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HEAT WAVES AND THEIR IMPACT ON INDOOR ENVIRONMENTS: AN ASSESSMENT OF HUMAN BIOCLIMATE USING THE UTCI

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1. INTRODUCTION

Heat stress is a serious risk to humans, especially in cities where the global increase in air temperatures is likely to be amplified through urban structures (Matzarakis; Endler 2010). Heat stress risks are manifold and well known. A significant increase in mortality due to heat stress has been shown by for example Almeida et al. (2013); D'Ippoliti et al. (2010); Gabriel; Endlicher (2011); McMichael; Haines (1997); Michelozzi et al. (2009); Smoyer et al. (2000); Ye et al. (2012) and further studies at the International Conference on Biometeorology. Analysis regarding heat stress and mortality/morbidity (McGeehin; Mirabelli 2001; Monteiro et al. 2013; Scherber et al. 2013) as well as impacts on human well-being (Kjellstrom; McMichael 2013) and on work performance (Lundgren et al. 2013; Witterseh et al. 2004) indicate a strong interrelationship too.

However, only a limited number of studies examine the role of indoor climates for hazardous atmospheric conditions (Pfafferott; Becker 2008). People in industrialized countries spend on average 90% of the day in confined spaces and hence the assessment of indoor heat stress is an important issue. In contrast to outdoor conditions, building characteristics and materials as well as heating or cooling systems influence indoor environments. Indoor thermal conditions in urban areas have been assessed by for example Mirzaei et al. (2012) and Beizaee et al. (2013) but they only focus on air temperature as the describing or forcing variable. However, important meteorological parameters to describe thermal conditions and hence heat stress are beside air temperature (Ta) also relative humidity (RH), air velocity (va) and the mean radiant temperature (Tmrt). Based on these variables are also thermal indices which are widely used to describe and assess human bioclimate. In total there are above 200 different indices worldwide including the recently developed Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012) which was used by Langner et al. (2013) to characterize indoor conditions and which is used in this study.

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The UTCI is based on a multi-node model of human heat transfer and temperature regulation developed by Fiala et al. (2012). Furthermore, an up to date clothing model takes into account the typical dressing behaviour under different thermal conditions. Developed by Havenith et al. (2012) it is representative for European and North American urban population in outdoor spaces. Bröde et al. (2012) provides a detailed description of the operational procedure to calculate the UTCI.

The present study aims to assess indoor heat stress by using the UTCI and focusses on its distribution in different buildings both on the spatial and temporal scale. Furthermore, possible driving factors of indoor heat stress are under investigation. The driving factors considered in this study can be divided into meteorological influences, building characteristics and user behavior.

2. METHODS

2.1 Study design

The measurements were conducted in five different buildings and a total number of 24 rooms in Berlin from the 1st of June to the 31st of August 2013 (92 days). The buildings differ in their usage and were constructed in various years (Tab 1). The investigated rooms in each building are located at different floor levels but are equal in size. 20 rooms are southwest orientated and 4 rooms northeast (indicated by N).

To estimate the average conditions per room, it was avoided to place sensors at locations where they may be influenced by direct solar radiation. All data were recorded at 5 minute intervals and then aggregated to mean hourly values. The UTCI calculations were done with the software program BioKlima (available from http://www.igipz.pan.pl /Bioklima-zgik.html). Measured levels of air velocity were mainly below the range of validity for the use of the regression function to calculate UTCI. According to Bröde et al. (2012), an air velocity of 0.5 m/s at a level of 10 m above ground is the lowest value that lies within the range of validity. Hence, values below this threshold as well as air velocity in rooms where no measurements were conducted were set to 0.3 m/s at the level of a person's body. At study sides were just Ta and RH was measured, the mean radiant temperature was set to air temperature, an assumption which was already used and explained in previous studies (Kántor; Unger 2011). A metabolic heat production of 135

