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Establishing resilience in times of climate change—a perspective on humans and buildings

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Abstract

With a contribution of 40% to the annual global CO_2-emissions, the built environment needs to drastically reduce its impact, while also providing pleasant and healthy indoor spaces and protecting people from weather extremes. Over time, particularly in western and industrialized countries, buildings have evolved to shield occupants almost completely from outdoor conditions. As a consequence, humans have become so used to a constant, comfortable indoor environment that we struggle to cope with thermal fluctuations. The time has come to shift perspective, as the very protective character of buildings and provision of omnipresent comfort are neither feasible nor desirable any longer. An enormous amount of energy and resources are spent to provide tightly controlled thermal environments, often with the same target temperature all year round. However, being mostly exposed to constant, comfortable indoor temperatures can have negative impacts on health and deteriorate our human capability to deal with thermal challenges. Importantly, spending time outside the thermal comfort zone is known to enhance human thermoregulatory capacities and thermal resilience, while also improving metabolic and cardiovascular health. This perspective essay aims to draw attention to novel and yet underrepresented avenues of coping with climate challenges, both with respect to the built environment and humans. Allowing more thermal variation indoors will save precious resources, decrease the negative impact of building CO_2-footprints, and stimulate physiological and psychological adaptation in humans, which can lead to improved resilience and health.

Keywords Resilience · Dynamic indoor environment · Adaptive comfort model · Climate change mitigation · Climate change adaptation · Human health · Healthy buildings

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1 Introduction

As we are finding ourselves in a global climate emergency (IPCC 2021), it is more important than ever to assess strategies of adaptation towards, and future prevention of, the fast-paced progression of global warming. The past decade has been the hottest on the record, and the climate is changing at a rate that is unprecedented in at least 2000 years, resulting in significant increases in weather extremes, such as heat waves but also local cold spells (Johnson et al. 2018). Considering the frequent reports of overheating of buildings—even in relatively mild climate regions—paired with the number of fatalities each year that may be attributed to extreme heat and cold events (Vicedo-Cabrera et al. 2021), we need to prepare ourselves to cope with the imminent climate challenges that we are facing. In this essay, we first summarize the current situation regarding thermal comfort and thermal adaptation research in humans, as well as building standards, and then derive a perspective on how to actively establish and improve temperature-related resilience in both humans and buildings.

1.1 Resilience of humans and buildings

The term resilience is featured in several of the United Nations (UN) Sustainability Development Goals (SDGs), for example in SDG 11 “Make cities and human settlements inclusive, resilient and sustainable” (United Nations 2015). Based on the UN, resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management” (UNDDR 2015). The understanding of the term resilience might depend on the context. In a reflection on different definitions of resilience in various context, Schweiker (2022) summarizes that the “core to all these [resilience] definitions is that an entity reacts to challenges or changes in order to remain in an equilibrium,” - whether this equilibrium may be the original state, or an even better one (Roaf 2018). Human thermal resilience, for example, does not only reflect the ability to cope with thermal challenges on a short term, where homeostasis can be retained. It also reflects the longer term, where repeated exposure to a thermal challenge induces thermal adaptation, which enhances the ability to cope (see 2.2). In this essay, the term resilience will be used in accordance with the above-described definitions, meaning the ability to remain in an equilibrium upon challenge, or the ability to demonstrate flexibility, adapt and “bounce back” readily to a status quo, or even an improvement of the status quo upon repeated challenge, in both human and built environment context.

1.2 Thermal environments - from a natural force to a human-controlled engineering marvel

Thermoregulation has always played an essential role in the evolution of life. Ever since the existence of the human species, our body needed to cope with varying thermal environments in order to survive. The natural thermal environment generally fluctuates significantly over seasons, but also over during day and night. Rapid weather changes with fluctuations in air pressure, winds, solar radiation, and precipitation can bring along substantial changes in the thermal perception of our environment. Evolutionary processes, the plasticity of the human physiological system and, importantly, behavioral adjustments (e.g., use of fire, seeking and creating shelter, clothing) made it possible to adapt to a wide array of different climatic zones (Ruff 1993, 1994). The human species turned out to be able to inhabit most of our planet.

Instead of adapting ourselves to our natural habitat, we nowadays design and engineer the thermal environment to our wishes and desires. This is true for most industrialized countries, where people are hardly ever exposed to the outdoors, as they spend on average around 90% inside buildings and vehicles (Klepeis et al. 2001). Thus, the indoor environment has become our primary, “not-so-natural” habitat, to which our physiology is responding, and to which we are likely adapted most. An increasing number of buildings is equipped with heating, ventilation, and air-conditioning (HVAC) systems aiming to create, what is considered, a comfortable indoor climate. In Germany, only about 2% of residential buildings, but about 50% of non-residential buildings are equipped with mechanical cooling (Bettgenhaeuser et al. 2011). For both types of buildings and across Europe, the prevalence of mechanical cooling is expected to rise sharply within the upcoming years, according to the International Energy Agency (IEA 2018). Compared with Europe, the use of mechanical cooling is much more widespread in South-East Asia and North American region, in both residential and non-residential buildings. In buildings with mechanical heating and cooling, the indoor environmental conditions are often virtually “uncoupled” from the natural outdoor environmental conditions.

