Unpacking Overheating Risks Through Exposure Duration

A demonstration of the effect of construction type in future climates

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ABSTRACT: This paper demonstrates how the examination of overheating exposure duration could complement the existing overheating risk assessment approaches by contributing information that are useful to the investigation of thermal health. A simulation study on the effect of different construction types and façade orientations in a typical London dwelling under five climate scenarios is conducted. The results suggest that an uninsulated timber frame construction is not only more overheated than a masonry cavity construction, but specifically it becomes more overheated by sustaining more continuously overheated intervals (COI) that are longer lasting and more severe in the current and every future climate scenarios. The timber frame construction also has more such intervals that extend into nighttime. A north-facing orientation is also beneficial in curtailing overheating, but the combined effect with the masonry construction is found to be the most effective in reducing the aggregated number of overheated hours as well as in minimising the number of intervals. However, a persistent level of overheating is found to extend into the nighttime and increase steadily with the warming climate regardless of construction types or façade orientations.
Keywords: overheating risks, thermal health, exposure duration, climate change, thermal mass

INTRODUCTION

In recent years there have been more and more occurrences of record high temperature, hot spells, and heat waves. With IPCC's prediction of worldwide increase in the frequency and magnitude of warm daily temperature extremes as well as a rise in overall mean temperature [1], it is clear that overheating in buildings is rapidly becoming a global concern for its impact on occupants' health. In just the past decade, the International Disaster Database has collated a record of more than 150,000 deaths due to heat waves worldwide [2]. Even for high-latitude places with relatively cool summers like the UK, a mortality risk attributable to heat exposure has been clearly identified [3, 4]. In fact, a London study covering data from 1976-1996 has found that a rise in heat-related deaths begins at an average temperature as low as 19˚C [4]. The escalating and far-reaching warming trend is particularly worrisome for the growing ageing population, who are more vulnerable not only because of their more fragile physiological state, but also because of social risk factors such as living alone, lack of mobility, and having fewer social contacts [5, 6].

Despite a plethora of epidemiological studies investigating heat-related morbidity and mortality based on the outdoor environment, there remains a knowledge gap of the link between health consequences and an overheated **indoor** environment [5]. This warrants concern particularly because existing overheating risk assessment approaches for buildings are primarily comfort-based. Specifically, they tend to focus on establishing a boundary of thermal acceptability and using it to make a binary judgement on whether a space is overheated or not. This imparts little information on how overheating unfolds over time as the judgement is based on aggregated numbers of overheating occurrences. For example, the CIBSE summertime overheating criteria deems a space or a room 'overheated' when more than 1% of the total occupied hours in a year have exceeded 28˚C (or 26˚C for bedrooms) [7]. The British/European Standards (BSEN15251) also specifies that no more than 3-5% of the total occupied period should exceed the adaptive upper limits (T_{limit}) (see METHOD section for further details on T_{limit}) [8].

While people may be more likely to experience thermal discomfort due to short hot periods because they would not have had the opportunity to adapt psychologically or behaviourally [9], prolonged heat exposure is more likely to overwhelm the body physiologically even without the occupants' active awareness such as during sleep [5, 10]. In fact, research has shown that not only does prolonged overheating contribute additional mortality risks on top of simply being overheated, but those risks also increase proportionally with the length of exposure [11]. Therefore, the length of time one remains exposed to an overheated environment, namely the **overheating exposure duration**, is consequential to thermal health and should be examined alongside overheating occurrence and severity. But this particular aspect of overheating cannot be gleaned from the existing approaches. Using a simulation study on the effect of different construction types on overheating in a typical London dwelling under five climate scenarios, this paper demonstrates how the analysis of overheating exposure duration can contribute additional information that is useful to the investigation of thermal health.

METHOD

A typical three-storey London mid-terraced dwelling (Fig. 1) of the age band 1967-1975 was digitally modelled and dynamically simulated in IES-VE (v. 6.4.0.7). Physical building attributes were based on information available from the English Housing Survey (EHS) 2010 Housing Stock Data [12]. It is assumed that the dwelling has glazing on the north and south facades and is surrounded by other terraced dwellings of equal heights. Additional details required for simulation were determined at the authors' discretion, with values and assumptions taken from or calculated according to SAP 2009, CIBSE Guide A, and ASHRAE Fundamentals [13, 7, 14]. The dwelling is assumed to operate in free-running mode during the non-heating season (May-September, henceforth referred to as 'summer'), allowing windows to open for natural ventilation whenever the recommended indoor temperatures for summer (25˚C for living spaces and 23˚C for bedrooms) were exceeded and the outside air temperature was cooler than the inside [7].