Tab. 1 Overview of the measurement sides as well as their characteristics; indoor air temperature (Ta), indoor relative humidity (RH), indoor air velocity (va), indoor mean radiant temperature (Tmrt); in buildings where just Ta and RH was measured, Tmrt was set be equal to Ta and va was set to be 0.3 m/s; *partly enlarged in 2006

side	abbreviation	year of construction	room size (m^2)	room volume (m^3)	number of rooms/start	orientation of rooms	measured values
Office 1	OF1	2003	50.1	97	5 06/2013	southwest	Ta, RH, va, Tmrt
Office 2	OF2	1962	19.4	62	5 06/2013	southwest	Ta, RH va,Tmrt
School	SC SC*	1909 2006*	52.2 70.6*	208 211*	3/2* 06/2013	southwest	Ta, Tmrt=Ta RH, va=0.3m/s
Retirement home 1	RH1	2004	17.7	44	5 06/2013	southwest	Ta, Tmrt=Ta RH, va=0.3m/s
Retirement home 2	RH2	1993	21.5	55	4 06/2013	southwest	Ta, Tmrt=Ta RH, va=0.3m/s

W/m^2 was assumed for all UTCI calculations. The analysis was conducted using the software program R Version 2.15.1 (RCoreTeam 2012) and all measurements were registered in Central European Time (CET). During the study period three heat waves were recorded from the German weather service. The first and the second heat wave lasted 3 days (18/06-20/06; 26/07-28/07) and the third one 6 days (02/08-07/08).

Because of the fact that it is likely that users may interfere with indoor climate, the effect of behavior patterns was additionally investigated. Therefore, user behavior (ub) within the rooms was compiled in a simplified method due to lack of investigation possibilities. Each room was assigned one value of user behavior over the whole period of investigation. Classes range from 0 to 3 and are divided into no ub (0), limited ub (1), common (2) and preventive ub (3). In summary, increasing classes are equivalent to increasing possibilities or knowledge about reducing indoor heat stress.

2.2 Instrumental setup

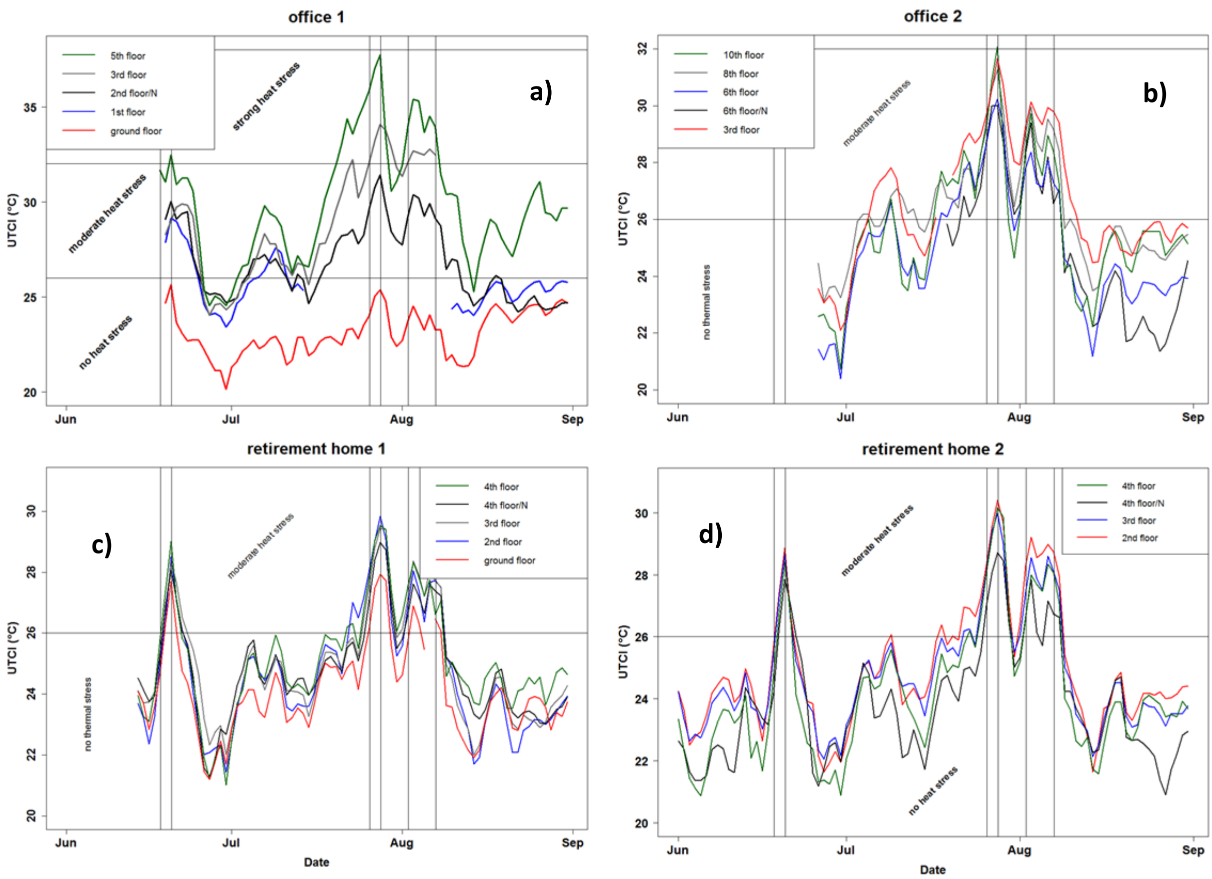
In the buildings office 1 and 2, air temperature, relative humidity, air velocity and mean radiant temperature were measured. To measure air temperature and relative humidity, each room was equipped with three Testo 174H loggers (accuracy of ±0.5 °C and ±3 %RH, respectively). Air velocity was derived by one PCE-009 hot wire anemometer per room (accuracy of ±0.5 %) and the mean radiant temperature through the use of one black globe thermometer per room (accuracy of ±0.5 °C; 150 mm in diameter; 0.4 mm thickness). The use of a globe thermometer gives a good approximation to the detailed integral radiation measurement (Bedford; Warner 1934; Kuehn et al. 1970). The sensors were fixed at a height of approximately 1.1 m above the ground, corresponding to the average height of the center of gravity for adults. Unfortunately, not all study buildings could be equipped with a full set of meteorological devices. The three remaining buildings were only equipped with three air temperature and relative humidity sensors (Testo 174H) per room.

