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A literature review on findings from empirical studies**

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COMFORT AT THE EXTREMES 2024
INVESTING IN WELL-BEING IN A CHALLENGING FUTURE

Thermal and indoor air quality in dwellings in Europe during summer; a literature review on findings from empirical studies.

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Abstract

Changing outdoor conditions, i.e. higher outdoor air temperature, higher occurrence of heatwaves and outdoor air pollution, increase the risk of overheating and accumulation of air pollution in homes. Previous studies showed that high indoor air temperatures and air pollution affect occupants' health, resulting in cardio-vascular and respiratory diseases, eyes and skin symptoms, and mortality. Measures to increase energy efficiency of renovated and newly built homes can further increase health risks during extreme weather events and can increase the outdoor temperature. Moreover, the rise of the outdoor air temperature in Europe is higher than the global average.

Therefore, understanding of the extent of current overheating and indoor air pollution and of the contributing factors is necessary to identify the required adaptability of dwellings in Europe to changing outdoor conditions. The objective of this study is to systematically review consequences of changing outdoor conditions, building characteristics, and technology on the indoor environment and occupants' health in homes in European countries during summer.

This review focuses on empirical studies, as these enable to capture real world interactions of occupants and buildings in relation to outdoor conditions. Varying outdoor conditions, building-, and occupant-related aspects in different European climate zones are discussed. Main findings are that overheating already occurs in normal summers in temperate and northern European countries, while variation in overheating is related to occupants' adaptive behaviour and building-related aspects. Based on the review, it is suggested to investigate adaptability of dwellings to changing occupants' needs, new energy efficient technologies, and changing outdoor conditions.

Keywords

Dwellings; overheating; indoor air pollution; health; adaptability

1. Introduction

Due to rising temperatures, air pollution, and more intensive heatwaves, as a consequence of climate change (De Sario et al., 2013; IPCC, 2023), the risk of overheating and indoor air pollution in buildings increases (Attia et al., 2021). Overheating and air pollution can affect health negatively, e.g. increase prevalence of cardiovascular diseases (Analitis et al., 2014; Khraishah et al., 2022), respiratory, eyes and skin complaints (Grigorieva et al., 2021; Ortiz et al., 2020; WHO, 2021) and mortality (Ballester et al., 2023). The current and predicted rise of

temperatures are higher in Europe than globally (European Environment Agency, 2023). While heat-related mortality is higher in a Mediterranean and continental climate, an increase is expected also in northern European countries (Baccini et al., 2011), where symptoms related to heat already occur during a normal summer (Näyhä et al., 2014).

In Europe, occupants spend 56% to 66% of their time at home (Schweizer et al., 2007), where about 80% of the energy is used for heating, cooling and hot water (European Commission, 2024). Moreover, buildings (including dwellings) cause 36% of the energy related greenhouse gas emissions in Europe (European Union, 2021). One of the main measures to lower greenhouse gas emissions is improving the energy efficiency of dwellings, i.e. to reduce fossil energy use and use renewable energy for heating, cooling and ventilation (European Union, 2021). However, measures to increase energy efficiency can have adverse effects. For example, high air tightness of façades can affect occupants' health negatively (Ortiz et al., 2020); technologies for renewable energy, such as building integrated photovoltaic panels, increase the outdoor temperature (T_{out}) locally through infra red radiation (Sheik et al., 2022). Therefore, an integrative approach is required to enhance energy efficiency and support occupants' health in dwellings, which are adaptable to continuously changing climate, technology, and health.

According to the New European Bauhaus (NEB, 2020) the quality of the built environment can be improved by dwellings that are adaptable to changing and future needs. However, insight into the adaptability of dwellings is limited through a lack of empirical evidence (Heidrich et al., 2017). As a first step, an overview of occupants' comfort and health in dwellings during summer can contribute to understanding required adaptability of dwellings in relation to recent technologies, changing occupants' behaviour, and rising temperatures. The objective of this study is to systematically review consequences of outdoor conditions on comfort and health in European countries during summer (non-heating season). This review focuses on empirical studies, as these enable to capture real world interactions of occupants in relation to the built environment (Bluyssen, 2020).

2. Methodology

A systematic literature search was performed between February and July 2024. The following three databases were used; Scopus, Web of Science and PubMed. Combinations of five groups of keywords and synonyms were used to find studies on the indoor environment (1) in dwellings (2) during hot weather (3) including health (4) of occupants (5). See Table 1 for all keywords. Papers were selected after reading consecutively titles, abstracts, and full texts. Subsequently, references and citations of the selected papers were examined (snowball).

Table 1: Keywords used in Boolean search.