1.3 Should comfort be standard?

The design and operation of indoor spaces has developed and changed tremendously over the past decades, aiming to provide maximum comfort. The invention of air-conditioning by Willis Carrier in 1902 marked the start of a technology-driven approach to climate design in the following decades: indoor climate design became dictated by what was technically feasible. Based on the publications of Fanger in the 1970s (Fanger 1970; Fanger 1973), and the subsequent development of comfort standards for indoor environments such as by the American Society for Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), it became the goal to strive for a thermally *neutral* environment in buildings. Thermal neutrality was assumed to provide most comfort for the majority of building occupants. According to ASHRAE Standard 55 and ISO Standard 7730 (ISO7730 2005), indoor temperature is supposed to only marginally fluctuate around an average neutral temperature, causing an accepted variance of only ±0.5 K around the targeted temperature set point. Although the guidelines do provide some variance such as “cyclic amplitudes should stay below 1 K” and “the rate of temperature change should stay below 2 K/h” (ISO7730 2005), these guidelines are usually strictly interpreted and the included options for temperature variations are not applied in practice. This may be due to the assumption that less variation must be better. Moreover, the standards have been assumed to be applicable in all types of buildings, across different climatic zones, seasons, and populations (ASHRAE 2020; de Dear and Brager 2002). As Fanger rejected the concept of physiological/perceptual acclimatizaton, based largely on a rather questionable interpretation of his own study results (Fanger 1973), he implied that thermal neutrality, and thus thermal comfort, would essentially be the same for all humans around the globe (Fanger 1973) (also see discussion in Schweiker et al. 2018).

The Adaptive Comfort Model (De Dear et al. 1998; Humphreys and Nicol 1998; Nicol and Humphreys 2002) recognized and implicitly incorporated the importance of physiological (seasonal) acclimatization, as well as psychological and behavioral aspects of human interaction with their thermal environment. This model was incorporated into the ASHRAE Standard 55 in 2013, and has since been incorporated in several standards across the globe (an overview can be found in Carlucci et al. 2018). Although the variation of thermal conditions indoors is accepted by the Adaptive Comfort Model, the latter has only been validated for naturally ventilated and not for air-conditioned buildings. To date, some standards have extended the concept to HVAC buildings as well, such as the Netherlands' ISSO74. However, in the 2019 EN16798 standard, the adaptive approach is still exclusively presented for free-running buildings, while the PMV/PPD model is still leading for HVAC buildings. However, in all current standards and guidelines, whether for free-running buildings or for HVAC buildings, the adaptive temperature ranges formed by the adaptive temperature limits are presented as a means to *evaluate* the realized indoor temperatures, rather than allowing for an adaptive temperature *control*. Instead, setpoints for heating and cooling are still often fixed parameters over the year, e.g., 21 °C for heating and 24 °C for cooling. Moreover, the current formulations based on classes in the standards and guidelines lead to a "performance class" of a building based on the general notion "the closer to the (assumed) optimum, the better," a notion that does not lead to the desired result of improved comfort (Arens et al. 2010).

Apart from vast monetary and energy demands caused by a tightly controlled indoor environment, reasonable doubt has been expressed about the healthiness of such uniform environments (Johnson et al. 2011; Keith et al. 2006; McAllister et al. 2009; Moellering and Smith 2012; van Marken Lichtenbelt et al. 2017). Considering the perpetual exposure to indoor environments, we should note that indoor spaces are of great significance to our health and wellbeing (Perdue et al. 2003). It should be noted that the concept of creating a *healthy* indoor environment (which is, in fact, not synonymous to comfort) was not mentioned as a goal in any of the indoor environmental standards until very recently: the Well Building Standard is one of the first to explicitly consider health besides comfort (International Well Building Institute 2016). As a matter of fact, from fields like sports and nutritional sciences, we know today that striving for maximum comfort (e.g., enjoying too much "comfort food" and being sedentary too often) does not necessarily lead to the establishment of better health, but rather the opposite (see paragraph 2.1). The very protective character of our indoor environments, designed to shelter us from experiencing any forms of cold or heat, makes us more vulnerable to temperature extremes.

