insulated dwellings – built with a focus on the reducing heating energy demands – can be considered as at least ‘low-energy houses’. In fact, 11% of the cases present characteristics close to the ‘passive standard’ (Plate-forme Maison Passive, 2020). By extension, they can be considered as representative of current building practices in Wallonia in terms of envelope performance.

The households size varied between 1 and 7 people, mostly families with children (mean of 3.5 people), and all the dwellings were owner-occupied. In terms of occupancy schedule, dwellings are mainly occupied at the end of the day and at weekends (cf. Figure 3). In 30% to 36% of the dwellings, respectively for subsample S2 and sample S1, occupants were usually present during the day. The respondent to the survey (one per household), was a male with average age of 44 years, in 80% of the cases. Almost all respondents (92% for S1 and 100% in S2) have high education qualification, and only 1% of S1 was unemployed. 92% and 95% of respondents formulate to understand or to master the technical principles of their house. This profile of educated, informed and aware respondents is likely to enhance the quality of the collected data, but cannot be considered as representative of the general population.

Results

The following section presents the data collected on the implemented summer design strategies, that is, presence of solar shading devices and the practice of ventilative cooling by windows opening. Further, the

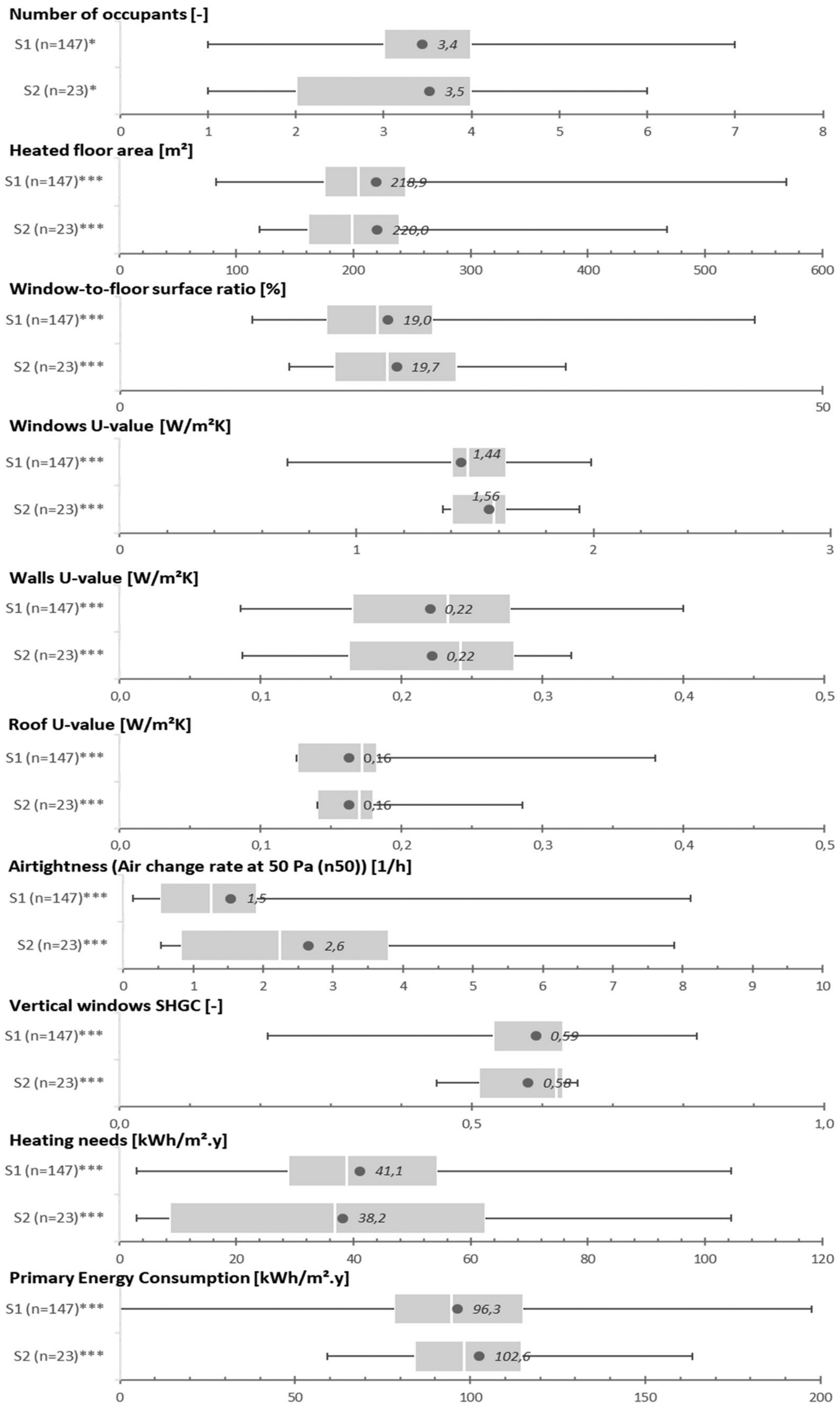

Figure 2. Quantitative characteristics of the buildings featured in sample S1 and subsample S2. *Source of data: *On-site verification; *** Belgian EPBD calculation.*