3. RESULTS AND DISCUSSION

Within the study period, the mean UTCI values range from 23.1 ± 1.2 °C to 29.9 ± 3.2 °C. Mean maximum UTCI from 24.1 °C to 31.6 °C with peak values of about 39°C. Mean minimum UTCI data during night range from 22.2 °C to 28.4 °C with highest single values of about 36 °C. Table 2 shows the number of days with moderate (strong) heat stress levels and distinguishes between the total number and the number of days in consecutive order. All rooms under investigation, except for one, experienced heat stress during the heat waves.

3.1 Spatial and temporal distribution of heat stress

The highest heat stress levels were measured at OF1 (Fig 1a). At two days, UTCI maximum values at the 5th floor exceeded the 38 °C threshold for very strong heat stress with values of about 39 °C. In contrast, the room at the ground floor is the only room where no heat stress was measured during the whole summer due to a passive cooling system. As expected, heat stress increases with increasing floor level. The differences of UTCI between the rooms at the two retirement homes (Fig 1c,d) are similar. However, at RH2 heat stress decreases with increasing floor level. This deviation can also be seen at OF2 (Fig 1b). The basic conditions at the school (Fig 1e) differ from the other sides. Beside the rooms in the solid old building, two rooms are located in the 2006 enlarged top floor with different window sizes and wall constructions (indicated by



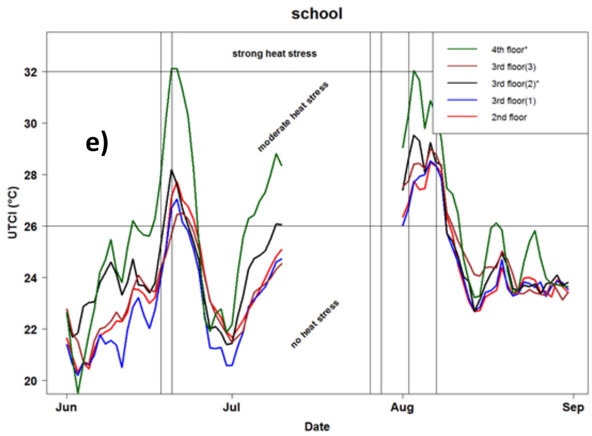


Fig 1. Mean UTCI values at all five study sides. Horizontal lines indicate the three heat waves. Vertical lines the different UTCI heat stress levels. N indicates rooms with northeast orientation.