1.4 Strict climate control and climate change: a vicious circle?

The latter becomes very important, when considering the increasingly serious prospect of climate change and the way buildings are nowadays designed and operated. Measures taken to comply with the strict indoor climate guidelines mentioned above, combined with the endeavor to reduce energy costs and the environmental impact, have led to the practice of highly insulating buildings, particularly in climatic zones with cold winters. Consequently, many modern buildings are nearly airtight, and the hermetic construction paired with a high internal heat load (due to appliances and occupants) make them vulnerable to overheating (Lomas and Porritt 2017). In cities and highly populated areas, where many buildings are made of steel, concrete, and glass concentrate, the so-called urban heat island effect (UHIE) also further intensifies the situation, as heat is absorbed and retained in the materials and thus attenuates natural cooling, i.e., during nightly hours (IEA 2018). Additional heat load is added by the many air-conditioning units required to keep buildings in cities operational, which release further hot air into their (outdoor) surroundings.

To illustrate: by using air-conditioning devices, on average, 1/3 of the removed heat from buildings is added to the urban environment, because their electrical power consumption is dissipated as extra heat. When considering an additional hazard posed by (partly planned) power outages and grid failures, and thus no electrically powered cooling, as it happened in summer of 2021 in Northwest US (Washington State Department of Health 2021), this scenario becomes increasingly concerning. In those situations, buildings that are dependent on mechanical ventilation and air-conditioning can become literally uninhabitable, with temperatures rising beyond human compensability (Aduralere 2018).

Observing this cascade of consequences, it becomes clear that we have entered a vicious circle, caused by the desire for thermal neutrality and comfort indoors, which will become more and more problematic as climate change progresses. Knowing that depending on the climatic zone, an increase in average temperature as well as extreme weather events will occur more frequently in the future, it is crucial to investigate potential alternative pathways to cope with the thermal challenges. In a recent publication by Jay et al. (Jay et al. 2021), the authors provide a list of cooling measures and strategies to attenuate the effects of hot weather and heat extremes, on individual, building, landscape, and urban scale. The authors highlight relatively cheap and easily accessible cooling methods, to efficiently and effectively reduce thermal strain, especially in the vulnerable populations and those who do not have access to, e.g., electricity and mechanical cooling. Expanding on this information, we discuss novel and yet underrepresented coping mechanisms, which add to the battery of adaptation and mitigation strategies for climate change in the context of indoor environments. Establishing concrete scenarios for the improvement of resilience from a human perspective, as well as from a perspective of building design and operation, will lead us the way to be better prepared for a future with global warming.

2 Establishing human thermal resilience

Humans migrated all over the world in the past 40,000 years, inhabiting many different climatic regions, and surviving large temperature fluctuations, both seasonally as well as diurnally (Daanen and Van Marken Lichtenbelt 2016; Diamond 1997). We most likely started evolving from tropical Africa, but even there, diurnal variation in felt temperature can be substantial. However, people can nowadays move from a 21 °C air-conditioned home, to an air-conditioned car, drive into a conditioned parking garage, from where an elevator can be taken to the air-conditioned office building, and vice versa on the way back home. This way, opportunity for exposure to natural thermal fluctuations is minimal. During lockdowns in connection with the COVID-19 pandemic, many people were confined to their homes, which may have resulted in even less opportunity for exposure to diverse (thermal) environments. Working from home, online shopping and delivery services of all kinds made it largely unnecessary to leave home for everyday needs and has created habitual changes that will likely be retained beyond the current pandemic situation. In contrast, COVID-19 has also brought along a promising increase in the use of recreational and green spaces (Venter et al. 2021). Even though the latter provides some hope and needs to be further advocated for, spending a very limited amount of time in the outdoor environment (i.e., ~10% per day (Klepeis et al. 2001), may reduce stimulation of the human thermoregulatory system and thus diminish acclimatization to natural daily and seasonal variations of temperature.

2.1 The natural pursuit of thermal neutrality

Interestingly, from an evolutionary perspective, it is logical *why* we constantly strive for thermal comfort: because it is in our genes. When the weather used to hit our ancestors with its full (uncomfortable) force, it kept them alive to seek shade from the heat or huddle up in the cold, in order to save precious water (sweat) and energy (food) for thermoregulatory purposes. Even though it is clear that at least in developed, industrialized countries, we do not need to worry about saving calories anymore, as the next meal is guaranteed, and we also have easy access to shelter, subconsciously, we are still driven by the natural desire to be comfortable.