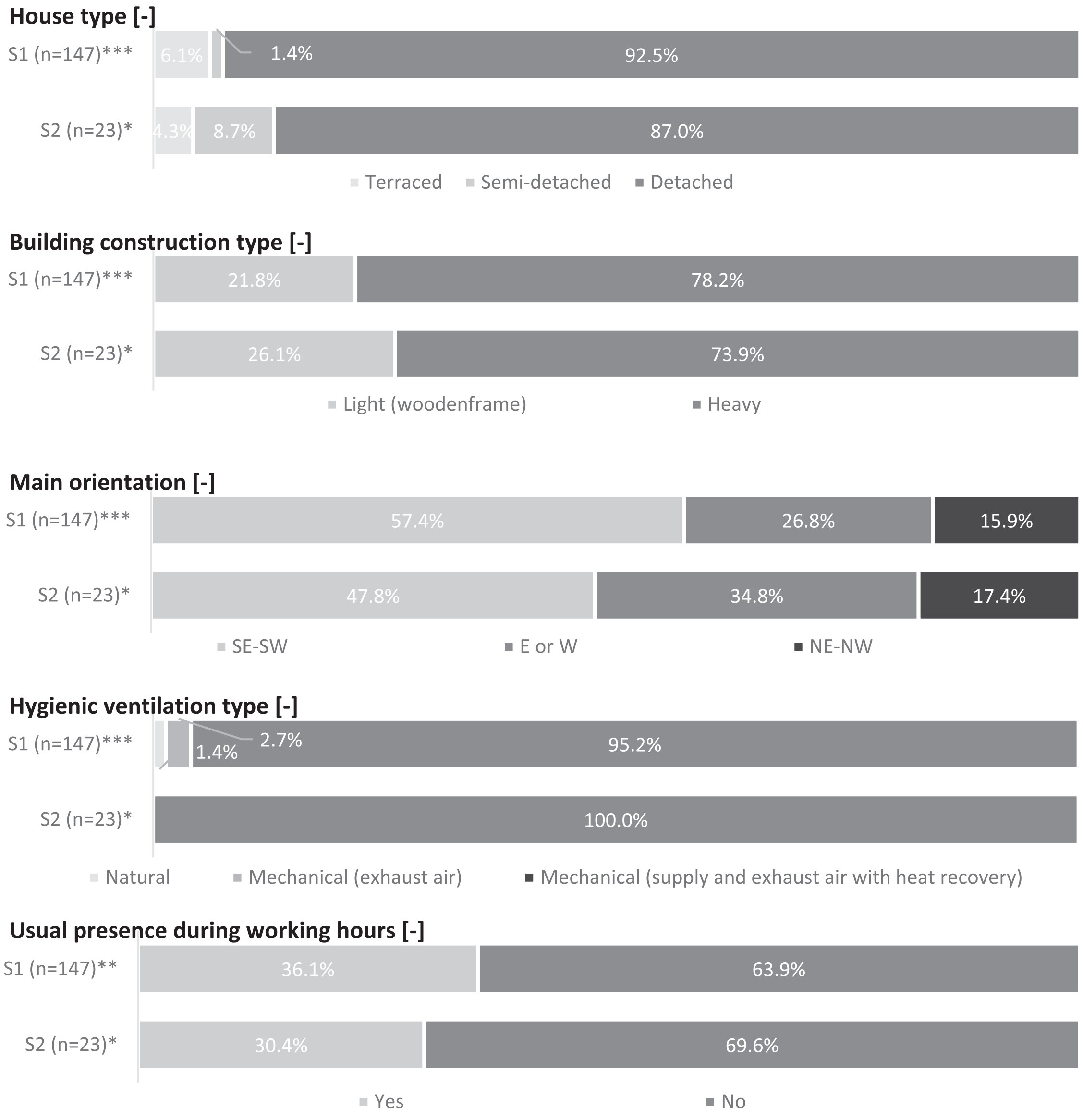

Figure 3. Qualitative characteristics of the buildings featured in sample S1 and subsample S2. *Source of data: *On-site verification; ** Survey; *** Belgian EPBD calculation.*

results of the statistical analysis are presented, which evaluated how effectively these strategies improved the perceived and measured indoor conditions. The results of each test, indicated on the upper part of each corresponding figure, are analysed using statistical significance and effect size of the detected differences.

Solar shading presence, position and control type

The following figures describe the presence, position (Figure 4) and control type (Figure 5) of solar shading in sample S1 and subsample S2. These data were collected by means of the questionnaire (questions Q2, Q3, Q4) for sample S1 and were discussed with the occupants for subsample S2.

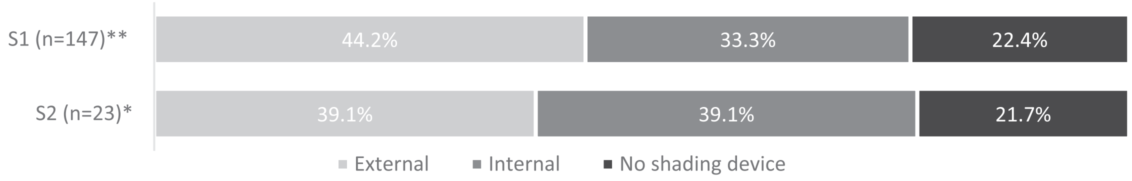

Figure 4. Solar shading presence and position encountered in sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

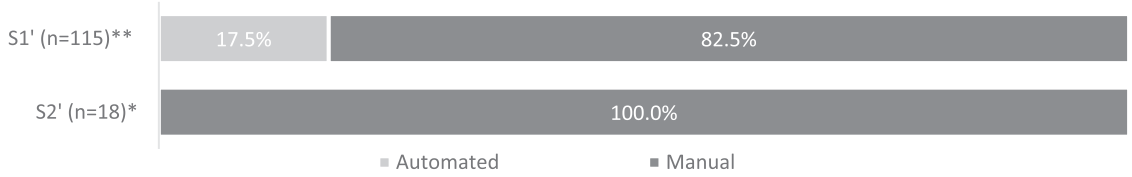

Figure 5. Solar shading device control types encountered in sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

Figure 6. Percentage of shading devices present at the end of the construction stage in sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

Figure 4 shows that around 40% of the houses were equipped, at least partially, with external devices. Also, more than a third of the sampled houses had a light-coloured or reflective internal shading. Around a fifth of the cases did not have any solar shading device. Figure 5 shows that very few were equipped with automatic control (17.5% in S1 and none in S2). Figure 6 illustrates that only between 16% (subsample S2) and 33% (sample S1) of these shading devices were placed at construction stage.

Detailed characteristics of shading devices, such as fixed or mobile, device materials, whether parallel to the glazing, etc. have not been collected in detail through the survey. Nevertheless, open commentaries suggest that shading devices parallel to the glazing, such as screens and venetian blinds, are the most common external systems, and that internal protections often were light-coloured internal curtains. On-site verifications confirmed these observations for subsample S2 ($n = 23$). No automatized system was encountered in subsample S2, but open commentaries of the conducted survey suggests that they were mainly based on incident solar radiation in Sample S1.

Ventilative cooling practice

Figures 7 and 8 illustrate the ventilative cooling habits of the occupants in sample S1 ($n = 147$) and subsample S2 ($n = 23$). These data were collected by means of the questionnaire (question Q5) for sample S1 and were discussed with the occupants for subsample S2.

The data show that ventilative cooling by windows opening was practiced between 50% of the cases (S2) in the living room and more than 70% in other rooms (S1 and S2). Night ventilative cooling seems easier to practice in the bedrooms (Figure 8) than in the living rooms (Figure 7) (45.6% of the cases versus 11.6% in sample S1). Results for the living room of subsample S2 (Figure 7) differ considerably, showing more night opening practice (43.5%) but also more cases where no ventilative cooling was practiced in the living room (47.8%). As a consequence, results of subsample S2 regarding night ventilative cooling practice could not be considered as representative of the habits of the larger sample.

Characteristics of windows type and opening mechanisms have not been collected in detail through the survey. Nevertheless, on-site verifications confirmed typical trends of the Belgian housing market: sliding and ‘tilt and turn’ were the main encountered types of windows in the living rooms while ‘tilt and turn’ and openable roof windows were mostly encountered in bedrooms. There is thus no doubt about the fact that the aperture areas of these opening systems have the capacity to contribute to effective ventilative cooling.

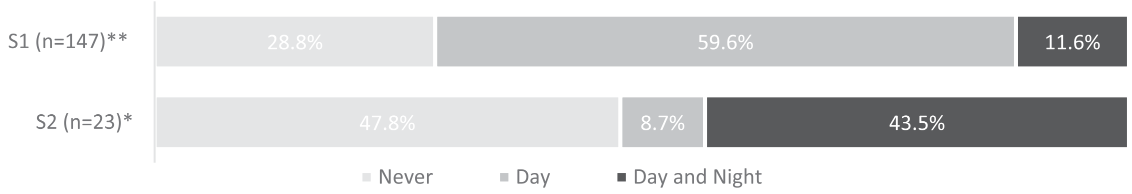

Figure 7. Percentage of cases where there is a ventilative cooling practice in the living rooms for sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

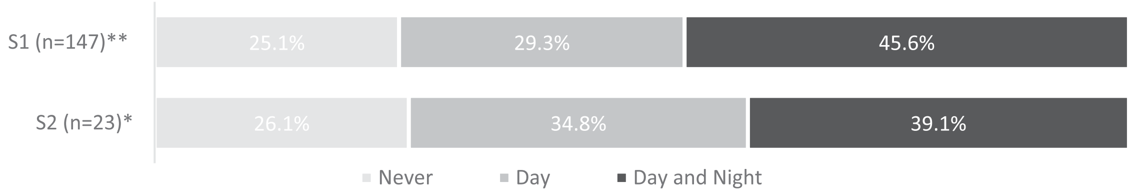

Figure 8. Percentage of cases where there is a ventilative cooling practice in the bedrooms for sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