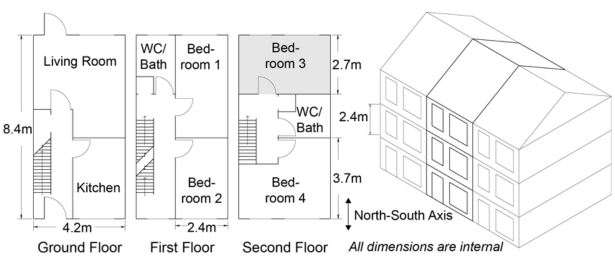

Figure 1: Plans of the case study dwelling.

As the main purpose of this paper is to illustrate an additional way of analysing overheating risks that complements the existing approaches, the effect of construction type was investigated only via a comparison between two thermally distinctive constructions of the dwelling for demonstration purposes. Specifically, this means that the dwelling was modelled first with an uninsulated masonry cavity wall (0.25m) construction, concrete floors/ceilings, and block internal partitions; then with an uninsulated timber frame wall (0.27m) and floor construction, while keeping all other specifications the same. Both constructions have a tiled roof with 100mm of insulation and double-glazed windows. In order to further thermally differentiate the two construction types, modifications were made to maximise the availability of thermal mass in the masonry construction, such as omitting the carpets and gypsum plasterboards. Table 1 lists the U-values for individual building elements for both the masonry cavity and timber frame constructions. The authors recognise that variations of masonry cavity or timber frame constructions will have different U-values and that different amount of thermal mass applied to different surfaces will produce different results. Sensitivity analysis addressing these issues will be investigated separately elsewhere.

Both constructions were then simulated under the current (1961-1990) and four future climate scenarios for London Heathrow: 2030 A1B, 2050 A1B, 2080 A1B, and 2080 A1FI by using the design summer year (DSY) weather files downloaded from the PROMETHEUS Project website [15]. Files used for the future climates all represent the 50th percentile of external temperature under the medium (A1B) or high (A1FI) emission scenarios. For each climate scenario, both dwelling constructions were simulated first with the living room facing south then with the living room facing north. This allows a comparison not only of two thermally distinct construction types but also of two different façade orientations.

Table 1: Case study dwelling construction U-values (W/m²k).

	Masonry Cavity	Timber Frame
External Wall	1.6	0.8
Party Wall	1.7	0.4
Internal Wall	2.1	0.7
Doors	3.0	
Windows	2.8	
Floor/Ceiling	2.0	1.2
Ground floor	0.4	0.5
Roof	0.4	

The hourly operative temperatures (T_{op}) for the summer season of all bedrooms and the living room in the dwelling were evaluated. For demonstration purposes, only the results of Bedroom 3 (shaded in Fig. 1) on the second floor with approximately 3.6m^2 glazing area will be presented and discussed here. As a thermal health-oriented overheating risks assessment approach is particularly relevant for the aging population who are more susceptible to heat stress as previously mentioned, Bedroom 3 is assumed to be occupied by, and therefore assessed with respect to, this vulnerable type of occupant. Young children and those who are ill are also considered to be vulnerable occupants. The room is assumed to be occupied for most of the day with a 9-hour period between 10pm to 7am designated as nighttime where sleep is the main activity in the room.

The data were analysed in two stages. An existing assessment approach per BSEN15251 was taken in the first stage. Individual hourly operative temperatures (T_{op}) data points were evaluated against an upper limit temperature (T_{limit}) and the room was determined to be overheated or not based on the percentage of the total occupied hours that have exceeded T_{limit} during the entire summer. A conservative benchmark of 3% (instead of 5%) was chosen for this study. In effect, T_{limit} is not a static threshold, but rather an adaptive upper limit that changes daily and is calculated based on the running mean of the outside temperature. As the focus for the present study is on vulnerable occupants, T_{limit} was computed according to the equation for Category I as outlined in BSEN15251 [8], which provides the strictest (lowest) upper limits on account of vulnerable occupants' heat sensitivity and limited adaptive capabilities. Furthermore, since T_{limit}

varies with the outside temperature, a separate set of T_{limit} was calculated for each climate scenario. This is assuming that the adaptability of occupants will increase with the warmer future climates.