The fact that the term "thermal comfort" has been used synonymously with "thermal neutrality" in indoor environmental standards (ASHRAE 2020; ISO7730 2005) demonstrates the strong correlation that is assumed between the two concepts. However, we would like to stress that there may be a discrepancy between the range of temperatures that is perceived as neutral (i.e., 0.0 ± 0.5 on the ASHRAE thermal sensation scale (ASHRAE 2020)) and the perception of comfort, which may go well beyond the boundaries of neutrality, especially in more dynamic scenarios. It could be that a temperature is perceived as warm (i.e., ±1 on the ASHRAE thermal sensation scale (ASHRAE 2020)), but is still deemed comfortable, which can be dependent on individual characteristics, thermal history and preferences (also see Nicol et al. 2012 and Schweiker et al. 2018). Moreover, also the subjective perception of what is neutral can be highly individual. For example, in a study by Jacquot et al. (2014), temperature ranges that were perceived as neutral by study participants, assessed during increasing and decreasing thermal ramps, varied between participants from as little as 1 °C to as much as 10 °C. Importantly, with regular exposure to a certain thermal stimulus, physiological and perceptual habituation occurs, making the formerly uncomfortable environment more comfortable over time (Rupp et al. 2015).

With all of this in mind, what does neutrality actually mean from a physiological perspective? It should be realized that thermal sensation and comfort refer to a subjective appreciation of a thermal condition, whereas physiological thermal neutrality implies a straightforward physical approach: the equilibrium between heat production and heat loss (thermal balance). Thermoneutrality means that no additional energy is needed to heat, and no additional evaporative cooling (sweating) is needed to cool the body, to keep the core temperature around its setpoint/balance point of ~37 °C (Gordon 2012; Kingma et al. 2012). The range of temperatures at which the body is in thermal neutrality is called the thermoneutral zone (TNZ). Within the TNZ, temperature regulation is solely achieved by changes of the blood circulation, with blood either being drawn towards the core to retain heat (vasoconstriction of blood vessels in extremities and skin) or shifted towards the extremities to enhance heat loss (vasodilation) (IUPS-Thermal-Commission 2003; Scholander et al. 1950). The human thermoneutral range for a (semi-)naked, resting, fasted person is only a few degrees wide. Depending on individual characteristics, it has been reported to be between 26.5 and 35.5 °C, but the precise range is influenced by factors such as body composition, age, sex, and the level of thermal acclimatization [Brychta et al. 2019; Craig and Dvorak 1966; Hardy and DuBois 1938; Hill et al. 2013; Kingma et al. 2014; Kingma et al. 2012; Pallubinsky et al. 2019].

2.2 Beyond the thermoneutral zone—acute responses and physiological adaptation to cold and heat

Physiological responses beyond the thermoneutral range differ between *acute* exposure to cold or heat and *acclimatization or acclimation* (Castellani and Young 2016;

IUPS-Thermal-Commission 2003; Taylor 2014). Acclimatization refers to its natural form, whereas acclimation refers to an artificially induced state, e.g., through heat acclimation protocols in athletes) (IUPS-Thermal-Commission 2003).

In an acute thermal challenge, as an immediate response to a disturbance of thermal balance, the body expends energy to warm up or dissipates heat to cool down. When vasoconstriction is not sufficient to protect the core temperature from decreasing, additional metabolic heat is produced by non-shivering and shivering thermogenesis (van Marken Lichtenbelt and Schrauwen 2011). Whenever vasodilation of the skin blood vessels is insufficient in dissipating heat to protect the core temperature from rising, evaporative heat loss will enhance by means of sweating (Cabanac and Massonnet 1977; Tansey and Johnson 2015). It is important to recognize that thermoregulatory capabilities are strongly influenced by various individual factors such as age, gender, ethnicity, fitness level, diet, medication, and health status (NIOSH 2016; Periard et al. 2015; Taylor 2006; Taylor 2014). Moreover, the thermoregulatory response is dependent on parameters such as the thermal stimulus, the type of exposure, the intensity, the duration and the activity performed in the respective thermal condition (Taylor 2014).

When the body is repeatedly thermally challenged, adaptive processes set in—and heat or respectively cold acclimatization occurs (Daanen and Van Marken Lichtenbelt 2016; Taylor 2014). Thermal adaptation occurs in a gradual transition (starting from day 1), during which thermal tolerance increases (Taylor 2014).

Cold acclimatization induces metabolic adjustments, such as an increase in resting metabolic rate (also at thermoneutral conditions) and a decrease in shivering during cold exposure. This goes along with an increased capacity of non-shivering ("chemical") thermogenesis. Secondly, insulative adjustments, including cardiovascular adjustments (e.g., increase vasoconstriction of the skin vessels leading to less heat loss and better core body heat conservation) occur. This way, acclimatization may change some basic thermophysiological responses of the body and may shift the TNZ as well as affect the responses to acute cold exposure. Even though physiological adaptation to cold is evident, the tolerance for cold in humans is relatively limited and largely depends on behavioral support. As humans are furless, sweating, tropical animals, the human physiological capacity to withstand heat is more advanced.