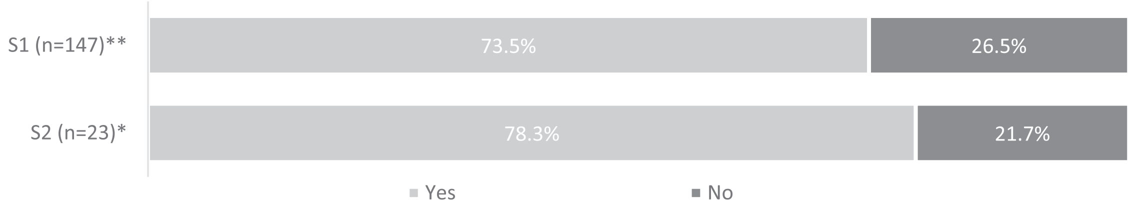

Figure 9. Percentage of cases where an overheating discomfort is encountered in sample S1 (above) and subsample S2 (below). *Source of data: *On-site verification; ** Survey.*

Impact on perceived discomfort

The distributions of responses illustrated in Figures 9 and 10 correspond to the following question:

> Q1. Do you experience overheating situations in your dwelling? In which room and season?

The figures show that the percentage of cases where overheating discomfort was reported by the occupants reaches 73% for sample S1 and 78% for subsample S2 (Figure 9). As illustrated by Figure 10, these occurrences of discomfort were reported mainly during the summer in the living areas, such as living rooms, bedrooms and kitchens. The definition of summer was not detailed in the survey. However, meteorological summer is considered from the beginning of June to the end of August in Belgium. During the other seasons, the percentage of reported discomforts is almost non-existent. Only a few percentage (maximum 5%) of respondents reported a discomfort during the spring season. The following illustrates, for sample S1 ($n = 147$), the influence of the presence of passive strategies on the frequency of overheating complaints reported by occupants. Results of the chi-squared tests conducted on these data are presented above each graph.

Figure 11 illustrates this for cases with solar shading absence/presence (left) and according to the position of solar shading (right). The analysis shows that, for the sample studied, the frequency of reported complaints does not differ significantly in case of solar shading presence, and stays around 70%. In fact, the statistical tests did not detect any significant difference ($\chi^2 = 0.68$, n.s.) with the Pearson effect size being <0.1 ($r = 0.02$). Similarly, an external position of the shading device did not lower the frequency of complaints compared to internal shading ($\chi^2 = 0.12$, n.s., $r = 0.01$). It is also interesting to note that 28% of the cases without solar shading did not encounter overheating discomfort (=9% of the sample). This should result from a combination of influencing factors: reduced glazing surfaces, orientation, lower SHGC, environmental shadings, etc.

Figure 12 illustrates the frequency of overheating complaints reported by the occupants of sample S1 ($n = 147$) for the cases with and without ventilative cooling practice by windows opening (left). The figure shows that window opening is more often exerted when overheating is encountered. This effect is small ($r = 0.20$) but statistically significant ($\chi^2 = 5.92$, $p < .05$). Conversely, the graphs on the right shows that, for the studied sample, the frequency of reported complaints does not

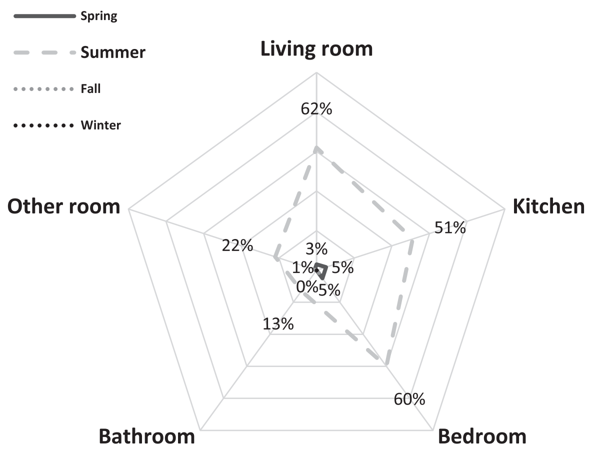

Figure 10. Localization and moments of overheating discomfort in sample S1. *Source of data: Survey.*

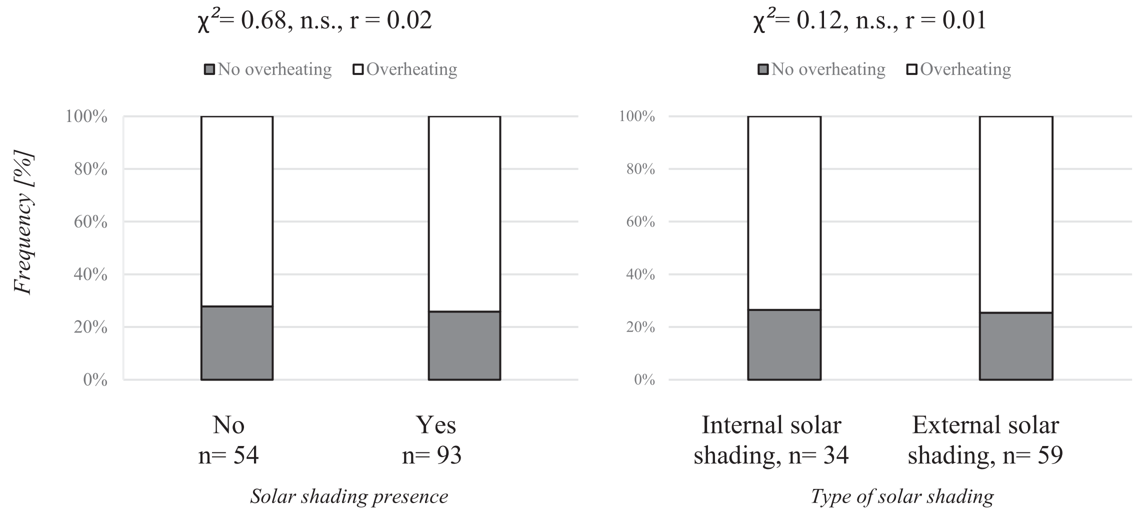

Figure 11. Impact of solar shading presence (left) and position (right) on reported overheating situations