In the second stage, the data were examined in terms of overheating exposure duration. This means that the same hourly operative temperature (T_{op}) data were combed for **continuously overheated intervals** (COI), an approach that was first introduced by the authors in [16]. Specifically, this approach parses the total number of hours where T_{limit} has been exceeded into several discrete intervals (Fig. 2). As a result, instead of having a single number to represent the total aggregation of hours where T_{op} exceeds T_{limit} over the entire summer, the interval approach will render several COI, or stretches of time within each T_{op} is continuously above T_{limit}. It follows that each COI has a specific duration (length of time in hours) and a specific severity (integral of the exceeded amount of degrees (K) for the duration of the interval, represented by individual shaded regions in Fig. 2) associated with it. These individual interval durations and interval severities (in degree-hours, K-hr.) provide two additional means to examine overheating risks.

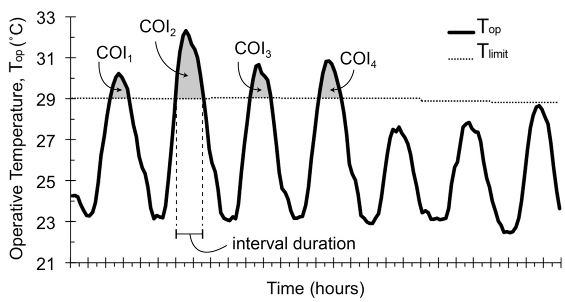

Figure 2: A sample of hourly operative temperature (T_{op}) data for 7 days with a total of 31 hours where T_{op} exceeded T_{limit}. This breaks down into 4 continuously overheated intervals (COI) each at 6, 10, 7, and 8 hours long, respectively.

To summarise the present study: overheating risk is assessed in two stages – first via an existing approach (BSEN15251) that determines whether the bedroom is overheated or not, followed by an interval approach that unpacks the overheating risks via continuously overheated intervals (COI). The results for the uninsulated masonry cavity construction are compared against those for the uninsulated timber frame construction for two orientations (south and north) under five climate scenarios.

RESULTS AND DISCUSSION

While all hours of the day were considered in all assessments, the nighttime hours (10pm-7am) were highlighted for further comparison. This is done to emphasise the additional or arguably more important detrimental effect nighttime overheating can have as suggested by many epidemiological studies [e.g. 4, 5]. Although one might expect the highest temperatures to occur during the day and therefore deem daytime overheating of the utmost importance, it is in fact the lack of nighttime relief from daytime overheating and the limited range of adaptive opportunities available while one is asleep that make nighttime overheating particularly worthy of further analysis. In all subsequent figures, black borders are drawn around nighttime hours and continuously overheated intervals (COI) that occur entirely or partially into the night.

The results from the first stage of analysis via the existing approach (Fig. 3) show generally increasing overheated hours with each future climate, as expected. But curiously, there are slightly more overheated hours in 2030 than in 2050 for the south-facing masonry construction, and comparable number of overheated hours for the north-facing timber frame construction.

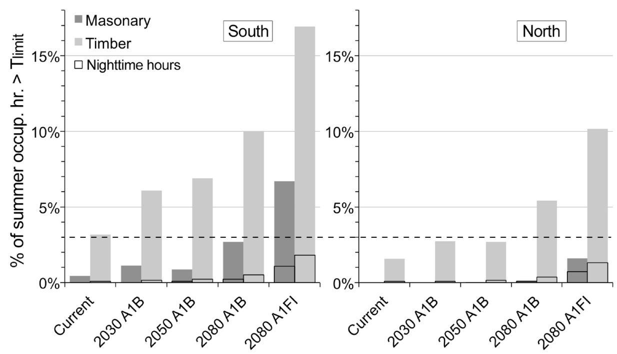

Figure 3: Comparison of percentage of summer occupied hours exceeding T_{limit} between masonry and timber constructions by façade orientation.

More importantly, Fig. 3 shows that there are considerably fewer overheated hours in the uninsulated masonry cavity construction, such that the bedroom remains under the 3% threshold all the way through 2080 regardless of orientation. The only instance where the room is deemed overheated (exceeding 3%) is when facing south and under the 2080 high emission (A1FI) scenario. This is not surprising as the masonry construction has substantial thermal mass to reduce the level of overall heat flow into the room despite its external walls are slightly thinner and with higher thermal transmittance (U-values).