Tab 2. Number of days with moderate heat stress at one room per study side; number in brackets indicates strong heat stress days; OF=office; RH=retirement home; SC=school

		OF1 5th floor	**OF2 3rd floor**	**RH1 4th floor**	**RH2 2nd floor**	**SC 4th floor**
hs days	total	67 (16)	31(-)	20(-)	23(-)	28 (3)
	consecutive	59 (9)	23(-)	9 (-)	17(-)	12 (2)

*). Mean UTCI in the new rooms (25.0 °C), exceeds the value in the old building part (23.8 °C) and indicate higher heat stress levels in recently constructed rooms. Internal mean UTCI variation between the rooms at the school and at the two residential care homes for the elderly varies just around 1 K (Fig 1 c-e). The two office buildings in contrast show noticeable differences of 4-7 K between the rooms (Fig1 a-b).

Over the course of the three heat waves, the five study sides experience heat stress at different levels and over different time spans. A time delay after the beginning and the end of the heat waves can be seen in all buildings. This lag-effect is mostly pronounced at the school after the first heat wave (Fig 1e) and can be traced back to user behavior and the characteristics of the building (compare 3.2.2). After the third event the lag-effect before and afterwards is less pronounced. The reasons for these alterations are already high UTCI levels before the heat wave and the onset of user behavior reducing indoor heat stress after the summer holidays. Table 2 shows for each building the numbers of days with moderate (strong) heat stress in the room where the highest UTCI values have been measured. It is distinguished between the total number and the number of days in consecutive order. Especially the latter one is

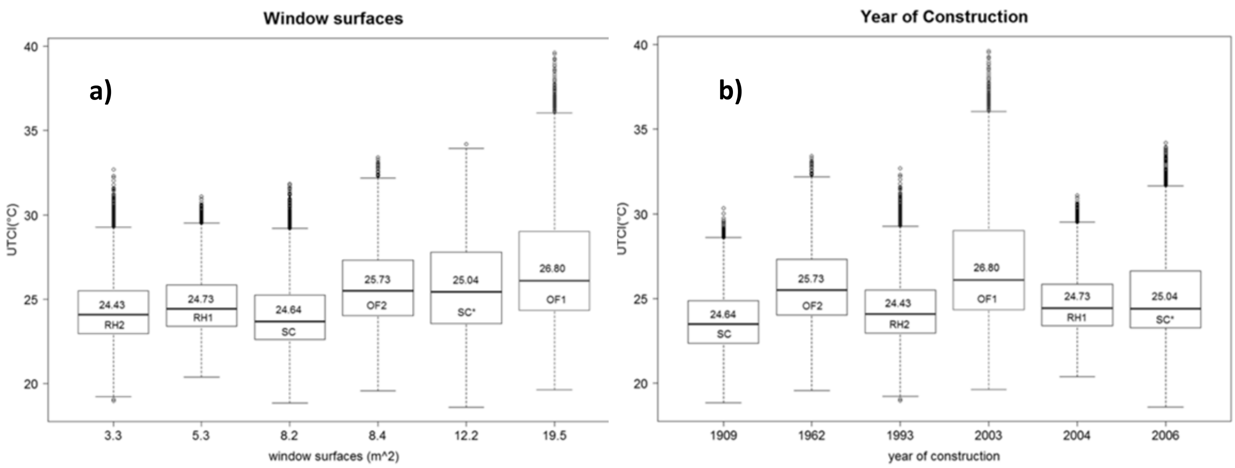


Fig 2. Influence of the building characteristics a) size of windows (m^2) and b) year of construction on the UTCI

important to consider in heat stress analysis due to a possible accumulation effect of heat stress (Parson 2003). Hence, the ability to cope with heat stress after a disturbed recovery phase at night is likely to decrease.