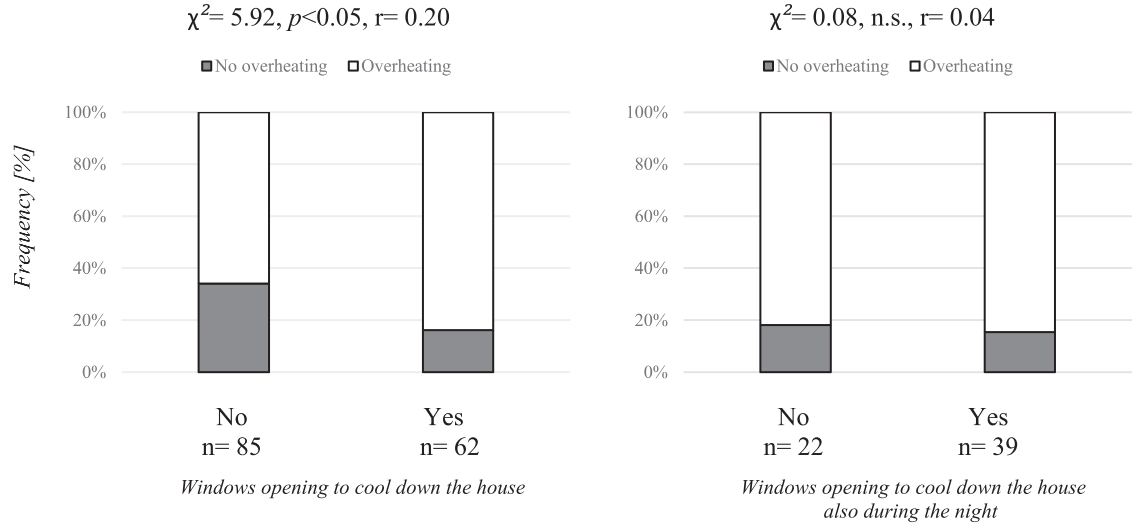

Figure 12. Impact of ventilative cooling practice (left) and moment (right) on encountered overheating situations.

show any significant ($\chi^2 = 0.08$, n.s.) and practically substantive ($r = 0.04$) differences for the cases that declare practicing ventilative cooling by windows opening also during the night.

Figure 13 illustrates the impact of the construction type, that is, the access to thermal mass, on the frequency of overheating complaints reported by the occupants of sample S1 ($n = 147$). The figure shows that, in lightweight buildings, the frequency of complaints is statistically and practically significant and slightly higher ($\chi^2 = 4.13$, $p < .05$, $r = 0.17$) than in other buildings.

Figure 14 illustrates the impact of the combination of solar shading presence, windows opening practice in non-wood frame (masonry) buildings on the frequency of encountered overheating situations. The statistical test did not show any significant and practically relevant differences with this combination ($\chi^2 = 0.19$, n.s., $r = 0.04$).

Since environmental controls, such as deployment of movable solar shading and windows opening, were mostly manually operated in the studied sample (cf. Figure 5), the impact of the presence of the occupant during the day has also been tested. The results illustrated in Figure 15 do not show a significant difference in the frequency of overheating complaints between buildings that were occupied during the day and those that were not ($\chi^2 = 0.01$, n.s., $r = 0.01$).

Impact on measured thermal conditions

Figure 16 presents the distribution of occupancy time exceeding 25°C in subsample S2 ($n = 23$) by means of boxplots (minimum, 25th percentile, median, 75th percentile, maximum). Numerical median values are also indicated to increase the readability of the graphs. The

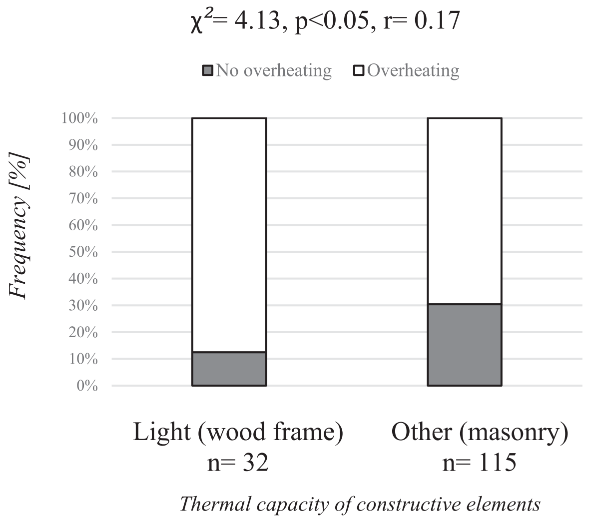

Figure 13. Impact of the construction type on reported overheating situations.

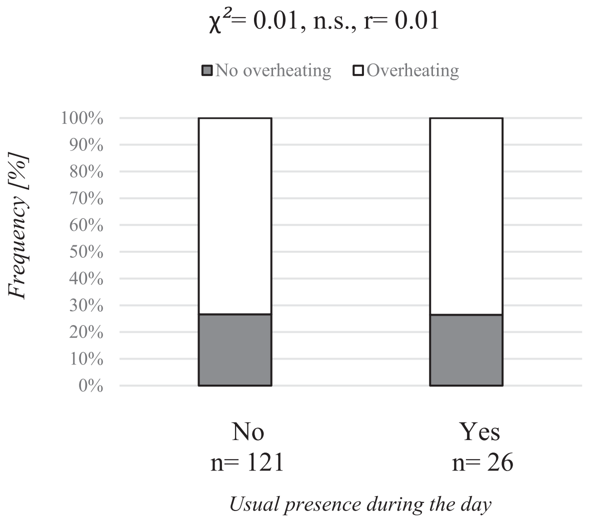

Figure 15. Impact of daytime presence of the occupant on reported overheating situations.

boxplots show that the distribution is quite similar for each room ranging from 1% to more than 30% of the occupancy time over 25°C with a median value of 6.4% (the Belgian Passive House Plateforme recommend not to exceed 5% (Plate-forme Maison Passive, 2020)).

Figures 17–23 illustrate by means of boxplots, for subsample S2 ($n = 23$), the influence of the implementated passive strategies on the distribution of occupancy time exceeding 25°C in the living room (left), and in the main bedroom (right). Results of the Wilcoxon tests are presented above each graph and median values are reported below.

Figure 17 presents the impact of the presence of solar shading on the percentage of occupancy time exceeding 25°C. The figure shows that, for the studied sample, the presence of solar shading did not lead to detect significant differences (living rooms, $W = 185$, n.s.; main bedrooms, $W = 135.5$, n.s.), although the small but practically relevant effect sizes show a tendency towards a decreased frequency of temperatures over 25°C with the presence of shading devices ($r = -0.28$ and $r = -0.27$, respectively). It should be considered here that the size of the sample might have had an impact on the detected significance of the statistical tests.

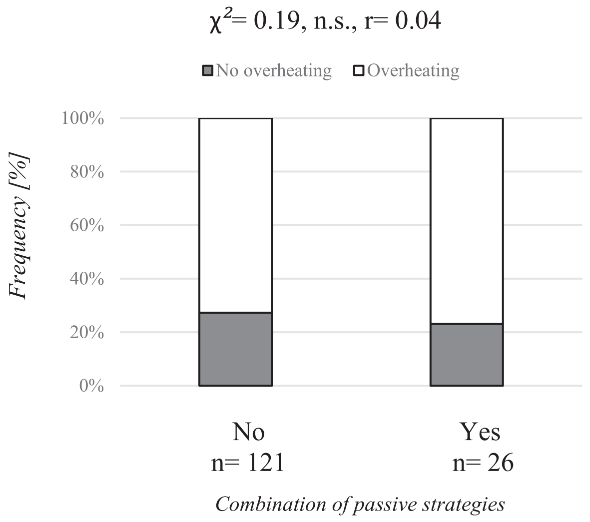

Figure 14. Impact of the combination of solar shading presence, ventilative cooling practice on reported overheating situations in masonry buildings.