The timber frame construction, on the other hand, exceeds the 3% threshold when the bedroom façade is facing south under every climate scenario, including the current climate (by 0.2%). Even when the bedroom façade is facing north, the amount of overheated hours comes close to or exceeds the 3% line in all but the current climate. In fact, the difference between construction types is so striking such that the south-facing timber frame construction in the current climate has more overheated hours than the south-facing masonry construction in the 2080 A1B scenario. Even when facing north, the timber frame construction in the current climate still has about the same amount of overheated hours as the masonry construction in the 2080 high emission (A1FI) scenario. The effect of the façade orientation is also strong, such that the south-facing timber frame construction in the current climate has more overheated hours than the same construction facing north in 2050.

As the juxtapositions of construction types and façade orientation illustrate, there are clearly far fewer overheated hours when the dwelling is of masonry cavity construction and when the bedroom is facing north. The effects are the most prominent when all hours of the day are considered. When only the nighttime hours (black bordered in Fig. 3) are considered, however, the effects are much less pronounced. In fact, neither construction types in north or south orientation incur 'enough' overheated hours to go over the 3% threshold in any of the climate scenarios. But more importantly is that for nighttime hours, the difference due to construction type or façade orientation is less noticeable than the difference due to future climates. Specifically, while both the timber frame construction and south-facing orientation still incur more overheated hours, the nighttime hour increase is not so much that they overtake their counterparts across further future climates. For example, the south-facing timber frame construction in 2050 has more total (both day and night) overheated hours than does the masonry construction of the same orientation in not only the same climate scenario, but also in 2080 A1B and A1FI scenarios. However, the portion of overheated hours occurring at night for timber in 2050 only exceeds those for masonry in the same climate and not for either emission scenarios of 2080. This suggests that nighttime overheating may become a persistent problem under future climates across even thermally distinct construction types and diametrically opposite façade orientations.

It should be noted that in this study, windows (there are two in Bedroom 3) were set to open throughout the entire day whenever the condition as previously described was met. This is obviously idealistic as the actual operation would differ based on a variety of reasons. Specifically, windows may be open during inopportune times such as when the outside is actually hotter than the inside, or not at all when the occupant is asleep or simply unwilling due to safety or noise concerns. But it is this best-case scenario simulation setting that makes the lack of pronounced nighttime difference between construction types and façade orientations that much more worrisome. Essentially, the situation presented in this study is such that even when allowing ventilation cooling whenever possible, a certain level of overheating will persist during the night and increase with the warming climate regardless of (or with little effect from) the construction types or façade orientations.

As aforementioned, the overheated hours presented in Fig. 3 are **aggregated** for the entire summer. Without knowing how these overheated hours occur relative to one another, it is easy to assume that the overall overheating situation is due to an accretion of isolated extremes (e.g. 1-2 hours), perhaps daily maximums, that occur throughout the entire non-heating season (5 months). However, the second stage of the analysis using the continuously overheated interval (COI) approach shows that in fact overheated hours occur in clusters.

The assessments done using the COI approach can be analysed by interval durations (Fig. 4) and by interval severities (Fig. 5). Intervals that occur entirely or partially during the night are marked by black borders. Both sets of results echo what the previous stage of analysis has shown, such that warmer climates generally cause more overheating in the form of more continuously overheated intervals that last longer and are more intense. The COI approach also confirms that the masonry construction and north-facing orientation incur less overheating than do their counterparts. However, the breakdown of the intervals by their durations and severities reveals more nuanced differences between the construction types and façade orientations.

First, while the number of intervals generally rise with the warming climates, the most pronounced increases are seen in intervals lasting 7-12 hours continuously, particularly for the south-facing timber frame construction (Fig. 4). While the number of intervals lasting 1-3 hours and 4-6 hours changes very little in all future climate scenarios, the number of intervals lasting 7-12 hours increases significantly: by 4 intervals from current to 2030, by 5 from 2030 to 2050, by 19 from 2050 to 2080, and by 21 from 2080 low (A1B) to high (A1FI) emission scenario. A similar but subtler increase pattern is seen when the bedroom faces north.