Indoor (1)	Dwelling (2)	Hot weather (3)	Health (4)	Occupant (5)
Ambient	Home	Overheating	Comfort	Person
	Housing	Heat wave	Wellbeing	User
	Residential housing	Extreme weather event		Human
	Residential building	Smog		People
	Single-family houses	Air pollution		Resident
	Single-family homes			
	Multifamily house			

The selection of papers was based on the following criteria:

- Peer reviewed and original journal papers written in English.
- Data collected in occupied dwellings or from occupants at home.
- Data collected in European countries during summer (non-heating season).

- Studies on relations between outdoor conditions and building characteristics, occupants' health, or comfort.
- Quantitative, qualitative, and mixed methods studies.

Characteristics of methods, analyses, criteria for overheating and for indoor air pollution, occupants, dwellings, region, and study period, were extracted and categorized.

3. Results

Search in the three databases generated initially 1493 titles. After screening of titles, abstracts, and full text reading, thirty-six papers were selected; after examination of references and citations this added up to sixty-eight. The studies were performed in twenty countries, including temperate oceanic (Cfb), humid mild (Dfb), dry warm (Dsa), warm Mediterranean (Csb), hot Mediterranean (Csa) and dry hot (Bsk) summers (Peel et al., 2007). One third of the studies was performed in the United Kingdom, for other countries the number of studies varied from one to eight. Synthesis of the studies is explained according to three main factors, i.e. outdoor conditions (dose-related), building-related and occupant-related.

3.1 Outdoor conditions and indoor thermal and air quality

Overheating in old, renovated, and new dwellings occurs during typical summers throughout Europe (Colclough et al., 2024; Costa-Carrapiço et al., 2022a; Darteville et al., 2021; Farahani et al., 2024b; Glad et al., 2024; Mavrogianni et al., 2015; Morgan et al., 2017; Ortiz et al., 2023; Ozarisoy et al., 2021; Pathan et al., 2017; Tabatabaei Sameni et al., 2015; Zuurbier et al., 2021). However, more dwellings are likely to overheat during atypical (hot) summers than typical summers (Hughes et al., 2019; Zahiri et al., 2023), and during heatwaves (Beckmann et al., 2021; Sakka et al., 2012). The relation between average indoor temperatures (T_{in}) and both average solar radiation and outdoor temperature (T_{out}) is weaker during heatwaves than typical summer days (Farahani et al., 2024a). Furthermore, T_{in} varies more than T_{out} during heatwaves (Alonso et al., 2024; Wright et al., 2005; Zuurbier et al., 2021).

During summer the ingress of outdoor air pollutants (fungi, O_3 , NO_x) is higher than during the heating season because of higher outdoor concentrations and increased window opening (Derbez et al., 2018; Langer et al., 2015; Szabados et al., 2023; Vu et al., 2022). However, concentrations of O_3 and NO_x tend to be lower than concentrations of other indoor air pollutants, such as formaldehyde and $PM_{2.5}$, because of chemical reactions (Szabados et al., 2023; Vu et al., 2022). Thresholds for indoor air pollutants are exceeded during summer (Coggins et al., 2022; Kaunelienė et al., 2016; Szabados et al., 2023; Vu et al., 2022), while exceedance of indoor CO_2 concentrations varies strongly (Alonso et al., 2024; Coggins et al., 2022; Derbez et al., 2014; Fernández-Agüera et al., 2019; Gupta et al., 2020; Kaunelienė et al., 2016; Langer et al., 2015; McGill et al., 2015; Wang et al., 2022).

3.2 Building-related aspects

Apartments are more likely to overheat than detached dwellings (Beizae et al., 2013; Colclough et al., 2024; Lomas et al., 2013; Pathan et al., 2017; Tabatabaei Sameni et al., 2015), especially small apartments adjacent to only one façade (Thomson et al., 2019). Some studies did not determine differences in overheating between apartments and semi-detached or terraced dwellings (Colclough et al., 2024; Lomas et al., 2013; McGill et al., 2017; Morey et al., 2020), while other studies did (Beizae et al., 2013; Pathan et al., 2017; Zuurbier et al., 2021). Furthermore, overheating (Arriazu-Ramos et al., 2023; Beizae et al., 2013; Desogus et al., 2015; Gupta et al., 2020; Lomas et al., 2024; Morey et al., 2020; Zahiri et al., 2023) and dissatisfaction (Ozarisoy et al., 2021) tend to be higher on top floors than at lower levels during summer. Also, the risk for overheating (Darteville et al., 2021; Gupta et al., 2020;

Gupta et al., 2019; Jang et al., 2022; Morey et al., 2020) and occupants' dissatisfaction (Mlecnik et al., 2012) in bedrooms are higher than in living rooms, even during cool temperate summers (Mitchell et al., 2019). Particularly, the prevalence and the intensity of overheating (Lomas et al., 2024) and the risk of mortality (Vandentorren et al., 2006) are higher in bedrooms in houses without loft or façade insulation than in insulated rooms. Overall, findings on overheating in relation to higher insulation of façades vary; no difference (Lomas et al., 2024); lower risk in recently built or renovated dwellings (Ahan et al., 2023; Farahani et al., 2024b); higher risk (Arriazu-Ramos et al., 2023; Beizae et al., 2013; Lomas et al., 2013; Lomas et al., 2021; Maivel et al., 2015; Mitchell et al., 2019; Morey et al., 2020; Pathan et al., 2017; Sarran et al., 2023).