The cases with external shading devices were also compared to those equipped with internal shading (Figure 18). Although the analysis did not detect statistically significant differences (living rooms, $W = 53.5$, n.s.; main bedrooms, $W = 30$, n.s.,), for the living rooms the small estimated effect size ($r = 0.21$) lead to infer a tendency for a higher percentage of time of occupancy exceeding 25°C with external shading. It should be remembered here that all shading devices in subsample S2 ($n = 23$) were manually operated. Also, the window-to-floor ratio was slightly higher in presence of external shading for the subsample S2 compared with the other cases (median of 18.5% compared to 16.5%, $W = 875$; n.s.; $r = 0.16$). The influence of the main orientation, which corresponds to the largest glazing area of the house, was also questioned; but the analysis did not highlight a clear tendency. The explanation is that all houses have various orientations: four orientations for the 20 detached houses; three for the 2 semi-detached houses and two for the terraced house, that could contribute to solar heat gains and increase the overheating risk of the building.

Figure 19 presents the impact of ventilative cooling practice on the percentage of occupancy time exceeding 25°C for the living rooms (left) and the main bedrooms

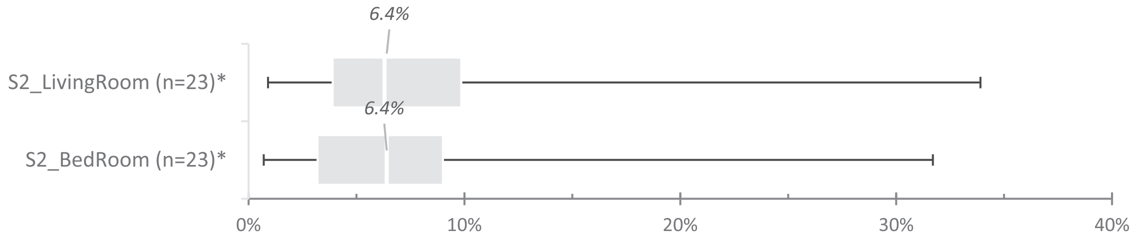

Figure 16. Distribution of occupancy time exceeding 25°C in the living rooms (top) and in the main bedrooms (bottom) of subsample S2. *Source of data: *On-site verification/measurements.*

(right) of subsample S2 ($n = 23$). While no significant and practically relevant difference could be detected in the main bedrooms ($W = 201$, n.s., $r = -0.04$), a small but practically relevant effect size ($W = 161.5$, n.s., $r = 0.23$) indicates, for the living rooms, a tendency for a higher percentage of occupancy time exceeding 25°C when ventilative cooling is practiced.

Figure 20 illustrates the impact of ventilative cooling practice when this strategy is also practiced at night. Compared to the cases practicing windows opening during the day only, the cases with night opening present lower percentages of occupancy time exceeding 25°C. The estimated magnitude of the effect was found to be large in the living rooms ($W = 46$, $p < .05$, $r = -0.61$) and moderate in the main bedrooms ($r = -0.32$), although for the latter case the test was not statistically significant ($W = 67.5$, n.s.).

Figure 21 shows the impact of the construction type on measured thermal conditions. No significant and practically relevant difference could be detected for the living rooms ($W = 72.5$, n.s., $r = 0.01$), while for the bedrooms the analysis did not detect statistically significance, but an effect of small size ($W = 87.5$, n.s., $r = 0.23$).

Figure 22 compares the percentage of occupancy time exceeding 25°C for the cases presenting a combination of solar shading, windows opening practice and heavy weight construction with the other cases. The differences detected were all not statistically significant (living rooms, $W = 74.5$, n.s.; main bedrooms, $W = 66.5$, n.s.), although an effect of small but practically relevant magnitude ($r = -0.24$) could be estimated for the bedrooms. Similar results (not illustrated here) were found for the cases presenting this combination of strategies but where the windows opening was also practiced during the night.

Since some environmental controls, such as adjustment of solar shading and windows opening, were manually operated in the studied subsample S2 ($n = 23$), the impact of the presence of the occupant during the day was also tested. This is illustrated in Figure 23, showing that the percentage of occupancy time exceeding 25°C was lower when the occupant is at home during the day for both the living room ($W = 51.5$, $p < .05$) and the main bedrooms ($W = 44.5$, $p < .05$), with estimated magnitude of effects ranging from medium ($r = -0.45$) to large ($r = -0.55$), respectively. It was

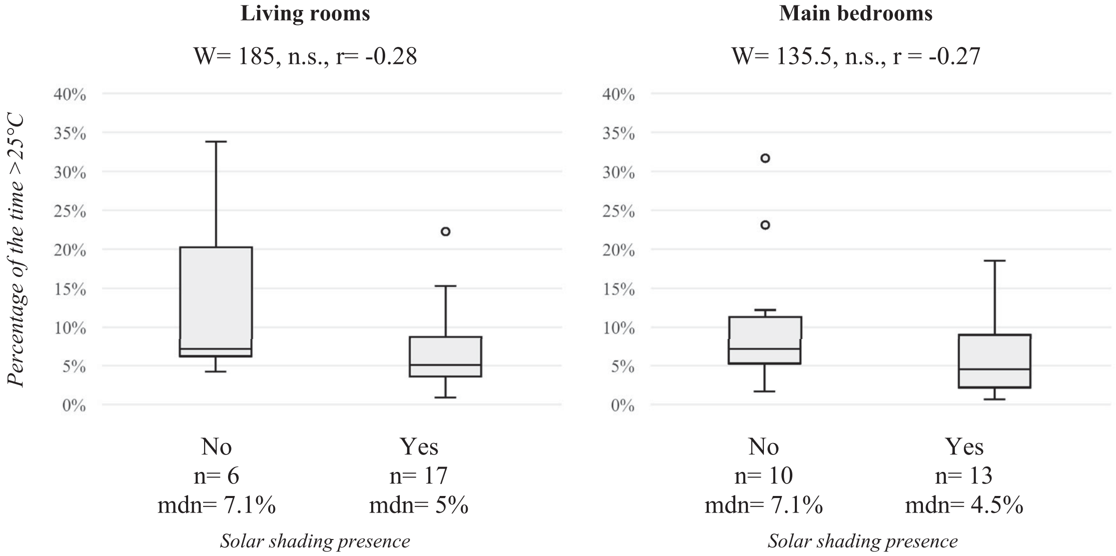

Figure 17. Impact of solar shading presence on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

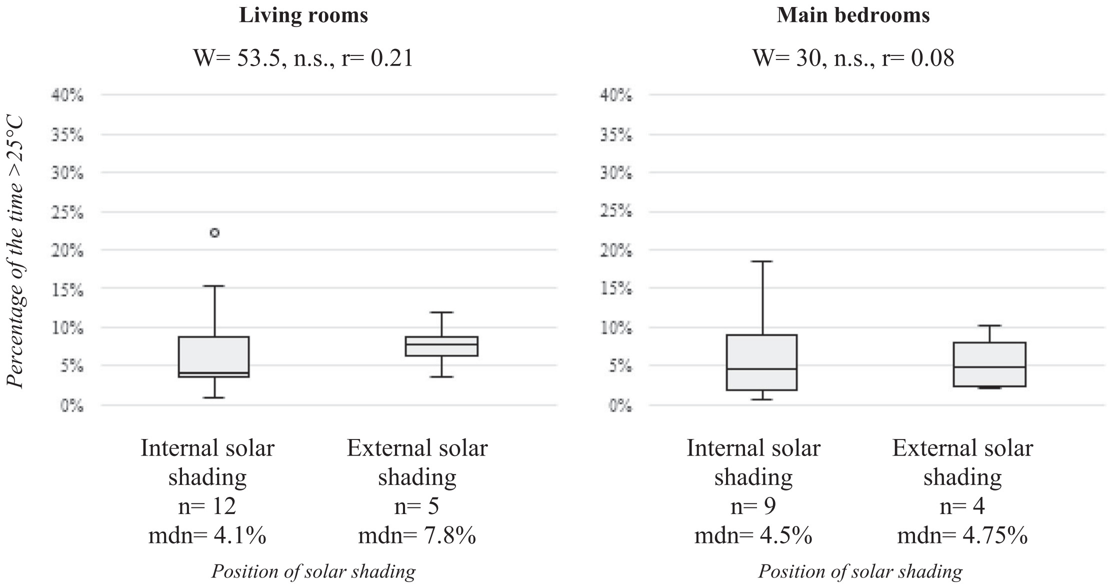

Figure 18. Impact of solar shading position on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

also noticed that more appropriate environmental controls were available in the buildings occupied during the day. In fact, all were equipped with solar shading, at least in the living rooms, and all occupants declared to practice window opening to cool down the rooms in these cases.