Second, whilst the masonry construction has significantly fewer overheated hours than does timber frame construction in both orientations (Fig. 3), the overheated hours that occurred, however few, still occurred **consecutively** in the form of continuously overheated intervals (COI), many of which lasting more than 3 hours (Fig. 4). For instance, when the bedroom is facing north, a total of seven intervals were identified under the 2080 A1FI scenario. However, only three of which were of 3 hours long or shorter; the remaining four lasted 10, 16, and 17 hours long with three of them extending into the nighttime. While these few intervals still may not be a cause for concern, their sheer duration (more than half of a 24-hr day and extending into the nighttime) in fact presents a more pressing overheating risk. This is because these intervals represent concentrated 'doses' of potentially health-threatening heat stress rather than an aggregation that may be composed of less consequential and isolated overheated hours.

Third, while generally more intervals of longer lengths are found as the climate becomes warmer for both construction types and orientations (Fig. 4) the breakdown of intervals by their degree-hours (K-hr.) (Fig. 5) suggests that the individual severities of these intervals are more varied. In all cases it is the lowest severity category (< 5 K-hr.) that has the most numerous intervals, suggesting that at least some of the longer intervals seen in Fig. 4 are continuous 'low-grade' overheating. Nevertheless, as studies have shown that heat-related adverse health effects can occur even at low temperatures [4], low-severity continuously overheated intervals (COI) should still be heeded if their durations are long. More importantly, the breakdown of interval severities in Fig. 5 is able to illustrate the effect of construction types and façade orientations more plainly.

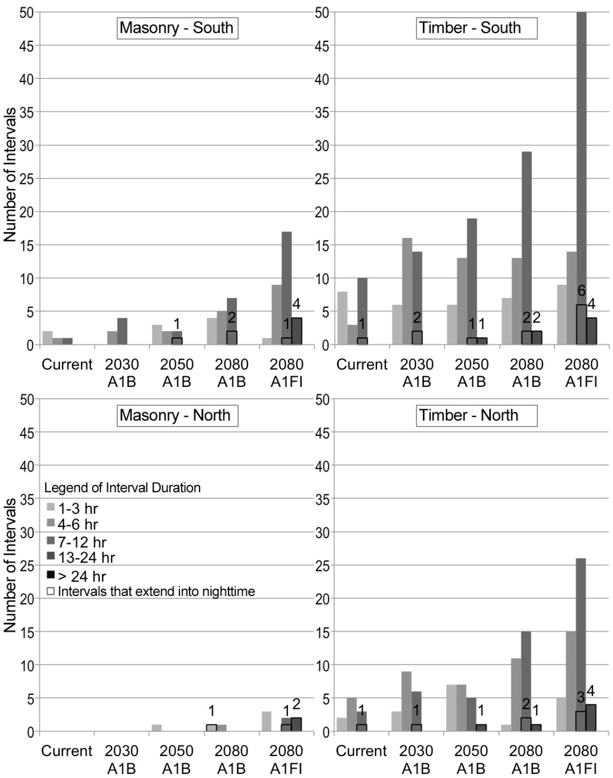

Figure 4: Assessment results in terms of continuously overheated intervals (COI) by interval durations.

Formerly Fig. 4 shows that the masonry construction and north-facing orientation incurred fewer continuously overheated intervals (COI) than did their counterparts for most lengths of interval duration in all climate scenarios. Fig. 5 further illustrates that the masonry construction incurred fewer intervals of all severity categories when compared to the timber frame construction. Specifically, the south-facing masonry construction has fewer intervals of medium- to high-severity categories (> 5 K-hr.) and the north-facing masonry construction has fewer intervals of all severity categories. This difference between façade orientations within the same construction type is not present for the timber frame construction, however. While the north-facing timber frame construction also incurred fewer intervals of medium- to high-severity categories (> 5 K-hr.) when compared to its south-facing counterpart, the number of intervals at low severities (≤ 5K-hr.) was not reduced as markedly by changing the bedroom orientation from south to north. In fact, in the 2050 climate, the north-facing timber frame construction actually has more intervals at low-severity category (≤ 5K-hr.). This suggests that, in the context of this study, while the masonry construction with substantial thermal mass (and ventilation cooling) is less likely to cause overheating than does the timber frame construction, this difference in construction type alone (whether on account of the thermal mass or the U-values or both) is not enough to curtail low-grade overheating, which can only be achieved in concert with a north-facing orientation.

