Creating health and resilience by a dynamic indoor climate

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Abstract. Even today, comfort and health are still considered as synonyms in the design of the indoor climate. On top of that there is a strong focus on average-person comfort which has resulted in tightly controlled indoor air temperatures. Our studies show that regular exposure to temperatures outside the thermal neutral zone may result in significant health benefits. Exposure to cold, but also to heat, positively affects our metabolism, the cardiovascular system, and, in addition, 'trains' our resilience to extreme temperatures (heat waves and cold spells). Importantly, it is not necessary to be exposed to extreme temperatures: mild cold and mild warm environments can already elicit beneficial health effects. Translating these insights to the built environment leads to the concept of dynamic indoor conditions. Here, we show that a dynamic indoor climate is acceptable or even pleasant and will contribute to a healthy indoor environment and, because of less strict climate control, will result in lower building energy consumption.

Keywords. health, comfort, resilience, energy. **DOI:** https://doi.org/10.34641/clima.2022.232

1. Introduction

Our indoor climate generally is strictly controlled around a presumed average-person comfort level. However, there is a growing amount of evidence indicating that regular exposure to temperatures outside the thermal neutral zone may result in significant metabolic health benefits. Exposure to cold, but also to heat, positively affects our metabolism, the cardiovascular system, and, in addition, 'trains' our resilience to extreme temperatures (heat waves or cold spells). Importantly, it is not necessary to be exposed to extreme temperatures: mild cold and mild warm environments can already elicit beneficial health effects.

It is important to realise that it is not necessary to be exposed to extreme heat or cold. Firstly, medium-term (days-weeks) temporal excursions outside the thermal comfort zone result in acclimatization, which in turn results in increased comfort ratings. Secondly, short-term (minutes-hours) exposure to low or high temperatures in a dynamic thermal environment may be perceived as acceptable or even pleasant (evoking so-called thermal alliesthesia). Additionally, another positive result is that allowing indoor temperatures to drift within an extended range and applying seasonal adjustments to this range can substantially reduce energy consumption in the built environment.

Accordingly, the study of dynamic thermal conditions is advocated, to assess the effects of thermal dynamics in actual living conditions as well as link and integrate short-term dynamic thermal changes (additional to seasonal differences) to the adaptive comfort model. This information is needed to support the design of healthy, comfortable, and energy-friendly buildings for a sustainable future. Therefore, we conducted and are conducting controlled laboratory tests, studying the effects of dynamic indoor conditions on thermophysiology, health, and subjective comfort parameters. An overview of the results of these and ongoing studies will be presented.

2. Research Methods

In the course of the last decennia we have conducted many laboratory studies to reveal physiological and metabolic health effects of mild excursions outside the thermal neutral zone (see below) and the thermal comfort zone. This begun with exploring the effects of mild cold on human energy metabolism and metabolic health, thus the effect of a cold environment without shivering. The so-called non-shivering thermogenesis was studied in detail and led to the discovery of brown adipose tissue in adult humans [1]. Later we started studying mild heat exposure and the effect on energy metabolism, the cardiovascular system and metabolic health. Critical to the success of our studies were the measurements in the respiration/climate chambers.

2.1 Respiration chambers at Maastricht University

All of our twenty laboratory-rooms are flexible in climate settings, but five of them are specially designed climate-controlled respiration chambers (a kind of room calorimeters). These airtight chambers enable studying human energy expenditure and substrate oxidation by measuring O_2-consumption and CO_2-production under standardized conditions over a period of 12 h up to 7 days. This means that humans can be measured under relatively normal living conditions. Though confined to the room, the subjects can engage in normal daily activities such as sleeping, eating, office work, etc. The rooms (18 m^3) can be equipped with a desk with computer, TV and DVD player, a bed, sink, and toilet. Depending on the study, the room can be used as a bed room, living room or an office. The chambers are equipped with a deep-freeze toilet for collecting faeces; urine is collected separately in bottles. Three air locks provide passage for the exchange of food, collection of urine, and for sampling of blood. Physical activity of the subjects can be performed by using a cycle ergometer, a treadmill or a stepping platform. All in all, the energetics, metabolic aspects, and subjective experiences of human volunteers can be studied in great detail.