Discussion

As a primary consideration, it is important to highlight the high frequency of overheating discomfort reported by the occupants, which accounted for more than 70% of the sampled cases. This is substantiated by the results of the monitoring campaign, which shows that around 60% of the cases (S2) exceeded the threshold recommended by the Belgian Passive House Institute (5% of occupancy time over 25°C in a year consistent with seasonal norms (Plate-forme Maison Passive, 2020)). These results are quite alarming, since other types of housing, such as apartments in cities are considerably more exposed to overheating risks than those analysed in this study: single-family houses located in rural or semi-rural areas (Lomas & Kane, 2013; Sharifi et al., 2019). Owing to global warming, this risk will clearly increase in future climate scenarios (Attia & Gobin, 2020; Hamdy et al., 2017; McLeod et al., 2013; Rahif

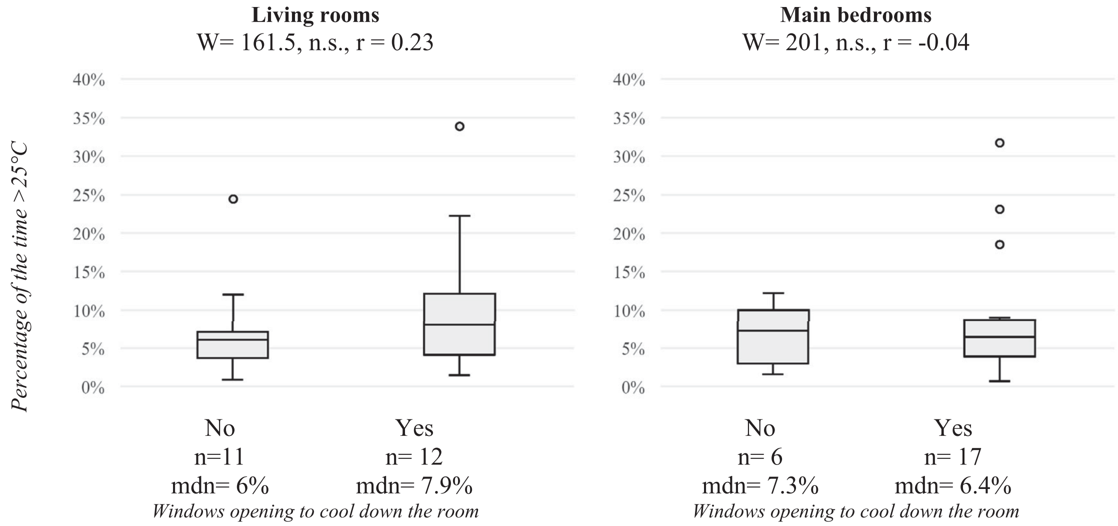

Figure 19. Impact of ventilative cooling practice on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

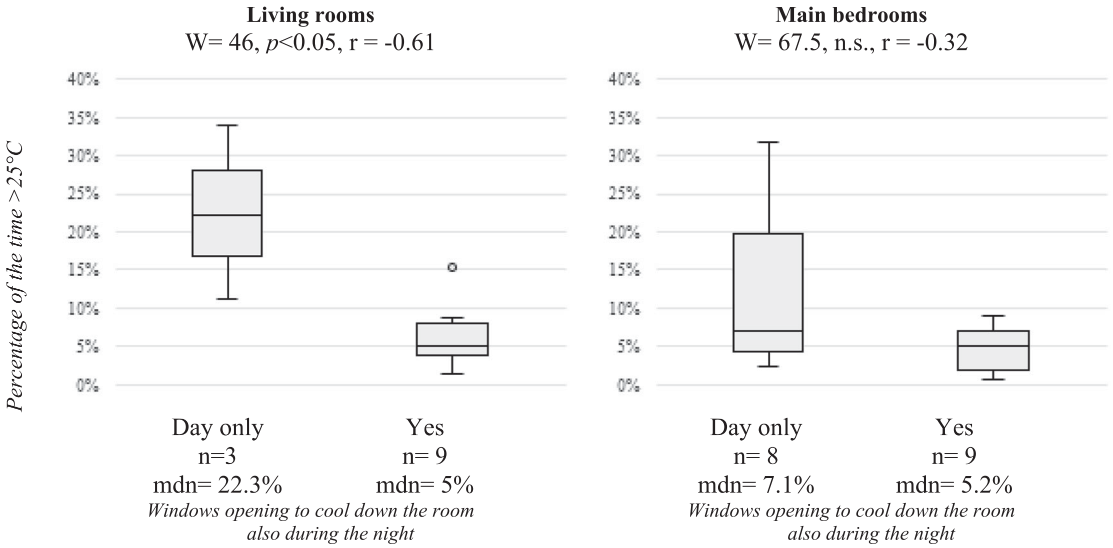

Figure 20. Impact of ventilative cooling practice at night on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

et al., 2022). Consequently, these findings confirm that summer thermal comfort in residential buildings should also become a priority in temperate climates (Tabatabaei Sameni et al., 2015; Toledo et al., 2016).

The results also illustrate that practitioners have not yet embraced the practice to implement passive strategies, in order to improve summer thermal comfort. While over 70% of the studied buildings were equipped with solar shading after some years of occupation (Figure 4), only 40% of these devices were external and a large majority was not present at the end of the construction stage (around 70% in sample S1, and more than 80% in subsample S2) (Figure 6). Only few solar shading systems were effectively present at the end of the construction stage. This supports similar findings in other contexts (Ozarisoy & Elsharkawy, 2019; Rohdin et al., 2014) and leads to question the reasons behind the difficulty to properly integrate building summer passive strategies in countries that have no such tradition. According to Social Practices Theory (Reckwitz, 2002; Schatzki, 1996), a practice such as the use of solar shading to increase summer thermal comfort, is supported by linked components. These components are related to *competences:* which include know-how, habits, institutionalized knowledge and explicit rules, etc., *meanings:* which are associated with beliefs, emotions, moods, etc. and *materials*: which include available technologies and products, etc. (Shove et al., 2012). As highlighted