There has been a lot of scientific interest in the impact of *extreme* thermal conditions, particularly heat, on human physiology and performance, e.g., in the context of sports and the military (examples include (Buono et al. 1998; Cheung and McLellan 1998; Nadel et al. 1974; Nielsen et al. 1993; Regan et al. 1996; Roberts et al. 1977; Sawka et al. 1983)). In general, these studies show that when repeatedly exposed to heat in combination with exercise, a multitude of physiological adaptation mechanisms are triggered, improving performance in and resilience towards heat (Fig. 1).

Key physiological adaptations to heat include improved cardiovascular function (cardiac as well as cutaneous vasomotor function), reduced resting body temperature and more efficient, and enhanced sudomotor function (earlier sweat onset, increased sweat gland sensitivity, increased sweat gland capacity, increased maximal sweat gland output) (Taylor 2014). Significant beneficial adaptations occur already within the first few days of repeated heat exposure (Fig. 1) and plateau after 7–14 days, depending on the type of exposure. The physiological strain reduces with each day of repeated exposure, whereas performance and comfort increases (Periard et al. 2015; Sawka et al. 2015).

Considering the indoor environment, it is crucial to understand how humans cope with thermal stimuli encountered in day-to-day situations, taking into account the oftentimes very low level of physical activity or sedentary state as well as less extreme thermal

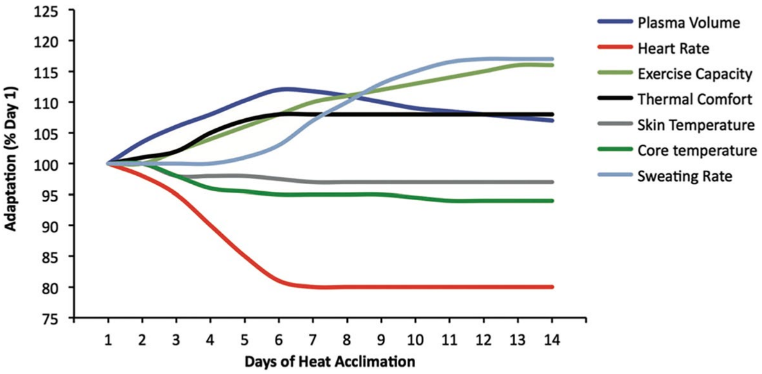

Figure 1 Time course of induction in human adaptation to heat stress, with exercise (From (Periard et al. 2015)).

environment inside buildings. Therefore, looking into *passive* thermal acclimation, as opposed to *active* and *extreme* examples of acclimation described above, is more relevant in this application. Only few studies evaluate the influence of passive heat exposure, in contrast to exercise-induced heat acclimation (Beaudin et al. 2009; Brazaitis et al. 2009; Brunt et al. 2016a; Brunt et al. 2016b; Fox et al. 1963; Henane and Bittel 1975; Hessemer et al. 1986; Shvartz et al. 1973). To address this knowledge gap, we have performed passive and mild heat acclimation studies at our lab, mimicking realistic summer indoor conditions. Two groups of young healthy and middle-aged overweight individuals were exposed to 34–35 °C ambient temperature, 4–6 h per day, and 7–10 adjacent days. Results show that even a relatively mild thermal stimulus can successfully improve heat tolerance, at a smaller magnitude than more extreme and active heat acclimation, but appropriate to the relatively smaller stimulus. The observed changes include decreased core temperature, improved heat loss via the skin and decreased sweating (young population only), as well as reduced cardiovascular strain (Pallubinsky et al. 2017; Pallubinsky et al. 2020). More studies are warranted to confirm these results, and to expand them to other populations.

It can be deduced from the information above that the human thermoregulatory system features great plasticity, allowing for adjustment to a wide range of thermal environments, but within certain limits that are influenced by individual characteristics. This suggests that exposing ourselves more to naturally fluctuating thermal conditions and seasonal changes of the environment has the potential to enhance our thermoregulatory capacity, improve thermal comfort and ultimately make us more resilient to thermal challenges such as heat waves or cold spells.