Glazed balconies are likely to result in overheating of adjacent rooms during summer (Fernandes et al., 2015; Grudzińska, 2021). However, double solar shading and sufficient opening for ventilation (more than 25%) reduce overheating indoors (Monge-Barrio et al., 2015). Furthermore, shelter from wind, birds, burglary, and improved thermal comfort during the heating season increase the occupants' acceptability of high temperatures due to glazed balconies during the non-heating season (Grudzińska, 2021). Findings on relations between overheating and orientation vary from none (in retrofitted low-rise dwellings without shading (Vellei et al., 2017)), and weak (dwellings with solar shading (Arriazu-Ramos et al., 2023; Darteville et al., 2024; Ortiz et al., 2023)), to strong (in south and south-west facing rooms on top floors (Zahiri et al., 2023; Zuurbier et al., 2021) and west facing rooms at high north latitudes; 58° and 60° (Berge et al., 2016; Glad et al., 2024) without solar shading). Glad et al. (2024) found that occupants even moved from west facing apartments because of overheating. During summer, indoor air quality, based on CO₂ concentrations, is similar (Wang et al., 2022) or lower (Baborska – Narożny et al., 2022; Gupta et al., 2019) in mechanically ventilated dwellings than in (solely) naturally ventilated dwellings. Overheating occurs both in dwellings with only natural indoor air exchange (Fernández-Agüera et al., 2019; McGill et al., 2017; Sakka et al., 2012; Vellei et al., 2017; Vidal et al., 2020) and in dwellings with mechanical exhaust and supply (Baborska-Narożny et al., 2017; Darteville et al., 2024; Farahani et al., 2024b; Gupta et al., 2019; Kaunelienė et al., 2016; McGill et al., 2015; McGill et al., 2017; Sarran et al., 2023; Stamp et al., 2022; Szabados et al., 2023). Automatically opened windows (Psomas et al., 2017), decentralized mechanical ventilation in apartments (Maivel et al., 2015), and low set-point/ switch off of heat recovery (Berge et al., 2016) decrease the risk of overheating.

3.3 Occupant-related aspects

Occupants tend to be more satisfied with indoor air quality during non-heating seasons than during heating seasons (McGill et al., 2015; Sarran et al., 2023). However, no relations were found between satisfaction with indoor air quality and ventilation rates, concentrations of CO₂, or concentrations of indoor air pollutants (Berge et al., 2016; Coggins et al., 2022; McGill et al., 2015).

Relations were found between satisfaction with thermal quality and T_{in} (Beckmann et al., 2021; Darteville et al., 2024; van Loenhout et al., 2016). However, occupants are likely to be satisfied with higher T_{in} than estimated by criteria for adaptive comfort (Ozarisoy et al., 2021; Petrou et al., 2019; Vellei et al., 2017; Zahiri et al., 2023), steady-state comfort (Baquero et al., 2022; Ozarisoy et al., 2021) and national standards (Alonso et al., 2024). Acceptability of high T_{in} differs due to habituation, expectations, and previous experiences (Costa-Carrapiço et al., 2022b; Grudzińska, 2021; Hassani et al., 2024; Thomson et al., 2019). Furthermore, elderly and those with chronic diseases prefer higher T_{in} than other occupants (Baquero et al., 2022; Beckmann et al., 2021; Hughes et al., 2019), although they tend to suffer more (Kemen et al., 2021; Thomson et al., 2019) and have a higher mortality risk due to hot weather

(Vandentorren et al., 2006). Also, high T_{in} affects sleep quality negatively (Ahan et al., 2023; van Loenhout et al., 2016; Vidal et al., 2020); while adapted sleeping times might reduce heat exposure during sleep (Hendel et al., 2017).

Adaptive behaviour varies between occupants due to differences in experiences (Yáñez Serrano et al., 2023), perception (Kemen et al., 2021), vulnerability (Vellei et al., 2017), and knowledge about environmental control (Baborska-Narožny et al., 2017; McGill et al., 2015; Murtagh et al., 2019). Dwellings can become less overheated during hot weather when occupants have become more familiar with their home (Fletcher et al., 2017), e.g., because of increasingly proper use of solar shading (Derbez et al., 2014), or improved control of mechanical ventilation and opening of windows (Berge et al., 2016). The main reason why occupants open windows is cooling (Berge et al., 2016; Mavrogianni et al., 2017; Wang et al., 2022), although it can be insufficient to avoid overheating (Ortiz et al., 2023; Sakka et al., 2012; Zahiri et al., 2023). Furthermore, CO_2 concentrations strongly vary in relation to window opening (Berge et al., 2016; Fernández-Agüera et al., 2019) but are generally lower than when occupants keep their windows closed (Mavrogianni et al., 2017).