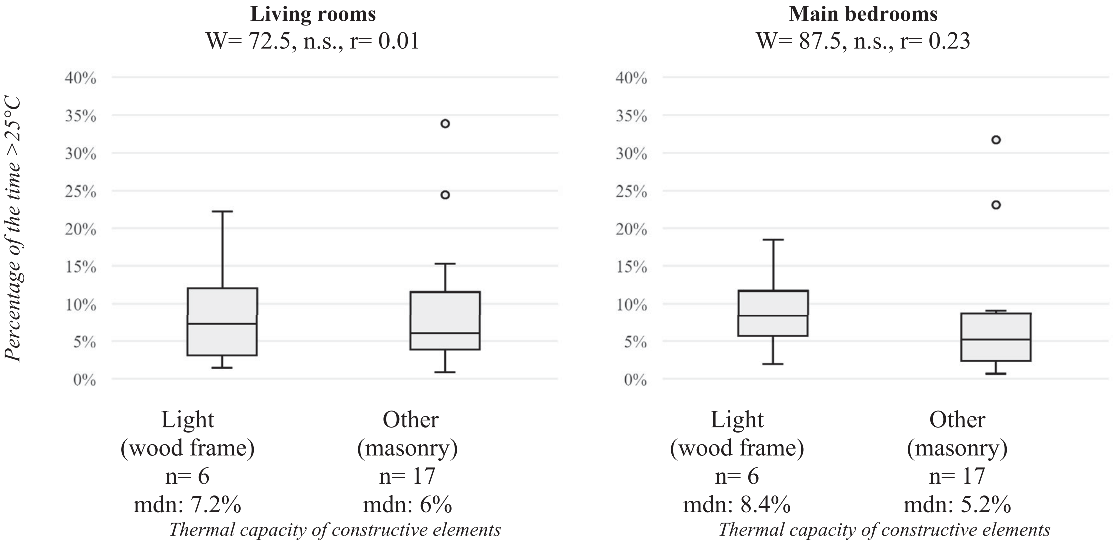

Figure 21. Impact of construction type on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

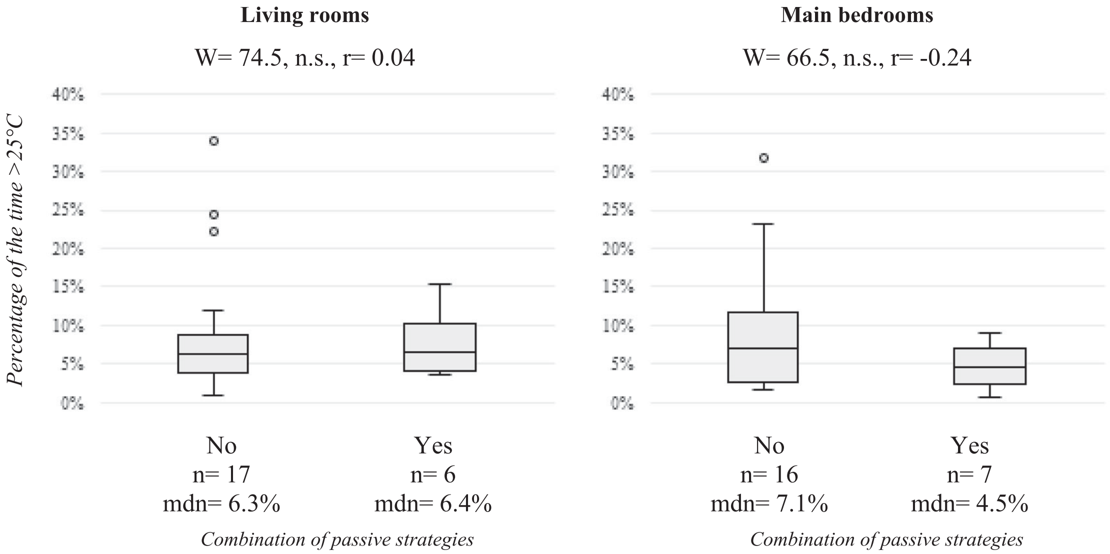

Figure 22. Impact of combination of solar shading presence, ventilative cooling practice and heavy construction type on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

by Shove (2003), these components must co-evolve to generate new practices, or to change existing ones. If, as in this case, the technology is mature, such as TRL 9 (Zhang et al., 2021), the reasons of its scarce implementation may probably be searched among *competences* and *meanings* components of social practices, and should probably be derived according to the type of solar shadings. It is also recognized that different actors interfere in the introduction, adoption and diffusion of innovations (Rogers, 2003). These include: the supply (enterprises) and demand (end users) sides, as well as the steering environment (policymakers). Consequently, the practices of occupants but also of all practitioners intervening in the building process (architects, engineers, builders, etc.) need to be specifically studied in order to properly identify levers and barriers to the implementation of such techniques.

The effectiveness of the implemented passive strategies should also be questioned. In the analysed sample, the presence of solar shading shows that indoor thermal conditions only marginally improved (Figure 17), yet did not substantially impact the rates of overheating complaints from the occupants (Figure 11). Conversely, when external shading devices were present, an even higher percentage of occupancy time over 25°C could be inferred (Figure 18). This might partly be due to the fact that external shading devices were placed mostly in critical cases (e.g. large glazing surfaces, challenging

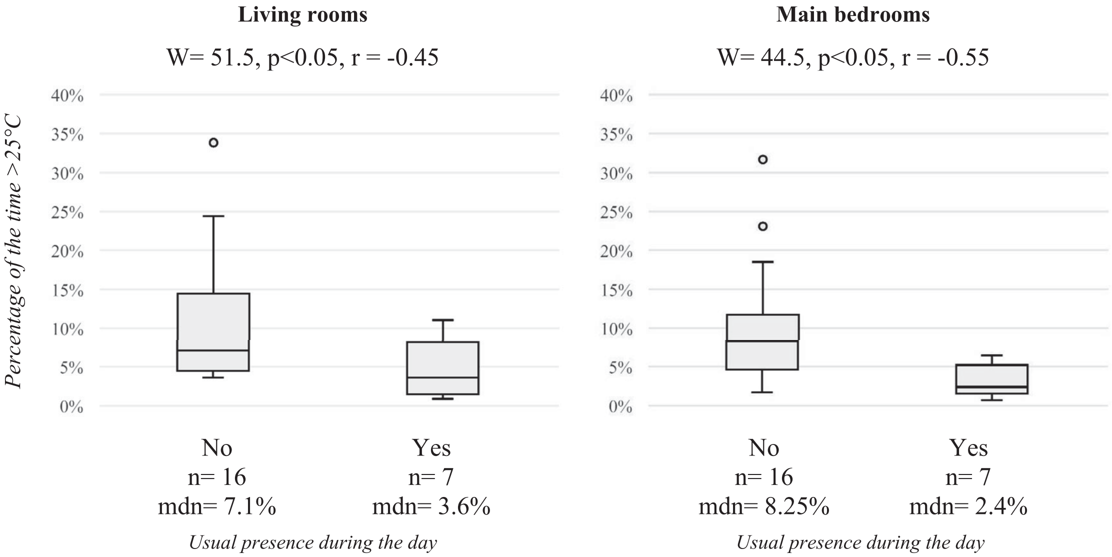

Figure 23. Impact of daytime presence of the occupant on percentage of time exceeding 25°C.

orientations, etc.), hence suggesting some design considerations that might go beyond the unique installation of protection systems. Ventilative cooling by windows opening is frequently practiced by occupants (Figures 7 and 8) and was evident in around 70% of cases. This strategy appears, however, as a reactive response to perceived discomfort and not as a measure to prevent it. Figure 12 shows, in fact, a statistically significant higher rate of overheating complaints when ventilative cooling is practiced. Figure 19 confirms that cases where windows opening is practiced in the living room present a slightly higher percentage of time over 25°C than the other cases. Night windows opening seems generally less practiced in the living rooms (only 11% of the cases for living rooms of sample S1 compared to 40% for the bedrooms). The reasons behind these differences, possibly those such as protection against insects, noise, security, lack of knowledge about the efficiency, etc. (Tillson et al., 2013), have not been specifically questioned in this study, and should be explored more in depth in further studies. Again, this must take into account the linked components of social practices: competences, meanings and materials (Shove et al., 2012). Nevertheless, the positive impact of this strategy, which is taking advantage of low outdoor temperature at night to improve the efficiency of ventilative cooling, could be illustrated by Figure 20. In fact, the data collected shows that temperature during the occupancy time was moderately to largely impacted for the cases applying night ventilative cooling ($r = -0.32$ for bedrooms; $r = -0.61$ for the living rooms).