3.2 Driving factors of heat stress

3.2.1 Meteorological parameter

The influences of the meteorological parameters air temperature, relative humidity, radiation and air velocity on indoor climate and heat stress in particular have been well investigated. Indoor air temperature is mainly influenced by outdoor air temperature but its diurnal course is inhibited due to the physical characteristics of the building (Höppe 1993). Thermal radiative fluxes within enclosed environments are of a higher importance then solar radiation. However, when direct solar radiation enters a room through the windows, an additional thermal load needs to be considered (La Gennusa et al. 2005). The meteorological input of the UTCI embraces these parameters and additionally the relative humidity and air velocity. Bröde et al. (2012) analyzed the sensitivity of UTCI and concluded that air velocity and relative humidity influence the UTCI, but are of a minor importance than air temperature and mean radiant temperature. This outcome is confirmed by the results of this study. The correlation between UTCI and its input parameter showed 0.98 (p=0.01) for air temperature and mean radiant temperature and just -0.15 (p=0.01) for relative humidity. The measurements of air velocity shows a mean of 0.0 m/s with irregular peaks not exceeding 0.6 m/s and hence no correlation with the UTCI.

3.2.2 Building characteristics

To explain the variability within the buildings, UTCI values at different floor levels have been analyzed. The correlation between floor levels and UTCI over all measurement sides shows a very weak relationship (r=0.18, p=0.01). However, it is likely that the influence of floor level at one side is overlain by a small effect of another building. Hence, the sides have been analyzed separately. 5 of the 6 sides show a very weak correlation between floor level and UTCI at p=0.01. SC and RH1 showed positive results (0.24 and 0.17 respectively) and OF2 and RH2 negative ones (-0.07 and -0.23). The prefix corresponds with Fig 1 (b,d) where the lowest UTCI values can be seen at the highest floor levels and vice versa. OF1 in contrast shows a strong positive correlation (r=0.75; p=0.01). Based on the results it can be concluded that floor level has an influence on heat stress development but a general statement about the direction is not possible.

To investigate the reasons of the differences of UTCI between the buildings, the influence of the year of construction as well as the different sizes of window surfaces has been examined. The size of the window area showed a more pronounced influence on the UTCI compared to floor level (Fig 2a) but the correlation is still weak (r=0.30; p=0.01). Nevertheless, the tendency of higher UTCI values in rooms with a bigger window surface is visible. The two office buildings have the highest heat stress levels and concurrently the largest window surfaces. One exception is the school (SC) where two different window surfaces and two different years of construction appear. Build in 1909, the school consists of very thick solid stone walls. This type of wall has a lower heat transmission coefficient (~1.2W/m^2K) compared to for example glass (2.8-5.9 W/m^2K) (Schulze 2004) and the rooms within the building need hence more time to heat up and cool down. Hence, the rooms within the new part heat up more quickly and have higher pronounced daily cycles. Furthermore, UTCI values within the old part of the building (window size of 8.2 m^2) are lower compared to the new part (12.2 m^2).