2.3 Healthy cold and healthy heat?

Next to the great advantage of making us more resilient to thermal challenges, exposing our body to temperatures outside the thermoneutral range can also have other beneficial effects. For example, it has been suggested that remaining in thermal neutrality, and thus avoiding stimulation of the thermoregulatory system, may expend less calories towards controlling body temperature (Johnson et al. 2011; McAllister et al. 2009;Moellering and Smith 2012 ; van Marken Lichtenbelt et al. 2017). Therefore, it has been hypothesized that the tight thermal indoor environment, alongside with oversupply of food and sedentary behavior, may be one of the reasons for the global obesity and diabetes “epidemic” we are facing today (Moellering and Smith 2012; van Marken Lichtenbelt et al. 2017). Indeed, regular exposure to thermal conditions *outside* the TNZ may have the potential to enhance metabolism and improve metabolic health. For example, it has been demonstrated that regular exposure to mild cold or mild heat improves glucose metabolism (Hanssen et al. 2015; Pallubinsky et al. 2020). In the study by Hanssen et al. (2015), it was established that regular exposure to mild cold has the potential to improve insulin sensitivity in patients with type 2 Diabetes Mellitus to a similar extent as pharmacological agents or exercise interventions. Additionally, heat is considered as a potential alternative treatment for cardiovascular issues and has been shown to significantly improve cardiovascular function (Brunt et al. 2016a; Brunt et al. 2016b; Pallubinsky et al. 2020). Notably, research shows that thermal acclimation also occurs in vulnerable populations such as individuals of older age and individuals with overweight and/or disturbed glucose metabolism (Hanssen et al. 2015; Pallubinsky et al. 2017). With increasing age, also higher physical fitness improves the thermoregulatory response to heat, which advocates for retaining a healthy lifestyle for superior thermal resilience (Pandolf 1997).

It can be concluded that regular heat and cold exposure increases our resilience towards heat and cold, as well as widens our comfort zone over time. So-called temperature training (acclimatization) can be viewed as an additional lifestyle factor beyond a healthy diet and regular physical activity. As stressed before, we need to recognize that remaining in a uniform, comfortable thermal environment is neither desirable nor healthy. Importantly, as shown above, we do not need to go to extreme lengths (like regular ice water immersion, sauna bathing, or exercising in the heat, which may exert certain benefits for health and performance (see e.g. Omar and Lucy (2023), Brunt and Minson (2021) and Periard et al. (2015)) to improve our thermoregulatory capacity and health. Even mild stimulation, if experienced regularly and for a significant amount of time, can improve human metabolic health and thermal resilience. The next part will discuss how the built environment can aid in this transition, to facilitate human resilience, and become more resilient itself.

3 Improving resilience of the built environment

The built environment has been and still is a major contributor to climate change being responsible for approximately 35% of the global energy demand and almost 40% of the global direct and indirect CO_2 emissions (United Nations Environment Programme 2021). Hence, the built environment plays a key role in climate change and the mitigation thereof. Besides limiting the primary energy demand and solely relying on fossil-free energy sources, the built environment faces a fundamental change in material use and construction technologies to fully decarbonize and become fit for a circular economy. Regarding energy demand, a wide spectrum of research and engineering endeavors is ongoing to fight climate change, ranging from (seasonal) thermal storage (Yang et al. 2021) to integrating renewable energy sources such as geothermal energy piles (Cunha and Bourne-Webb 2022), photovoltaics (Pillai et al. 2022), and wind (Škvorc and Kozmar 2021).

Besides minimizing emissions, research activities focus on how to improve the thermal resilience of the built environment as climate change already affects the thermal conditions in buildings, particularly during heat waves and due to the UHIE. Climate resilience has been addressed on multiple scales. At the urban scale, mitigating measures have been studied such as optimizing convective cooling of cities by wind (Hsieh and Huang 2016;

Toparlar et al. 2018) latent cooling via evaporation of water (Montazeri et al. 2017), radiative cooling (Carlosena et al. 2020), and the effects of vegetation (Erell and Zhou 2022). On the building scale, thermal resilience has been studied by investigating measures such as night ventilation (of which the effect is ironically limited by the UHIE) (Ramponi et al. 2014), smart adaptive facades to enable interaction of the building and its environment (Loonen et al. 2013), and retrofitting solutions for climate resilient facades (Lassandro and Di Turi 2017). At the room level, measures include storing thermal energy on the short term (day to day), e.g., in building slabs such as concrete floors (Reynders et al. 2013) and via the application of Phase Changing Materials (Bergia Boccardo et al. 2019).

3.1 A paradigm shift towards dynamic indoor climate conditions

Interestingly, indoor temperature settings play an important role in both fighting climate change by reducing building emissions, but also in creating human thermal resilience. A paradigm shift from the “ideal” thermoneutral-focused climate to appropriate thermal indoor requirements respecting comfort and productivity, enhancing thermophysiological capacity, and improving health, paves the way to human thermal resilience in the built environment. As people spend on average 22 h per day indoors (Klepeis et al. 2001), the built indoor environment could unlock a huge potential to contribute to our daily dose of thermoregulatory effort, via smart dynamic indoor temperature control. Importantly, the influence of thermal conditions on levels of productivity of (office) building occupants is a recurring point of discussion in the scientific community, based on the concern that non-neutral thermal conditions would decrease the ability of workers to perform their tasks efficiently. Porras-Salazar et al. (2021) have recently published a comprehensive meta-analysis on the effect of indoor temperature on office work performance, concluding that against the common assumption, there is no significant relationship between temperature and productivity within the range of 18–34 °C. Admittedly, this does not necessarily mean that there is no relationship at all between temperature and work performance, but rather that this relationship is probably smaller than expected, and dependent on aspects like the type of task and thermal acclimatization of the individual.