The effect of higher thermal mass was also analysed. More complaints about overheating were noticed in lightweight buildings than in the other cases (small effect, statistically significant) but the effect on temperature exceeding 25°C for subsample S2 was not so evident (Figure 21). This observation could be explained by the thermal behaviour of lightweight buildings (e.g. wood frame), which are known to increase/decrease more rapidly their indoor temperature due to their lower thermal capacity (Staepels et al., 2013). The impact of higher thermal mass depends, in fact, on several other dynamic parameters, such as, accessibility of thermal mass, presence of furniture (Johra et al., 2017), ventilation schedule (van Hooff et al., 2015), occupancy schedule, etc. Based on literature, the effectiveness of thermal mass in maintaining acceptable summer thermal conditions in residential buildings, can also substantially vary, depending upon climate patterns (Verbeke & Audenaert, 2018).

Nevertheless, it is commonly recognized that the combination of a higher thermal mass with other passive strategies, especially ventilative cooling, can considerably improve summer thermal comfort (Sorgato et al., 2016). This could not be detected in the studied samples, as the combination of strategies such as solar shading presence, practice of ventilative cooling and masonry construction type, etc. only provided a small decrease of temperature. This decrease was statistically non-significant for the bedrooms of subsample S2 (Figure 22) and did not lead to a lower rate of reported discomfort (Figure 14). The simple provision of environmental controls, even if increasing the occupant's adaptive capacity (Adekunle & Nikolopoulou, 2016), was not found sufficient to guarantee summer thermal comfort.

These findings lead to question the operation of passive control strategies by occupants. Even if occupants declare practicing ventilative cooling, do they open the windows adequately to provide effective ventilation that allows for the discharge of accumulated heat in the buildings? Do they open the windows when outside temperatures are lower than inside? Do they effectively close the windows when outdoor temperatures exceed indoor temperatures? Results of Figures 7 and 12 – respectively showing that windows opening in living room is practiced only mainly during the day of sample S1 (Figure 7), and that the opening is often practiced in response to a perceived discomfort (Figure 12) – suggest the contrary. Similar questions could be asked regarding the use of solar shading, such as whether the solar shadings were placed adequately for each glazing or whether they were preventively operated each time the sun hit the building façade. The small proportion of external shading devices installed (Figure 4) and the availability of automated controls (Figure 5), again, suggest the contrary. This reinforces the conclusions of previous studies showing that occupants' actions are key factors to avoid overheating (Ozarisoy & Elsharkawy, 2019), although occupants might not always make proper use of passive strategies in dwellings (Kuczyński et al., 2021).

Modes of operation appear, therefore, to be as important as the technical characteristics of the devices themselves. Figure 23 shows that the presence of the occupant during the day can limit the percentage of time when temperature exceeds 25°C. For all these cases, at least the living rooms were equipped with solar shading, and all the occupants declared practicing ventilative cooling. This suggests that these environmental controls should be operated continuously, or in a preventive way, in the absence of the occupants during the day, to avoid the accumulation of heat inside these highly insulated buildings. However, the presence of the occupant during the day does not lower the frequency of overheating complaints (Figure 15), this, reinforcing the finding that environmental controls are more often operated when the discomfort is already perceived (Figure 12) as previously suggested. This phenomenon has recently been described, where the 'time lag' of behaviour occurrence regarding the operation of solar shading in office buildings was introduced and quantified (Li et al., 2022). Things could be more complex in the context of residential buildings, where the occupant could be away for part of the day, not occupying the specific room where an operation: such as closing a solar shading, could be beneficial. Alternatively, the occupant could simply not be able to operate the environmental control, such as, in the case of elderly people (Kuczyński et al., 2021). More research on how environmental controls are operated in residential buildings is thus needed. That would imply the collection in much higher detail, of the habits of the occupants regarding the moment, frequency and duration of opening/closure that was done in the present study.

In the context of generalized development of smart buildings (European Parliament, 2018), the integration of Internet Of Things (IOT) in buildings (Kumar et al., 2021) has certainly the potential to help the occupant in properly acting on environmental controls, or to improve and optimize their operation. Connected devices could sense the correct parameters at the right time and place and, on this basis, actuate the right response. Alternatively, these devices could adequately inform the occupant to manually intervene in a preventive manner. However, only a small proportion of automatized systems were found in this study (Figure 5). Understanding the barriers inhibiting a better implementation of automatized systems seems necessary. Again, this needs to integrate all the components: competences, materials and meanings, that influence the related social practices. This must also consider all the actors intervening in the decision-making process, such as: end users, designers, contractors, manufacturers, regulators, etc. Also, selecting the adequate mode of operation of environmental controls, such as, manual, automatized, fixed, etc. requires a more thorough characterization of the occupants' profiles, needs and preferences. This as a key determinant to prevent overheating risk in residential buildings and should be included in energy standards (European Parliament, 2018).

Conclusions

In temperate climates, a combination of solar shading devices with ventilative cooling via windows opening, are key passive strategies for ensuring summer thermal comfort in residential buildings. Their combined effect towards controlling solar gains and dissipating the heat accumulated in the building, has been demonstrated to prevent overheating risks (van Hooff et al., 2015), to limit the need of active cooling (Yang et al., 2021) and to facilitate the use of more sustainable cooling systems based on low enthalpy (BBRI, 2022).

Based on a cross analysis of qualitative (survey) and quantitative (measurements) data collected in a sample of 147 highly insulated houses, this study has shown that the implementation of these techniques is not yet sufficient to reduce the risks of summer thermal discomfort in highly insulated residential buildings in Wallonia, Belgium. It is therefore crucial to understand barriers that inhibit a more effective integration of these environmental controls. The study also questioned the proper operation of these strategies that, in highly insulated buildings, is probably as important as the characteristics of the devices themselves. Proper control of passive strategies should anticipate the occurrence of discomfort, rather than being motivated by it. In a context of Internet Of Things and smart buildings development (Kumar et al., 2021), automatized systems could probably be part of the response to this challenge. If barriers for implementing smart and active technologies need further investigation, this study suggests that the choice of an appropriate operation system must be occupant-centred (O'Brien & Tahmasebi, 2023). That is, operational choices such as fixed, automatized or manual mode must correspond to the effective needs and possibilities, and should be based on the accurate characterization of the occupant's needs, preferences and profile: such as, absence during the day. This should go alongside a more thorough understanding of the components (competences, meanings, materials) upon which social practices rely for each group of actors intervening in the decision-making process: end users, designers, contractors, manufacturers, regulators. Also, in temperate climates, these are key determinants for reducing the overheating risks in residential buildings and limit, in the future, the diffusion of active cooling with their induced environmental impacts.

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