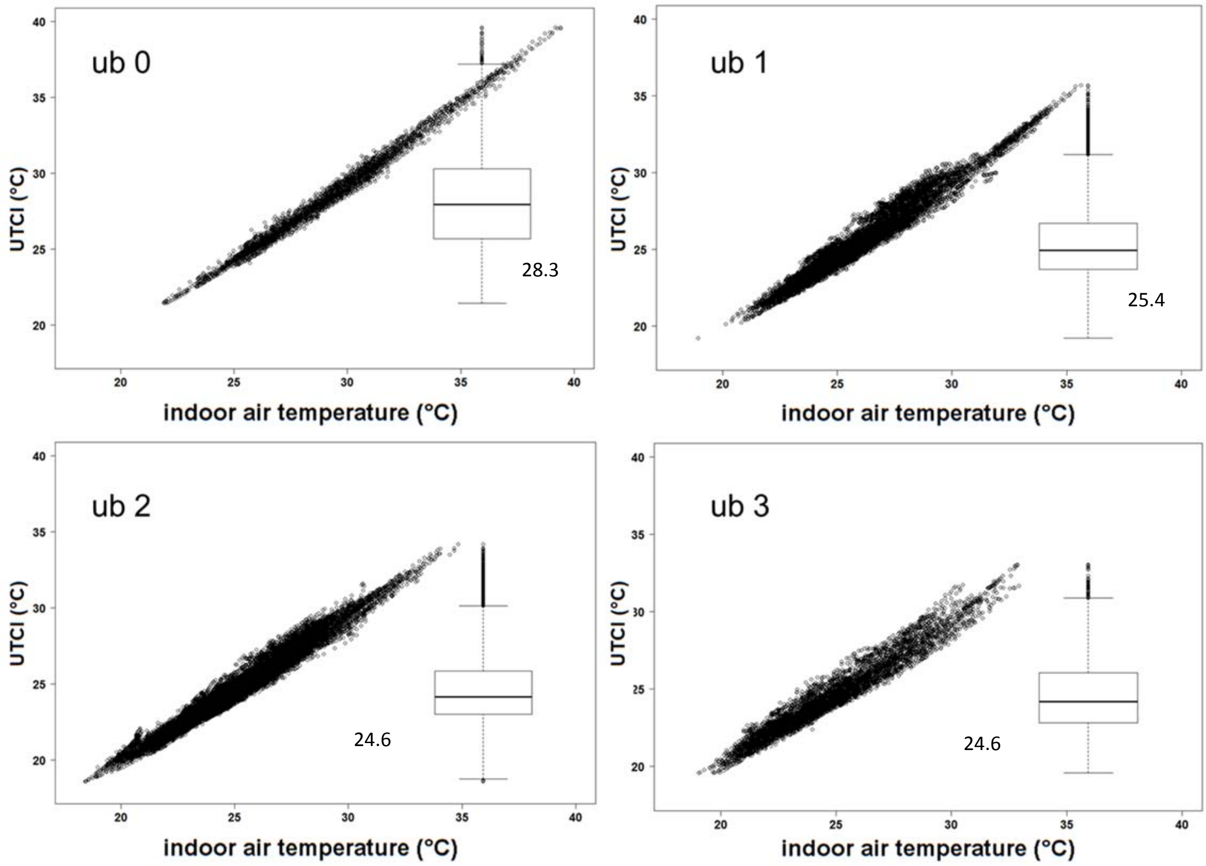


Fig 3. The influence of different user behavior patterns on the UTCI and indoor air temperature; the variance of UTCI is additionally expressed by a boxplot diagram; the number indicates the mean UTCI in °C

RH1 with a window area of 5.3 m^2 (Fig 2a) experiences higher heat stress levels than SC (8.2 m^2). This deviation can be explained again by the characteristics of the building. Beside the thick solid stone wall, the size of the room as well as the room volume is bigger than the other study rooms (Tab 1). Hence, the higher amount of solar radiation entering the rooms is dampened due to the lower heat transmission coefficient of the wall and the bigger air capacity. These characteristics lead to a compensation of the bigger window surfaces. The new part of the building (SC*) consists of bigger window surfaces than the old part but the room volume is almost the same. UTCI level are hence higher. These results confirm the achievements of 3.2.1 that the mean radiant temperature is beside the air temperature the main driving force of indoor climate and hence of heat stress. The correlation of UTCI with the year of construction shows a very weak positive relationship (r=0.17; p=0.01). The comparison of OF1 with RH1 underlines this result. OF1, constructed in 2003, experiences the highest heat stress within this study whereas RH1, constructed just a year later shows one of the lowest mean heat stress levels in all buildings (Fig 2b).

3.2.3 User behavior

Increasing heat stress with increasing floor levels has been observed at three study sides. RH2 and OF2 deviate from this average distribution, because the highest UTCI values are observed at the lowest floors and vice versa (Fig 1 b,d). To investigate these deviations, user behavior within the study rooms has been investigated. Figure 3 displays the UTCI and the main driving factor indoor air temperature at different levels of user behavior. The highest UTCI value (39.6 °C) is observed in a room with no user behavior (class 0) and the lowest ones in rooms where the person within the room has the possibility to interfere with the room climate (class 1-3). UTCI values at ub 0 show the highest range (18.2 K) and the biggest interquartile range (4.6 K). With increasing user behavior the range of the UTCI values decreases (ub 1: 16.5 K; ub 2: 15.6 K; ub 3: 16.5 K), indicating a positive influence of ub. Furthermore, the boxplot as well as the number in figure 3 shows that the mean of the UTCI decreases too.