4. Discussion

This review provides insights into consequences of outdoor conditions on indoor air quality and thermal quality in dwellings in European countries during summer. Main correlations of thermal and indoor air quality with layout (dwelling type, floor level, room type), building envelope (insulation, orientation, shading, glazing), and technology (mechanical ventilation, automatic windows) are shown. Inconsistencies between studies on correlations between overheating and dwelling types, insulation, and orientation of façades, might be related to differences in the outdoor environment, adaptive behaviour, and interactions of building related aspects with thermal and indoor air quality. Based on these inconsistencies, it can be concluded that overheating is not related to just one single building related aspect; a comprehensive inventory and analysis of building related aspects and local outdoor environmental characteristics might contribute to a better understanding.

No empirical evidence of new technologies that increase the passive cooling capacity, such as green building envelopes (Ottelé et al., 2017; Perini et al., 2011; Stache et al., 2022), or use of phase changing materials (Tenpierik et al., 2018; Tenpierik et al., 2019), was found. Also, the reviewed studies did not include information on new technologies for renewable energy, e.g., photovoltaic panels optimized to reject infrared radiation and improve building integration (Ortiz Lizcano et al., 2020; Ortiz Lizcano et al., 2022). However, as new technologies may evolve and can affect both adaptive behaviour (Hellwig et al., 2022) and required adaptability of buildings (van Ellen et al., 2021), more studies on how new energy efficient technologies contribute to less overheating and indoor air pollution in dwellings are required.

There is ample evidence of discrepancies between overheating criteria and satisfaction with thermal comfort. This can be related to limited consideration in overheating standards of the effects from urban heat islands, heatwaves, climate change (Attia et al., 2023), and variation of psychological and physiological reactions to indoor conditions between individuals (Bluyssen, 2022). Higher tolerance of high temperatures was found for those who are traditionally used to cope with high T_{out} . On the other hand, occupants' preferences can change due to contextual changes (Eijkelenboom et al., 2021) and improve their adaptation strategies to stay comfortable indoors because of changing outdoor conditions (Hellwig et al., 2022). Therefore, it is necessary to increase our understanding of correlations between changing outdoor conditions, acceptability, and evolving adaptive behaviour indoors.

While adaptive behaviour can improve comfort, adaptive behaviour can be insufficient to support health of occupants. For example, the review showed that thermal quality is likely to be a stronger driver for adaptive behaviour (e.g., use of solar shading, opening windows)

than indoor air quality. This might have adverse effects, such as deprived sleep quality because of high concentrations of indoor air pollutants when windows are closed and fans are used for cooling (Yan et al., 2022), or, depending on the intensity of traffic and urbanization, too high ingress of outdoor air pollutants when windows are opened for cooling (Belias et al., 2023). Furthermore, while bedrooms seem prone to overheating, possibly due to low thresholds for temperatures in overheating criteria (Beizaee et al., 2013) and high exposure to solar radiation at top floors in houses, behavioural adaptation is limited during sleeping time. Moreover, during working hours, when away from home, the risk for overheating is higher, possibly because of limited opportunities for behavioural adaptation. Furthermore, adaptive behaviour of unhealthy elderly might be insufficient because they are more likely to accept high T_{in} , while they are more vulnerable to heat than others.

5. Conclusions

Overall, this review shows that overheating already occurs in normal summers in European countries with temperate, mild, warm, or hot summers. Indoor air quality is likely to differ during the non-heating season as compared to the heating season due to variation of air exchange and of outdoor air pollutants. The effect of outdoor temperature on indoor temperature highly depends on building-related aspects (such as housing type, floor level, type of ventilation) and occupant-related aspects (health, adaptive behaviour), especially during heatwaves. Because of inconsistent relations between indoor temperatures and housing type, orientation, and insulation, it can be concluded that comprehensive analysis of building-related aspects and the urban environment is required. Furthermore, overheating standards and thresholds for indoor air pollutants do not comply with perceived thermal and indoor air quality. Moreover, adaptive behaviour of occupants can affect health negatively and can change due to changing acceptability, expectations, or familiarity. Therefore, better understanding of occupants' adaptive strategies and their relation to comfort and health is required. Due to the ongoing climate change (including uncertainties on the extent of rising temperatures), changing adaptive behaviour, and evolving energy efficient technologies, study of adaptability of dwellings to these changes is required to contribute to energy efficient, health supporting dwellings.

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