The climate is constantly controlled and monitored by an automated information system. The temperature range can be controlled from 10˚C to 45°C and the relative humidity from 20% RH to 80% RH. The rooms are equipped with a Philips SkyRibbon LED light system. The latter allows for tunable white light with correlated colour temperatures ranging from 2000 K to 10000 K, offering a maximum intensity of 1600 lux (under 4000 K). Both temperature and light conditions can also be modified by the participants within pre-set ranges. Air is re-circulated through the air conditioning unit within the enclosed compartment. This allows a circulation rate in the range of 200 – 800 m^3/h. The air can be supplied in two different ways, through mixing or displacement ventilation. For full description of the respiration chamber including technical information, see references [2, 3].

2.2 Physiology and thermal experience

Different sensors are used to assess a variety of physiological parameters during our respiration chamber studies. Core temperature is measured using telemetric pills (VitalSense, EquivitalTM, UK, or CoreTemp, HT150002; HQ, Inc. Palmetto, FL, USA). Skin temperatures are measured by means of wireless iButton dataloggers (DS-1922 L, Maxim, USA). Physical activity is measured using a three-axial accelerometer attached to predefined skin sites (MOX, Maastricht Instruments, NL or Actigraph, wGT3X-BT, USA). Depending on the study, several cardiovascular parameters are collected such as heart rate (HR) by the Polar H10 chest belt (Polar, USA) and blood pressure (Omron M6 Comfort IT, Omron Healthcare, JPN). In addition, often sweat rate is measured by Qsweat (WR medical Maplewood, USA), and skin blood perfusion by laser doppler flowmetry (PeriFlux System 5000, Perimed, SE). Muscle biopsies and blood samples are often used to reveal additional cellular and metabolic parameters.

For thermal experiences, participants fill in questionnaires: Subjective thermal sensation is evaluated using the standard 7-point ASHRAE thermal scale and a continuous visual analogue scale (VAS) is used to indicate thermal comfort. Other regularly used questionnaires are Subjective thermal preference and local thermal sensation by ASHREA 7-point scale.

Results

3.1 Thermal neutral zone

There are limited studies that link thermal comfort to thermophysiology. A classical physiological indicator for the thermal comfort range is the thermal neutral zone (TNZ) [4]. In physiology, the TNZ is defined by the thermo-physiological parameters metabolic rate and sweat production. Below the TNZ metabolic rate increases by non-shivering and shivering thermogenesis to provide extra heat to the body, and above this zone sweat production takes place to cool the body down. The TNZ determines to a large extent thermal comfort and shows considerable overlap with the thermal comfort zone, although individual variation is large [5].

3.2 Physiology and mild temperature conditions

With respect to *cold exposure* just beyond the TNZ, we have repeatedly shown, in line with some older studies [6], that body heat production increases by non-shivering thermogenesis (NST) e.g. [7, 8]. That means that in mild cold conditions the human energy balance can be influenced without noticeable shivering and without appreciable discomfort. Indeed, in both young adults and elderly we have shown experimentally that gradual temperature variations are accepted without significant discomfort [9, 10]. We also tested mild *cold acclimation*, revealing after ten days of regular cold exposure a significant increase of NST, a significant decrease in thermal discomfort and the desire to change temperature, combined with significant improvement of insulin sensitivity [11]. Our results also show a significant individual variation in NST and a variation between groups: blunted in obese and reduced in elderly [8, 12]. In general, our results clearly show metabolic and cardiovascular adaptations of our body to (mild) cold and regular cold exposure and an improved resilience to cold.

Just as some classic, active and extreme (exercise-induced) heat acclimation protocols, also passive and mild *heat acclimation* induces typical physiological adaptation [13]. Thermal acclimation is a fine-tuned process, which is why in the passive and mild heat acclimation studies, we observed typical acclimation effects to heat, but to a lesser extent as in the active heat acclimation studies. Indeed, mild heat acclimation shows improved sweat production, improved skin blood perfusion, lowering of heart rate and blood pressure and also a lowering of the core body temperature. All these are indicators of improved heat resilience. On top of that, in line with the cold studies, we found that sugar metabolism is improved: lower blood sugar levels and improved insulin sensitivity were observed after passive mild heat acclimation [14]. Although mechanisms seem to be different, both regular exposure to cold *and* to heat reveal improved metabolic health and increased resilience to temperature extremes.