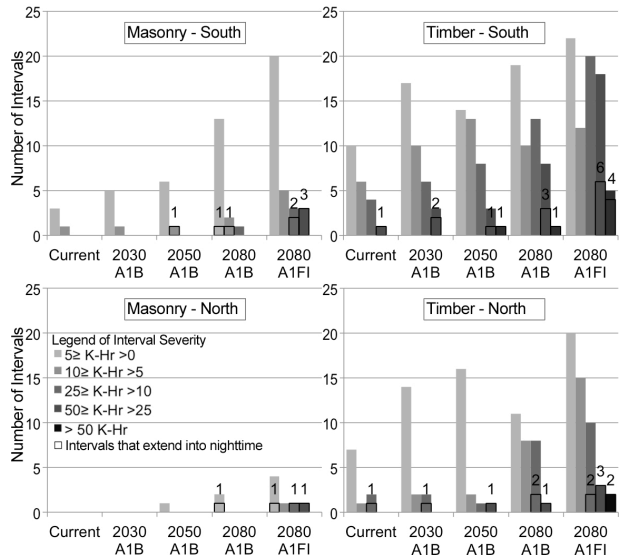

Figure 5: Assessment results in terms of continuously overheated intervals (COI) by interval severities.

Fourth, similar to what was seen previously in Fig. 3, while there are appreciable differences between construction types and façade orientations when considering all intervals (intervals that occur anytime of the day), the differences are less prominent for intervals that occur either entirely or partially into the night (black bordered in Fig. 4 and 5), albeit there are less intervals for comparison to begin with. But worth noting is that these nighttime intervals all tend to have long durations (at least 7 hours and up to 24 hours long) as well as high severities (with some having more than 50 K-hr. within one interval). This is especially worrisome as the nighttime is when the vulnerable occupants may be even more susceptible, particularly if they have experienced several hours of overheating during the day already. Most importantly, these nighttime intervals, however few of them, can be easily overlooked because they are well under the 3% threshold in the aggregated assessment (Fig. 3) in all climate scenarios.

CONCLUSION

This paper demonstrated how the examination of overheating exposure duration could complement the existing overheating risk assessment approaches by contributing information that are useful to the investigation of thermal health. Specifically, the analysis of continuously overheated intervals (COI) not only confirms the findings from the existing assessment approaches, but it also unpacks aggregated overheating risks so that the way overheating unfolds becomes more transparent.

Within the limited scope of this paper, the simulation study results suggest that the timber frame construction is not only more overheated than a masonry cavity construction as seen in Fig. 3, but specifically it becomes more overheated by sustaining more continuously overheated intervals (COI) that are longer lasting (Fig. 4) and more severe (Fig. 5) in the current and every future climate scenarios. The timber frame construction also has more such intervals that extend into nighttime. While a north-facing orientation is also beneficial in curtailing overheating, the combined effect with the masonry construction is found to be the most effective not only in reducing the aggregated number of overheated hours, but also in minimising the number of continuously overheated intervals (COI).

Although the presence of thermal mass in the masonry construction contributes to an overall reduction of overheating, the higher heat capacity of the thermal mass also delays the heat transmittance, leading to a few but seemingly unremitting nighttime intervals that can be particularly harmful to the vulnerable occupants. Furthermore, these nighttime intervals increase steadily with the future climates with less influence from the construction types and façade orientations. This suggests that while there may not be enough of these nighttime intervals to warrant the same kind of concern deserved by the more numerous daytime-occurring intervals, given more intense future climate patterns, continuously overheated intervals (COI) that extend into the night could possibly be harder to mitigate even via more involved measures like applying thermal mass, changing U-values, or even switching room façade orientation by moving occupants to another room.

In summary, the present study illustrated that the overheating situation can be complex and its assessment warrants detailed examination beyond a binary judgement especially in the context of future climates, which have their own inherent uncertainties. Follow-up studies will investigate more construction types and practical overheating mitigation measures such as insulation. More broadly, should future epidemiological studies be able to relate distinct interval durations and severities to specific physiological consequences, then the COI approach could be used to identify potentially health-threatening building stocks within a city or region and to select appropriate mitigation strategies to protect vulnerable occupants.

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