A dynamic indoor climate incorporates an extended temperature range, in which the indoor temperature is permitted to “float freely,” and in which that temperature range is slowly adapted to the seasonal changes in outdoor conditions. This way, the range is lower in winter, e.g., 19–22 °C, and gradually rises towards summer, to, e.g., 24–27 °C. An appropriate rate of change in temperature control range over the seasons is particularly important to allow for gradual physiological and behavioral acclimatization (and thus perception and productivity). In Hellwig et al. (2022a), the authors discuss how integrating the adaptive approach into design processes may enhance resilience of both humans and buildings. Previous laboratory studies have provided important insights into the application of such a dynamic profile. For example, Schellen et al. (2010) showed that during a dynamic temperature profile, starting at 17 °C and increasing at a rate of ±2 K/h to 25 °C, the acceptance rate was high, with only incidental reporting of slight discomfort. However, significant differences were found between elderly and young people. Moreover, Ivanova et al. (2021) demonstrated that thermal comfort was achieved over a wider range of sensation votes during a dynamic temperature profile (Schellen et al. 2010) compared to a fixed temperature of 21 °C.

Due to the combination of improved façade insulation, air tightness, high internal heat loads, and climate change, resilient cooling strategies become ever more important in the near future (Attia et al. 2021). For example, the range of ambient conditions could be extended (even more) by effective convective cooling of the body by elevated air speeds. Using fans instead of, or augmented with, air-conditioning devices, substantially contributes to lowering the energy demand and greenhouse gas emissions (Malik et al. 2022; Zhang et al. 2021), while facilitating thermal comfort. Fans can be smartly integrated into Personal Environmental Control Systems (PECS). Besides energy savings, recent research indicated health-promoting effects by demonstrating that thermophysiological stimuli from varying ambient thermal conditions can be maintained, while mitigating discomfort via a PECS that only targets the extremities (hands, feet, and head region), and by intentionally not targeting the torso (Luo et al. 2022). This way, it may be possible to retain a thermal effect large enough to enhance thermoregulatory capacity and induce thermal acclimatization, while maintaining a thermally acceptable and comfortable environment for the user and without compromising productivity.

3.2 Energetic benefits

Besides the physiological implications on thermal resilience, employing the adaptive temperature limits, based on the adaptive comfort model (e.g., de Dear and Brager 1998), as basis for adaptive setpoints can lead to substantial energy savings as well. Although the adaptive standards are meanwhile incorporated in building regulations (de Dear et al. 2020; Hellwig et al. 2019), the majority of current buildings' control systems are not benefitting from the huge energy saving potential. A first version of an adaptive control algorithm was presented already back in 2002 (McCartney and Fergus Nicol 2002); however, it was lacking the of a free-running temperature as it calculated one comfort temperature instead of a range that was adjusted over the seasons. Later endeavors have included a dynamic indoor climate control based on a temperature range. For example, Kramer et al. (2017) have demonstrated substantial energy savings up to 63% in a museum in the Netherlands, using dynamic climate control for both temperature and relative humidity, which allows varying temperature within the entire comfort range. Khovalyg et al. (2022) have shown up to 59% savings of heating demand in a case study office in Switzerland, by temporarily exceeding the comfort range using predetermined hourly temperature profiles during office hours. Interestingly, a better performing building would then result in more energy savings instead of a stricter indoor climate, compared to the current situation in which the adaptive temperature limits are only used for evaluation. Moreover, dynamic indoor climate conditions may help to achieve energy flexibility. The current energy transition in the built environment focuses very much on electrification: renewable energy sources are used for electricity production and electrification of heat and cold production, e.g., by heat pumps. The temporal mismatch between electricity demand and production from renewables puts a substantial strain on the existing electricity infrastructure. Hence, energy flexibility of buildings has become very important: load shifting, peak shaving, and storage are mechanisms that address the temporal mismatch between energy demand and electricity production (Finck et al. 2018). Moving from a strict indoor climate control to allowing more variation, based on a temperature range with additional seasonal adaptation, provides the necessary "freedom of movement" for smart control algorithms to manipulate heating and cooling setpoints over time, and therefore, increase energy flexibility. Papachristou et al. (2021) assessed the effects of several comfort strategies, i.e., different heating and cooling setpoints, on energy flexibility and found promising results. Moreover, applying a dynamic indoor climate in buildings with integrated phase change materials further increases the potential energy flexibility (Wijesuriya et al. 2022) and could increase the cooling resilience in the case of heat waves or power outages (Zhang et al. 2021).