However, it has to be mentioned, that the number of cases per class is unequally distributed (class 1=7; class 2=13) and very low in class 0 (2) and class 3 (4). Hence, the interpretation of the results has to be done with precaution. Nevertheless, the statistical outcomes correspond with the actual situation. As an example, a comparison within RH2 (Fig 1d) and OF1 (Fig 1a) is described. The resident at the lowest floor is bedridden (ub=1) and has hence no possibilities to interfere the room climate. Only staff can occasionally use measures to reduce heat stress. The person at the highest floor is mobile and aware of heat stress risks (ub=3). At the OF1 the lowest room is treated with a flexible passive cooling system (ub=3), whereas the office at the 5th floor, the highest floor, was not occupied during the measurement period (ub=0). The lowest UTCI values were recorded at the rooms with ub 3 and the highest ones in rooms with ub 0 or 1 (Fig 1a,d). An additional example of the possible influence of ub on indoor climate can be found at the school. The pronounced lag-effect after the first heat wave is likely to occur due to missing user behavior. Summer holidays started during the first heat wave and hence no measurements to counteract the indoor heat stress were taken during the event. As a consequence indoor thermal conditions lasted longer. After the third heat wave UTCI values decreased within a very short time period. During this period normal school days were in progress and hence user behavior.

In summary, it can be assumed that user behavior is likely to influence indoor heat stress but more detailed data are necessary to produce reliable results.

3.3 UTCI in indoor environments

The UTCI was originally developed for outdoor conditions and hence, the question may occur, why are we assessing indoor climate using this index. Jendritzky et al. (2012) describes the innovations of the UTCI compared to other thermal indices. The main advantages are Fiala's multi-node human physiology and thermal comfort model (Fiala et al. 2012) and a state of the art clothing model considering a behavioral adaptation of clothing insulation by the average urban population (Havenith et al. 2012). Aiming a standardize application in the main areas of biometeorology the UTCI should hence be adopted to make research results comparable.

Due to the fact that on average 90% of a day within industrialized countries is spent indoors, research recently started to focus on indoor climate and its assessment. Furthermore, indoor and outdoor climate are closely related and need hence to be compared to assess the thermal environment. The thermal index PMV (predicted mean vote) (Fanger 1973) was developed for indoor conditions but does imply significant shortcomings in relation to thermo-physiology and heat exchange theory (Jendritzky et al. 2012). Moreover, the outcome (7-point-scale) is not comparable to outdoor conditions and not plausible to lay people. Hence, there is a certain need to adapt the UTCI to indoor conditions to have a reliable assessment tool for indoor thermal environments.

Up to now and also valid for this study, the use of the UTCI in indoor environments has some limitations. First, the measured air velocity (v) is not within the range of validation for the UTCI calculation. v is only valid from 0.5 m/s to 30m/s at 10 m level (Bröde et al. 2012) whereas the measured values are within the range from 0.0 m/s to 0.7 m/s at body level. Based on the limits of validation the UTCI calculation program BioKlima set all values below this validation threshold to 0.5 m/s at 10 m level which corresponds to 0.3 m/s at body level (Bröde et al. 2012). This increase in air velocity possibly leads to an underestimation of heat stress as within the UTCI calculation higher v levels reduce the thermal load. Second, the activity of a person is defined at a metabolic rate of 135 W/m^2 (walking with a speed of 4 km/h). This value is far above average indoor levels, where a sitting position (55 W/m^2) is the main activity for most measurement sides. The determination leads likely to an overestimation of heat stress because of a higher internal heat production and hence a higher thermo-physiological model output.

4 CONCLUSION

In summary, the results indicate that indoor heat stress is a prevailing threat during heat waves throughout the day. People within the buildings are likely affected by heat conditions regarding thermal comfort and health issues, especially when they have no possibilities or knowledge about adaptation measures. Furthermore, the study confirms the previous findings that the meteorological parameters indoor air temperature and mean radiant temperature are the main driving factors of indoor climate. Building characteristics showed a significant influence. Nevertheless, the year of construction, floor levels as well as the size of the window surfaces vary in their influence and no clear conclusion can be drawn. The analysis of user behavior shows a possible influence on indoor heat stress. Immobile people are at higher risk to experience heat stress due to their limited adaptation possibilities. The highest values were observed in rooms with no user behavior. However, the results of the study are limited and a subsequent study will be developed. First, user behavior will be measured in a more detailed way and second, the UTCI calculation will be adapted to indoor environments.

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