3.3 Towards a successful transition

What is needed for a successful transition towards dynamic indoor climates? Current standards and guidelines incorporate the adaptive temperature limits only for indoor climate evaluation, but not for actual adaptive control: setpoints for heating and cooling are often still constant values. Hence, a better performing building, e.g., due to higher insulation values, potentially results in a stricter indoor climate, while not fully utilizing the permissible temperature ranges for maximum energy efficiency. Therefore, adapting these guidelines to enable actual adaptive (dynamic) control of indoor temperature is a crucial step towards practice and leads to a win-win situation. Moreover, current Building Management Systems often only accept fixed setpoints for temperature control. Hence, technological advancements are needed to facilitate the adoption of gradual adjusting the setpoints based on data-analysis of the varying indoor climate and outdoor climate conditions. Most importantly, from ASHRAE Research Project 884, we know that three mechanisms are important for the acceptation of more relaxed indoor climate conditions: (i) physiological adaptation, (ii) behavioral adaptation, and (iii) psychological adaptation, e.g., expectations of users towards indoor climate (de Dear et al. 1997). Hence, occupants' actual, perceived, and expected freedom to adjust their environment and clothing level according to their thermal comfort needs are important assets for the acceptation of more relaxed thermal conditions. A comprehensive framework on how to implement adaptive thinking into building design and operation, taking into account the three adaptive mechanisms, is available from the IEA EBC Annex 69 (Hellwig et al. 2022b). In current standards, buildings are classified into so-called naturally ventilated buildings in which occupants have freedom to open windows, and in so-called HVAC buildings with mechanical cooling and air conditioning without openable windows. For a high acceptance rate of dynamic indoor conditions, it is important to design hybrid buildings, which integrate the best of both worlds, i.e., providing appropriate ways for occupants to manipulate their thermal environment (Roetzel et al. 2010), also with fans and PECS, combined with smartly controlled HVAC systems that facilitate dynamic control of the indoor climate.

4 Perspectives and highlights

The purpose of this essay is to highlight alternative and yet underemployed avenues for enhancing resilience in humans and buildings, to sustainably cope with global warming and climate change. The following perspectives that have been established are highlighted:

1) A dynamic indoor climate is the key towards a resilient and more sustainable future: it is incontestable that HVAC systems are useful and unavoidable in many buildings, to make our living and working spaces safe and pleasant. However, we need to move away from the misconception that it is *necessary* to create a stable and uniform environment to provide comfort for a hypothetical "average person" at all times. A more dynamic indoor environment, seasonally, and diurnally, creates health-promoting conditions for building occupants without having to sacrifice comfort. Dynamic thermal exposure leads to (a) seasonal acclimatization in humans, (b) increasing human thermal tolerance, and

thermoregulatory capacity and thus *resilience*, (c) reducing the energy consumption of buildings while (d) increasing their energy flexibility (demand response)—a prerequisite for a successful energy transition.

2) The application of local climate conditioning in close proximity of an occupant is more advantageous than climate conditioning of an entire space, for multiple reasons: (a) broader ambient temperature ranges and less strict control setpoints can be applied, which bring along the opportunity for additional energy savings, (b) improving occupant satisfaction by providing individual control, and (c) stimulation of the human thermoregulatory system can be retained, while thermal comfort is ensured by means of local relief (e.g., cooling of the head with a fan).
3) Next to "classical" lifestyle factors such as nutrition and physical activity, healthy thermal indoor environments should be regarded as a major factor for healthy living. Hence, the boundary conditions for health-promoting thermal environments (i.e., more seasonal and daily variation, allowing for spatial differences but provide personal control) need to be defined and subsequently incorporated into indoor environmental standards.
4) Further research is warranted: for example, more evidence is needed on how to improve thermoregulatory capacity and how to safely induce acclimatization in vulnerable and high-risk populations, as those may also benefit from certain controlled doses of temperature training. Vulnerable populations should not be made even more vulnerable by shielding them from any (beneficial) thermal exposure.

Even though this essay addresses major improvements for sustainability and healthiness of the built environment, it is evident that a transition phase is needed to be able to incorporate the proposed changes. As the concepts are new and potentially even opposite to what has been taught and learned within both the research, engineering and stakeholder community, as well as in the general population, it is necessary to provide information and education about the benefits and advantages of a more variable and natural indoor environment, for benefits of both the environment *and* human health. By raising awareness and explaining the positive effects of a more variable, more natural indoor climate, it may be anticipated that healthy and environmentally friendly choices will be made more often, both by individuals, but also in building design, construction, and operation. On top of that, updating regulations and incorporating the suggested concepts into indoor environmental standards will generate further momentum.

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Declarations

Competing interests The authors declare no competing interests.

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