3.3 Towards dynamic indoor climates for the built environment

These results show that, due to the application of the traditional standards and the resulting small variation of the indoor climate, the human thermoregulatory system is much less challenged. This affects our metabolism and makes occupants vulnerable to temperature extremes. More frequent exposure to heat and cold has a positive effect on metabolic health and may create more resilience to these deviant temperature conditions. As described in the adaptive comfort model [15, 16], which nowadays is included in the ASHRAE standard 55, field studies show that people adapt to climatological, seasonal and daily variations in temperature and tolerate a much wider range of temperatures than prescribed by the predicted mean vote model [17] .

Integrating this adaptive model into buildings' indoor climate control results in a more dynamic indoor climate and also leads to lower energy consumption and costs for heating and cooling. However, physiological parameters and health aspects are not specifically included in the adaptive model, which underpins the need for further development of modern indoor climate standards.

Moreover, although the adaptive comfort model has changed the paradigm from maintaining a constant indoor climate to seasonal changes in temperature control, the adaptive comfort model has been designed and validated for so-called Naturally Ventilated Buildings only.

In the DYNKA research project we focus on dynamic indoor temperature conditions for offices with HVAC systems to elicit health benefits combined with energy savings. Building energy simulations have been performed to demonstrate the energy saving potential on a building level by relaxing the ambient indoor temperature requirements to NEN-EN16798 categories III and IV. The permissible operative indoor temperatures were determined based on the Running Mean Outdoor Temperature (RMOT). In this standard, the setpoints are, however, only stipulated for the Winter (RMOT<10˚C) and Summer scenario's (RMOT>15˚C). Hence, the settings for 10˚C<RMOT<15˚C were determined via interpolation. In this way, temperature ranges were constructed for HVAC-buildings analogue to the adaptive comfort model for NV buildings. To increase thermal comfort levels, a daily temperature drifting was introduced, as well as night ventilation, starting cooler and warming up gradually during the day. The building simulation models comprise office buildings of approximately 5,000 m2 and with three floors with three different years of construction: 2012, 1990 and 1970. The building simulation results were compared to reference models, with conventional thermostat setpoints of 21°C for heating and 23°C for cooling. The results showed that for category III, savings in energy demand up to 45% are possible in a climate region like the Netherlands, depending on the year of construction. For category IV the energy demand savings are up to 62%.

By aligning the indoor climate control with the dynamic thermal needs of humans and applying them in the built environment, health and thermal resilience can be improved and at the same time the energy demand of buildings can be greatly reduced, but more research is needed on balancing comfort, health and energy efficiency.

3.4 Personal control

Finally, as we described above, there are significant differences in thermal responses and thermal experiences between individuals and groups of people. It is also well known that if individuals have enough time to adapt and, secondly, have some control of their living environment, they accept larger ranges of temperatures to be exposed to. Therefore, rooms and offices may need controllable thermostats, preferably windows that can be opened, and personal control systems. Recently we have shown that a dynamic climate with 8°C variation over the day can lead to acceptable comfort, and with a PCS, this comfort was even improved. Importantly, the PCS was designed to locally affect the body temperature, without compromising the health effects of the dynamic indoor climate [18].

3. Discussion

Our results over the years clearly highlight the advantages of a dynamic indoor environment for health, resilience and for building energy savings.

For application of this knowledge, building users need to be convinced to apply this new concept. For office environments, more knowledge is needed on how alertness and productivity are affected by the dynamic climate. There are indications that productivity may be enlarged compared to a fixed indoor climate. This topic will be a next step in our study series.

Conclusions

Our studies reveal that a dynamic indoor climate can be acceptable and can contribute to a healthy indoor environment. Secondly, a dynamic indoor climate needs less strict control and therefore will result in lower building energy consumption.

4. Acknowledgements

We thank Loes Visser, Pascal Rense and Wei Luo for their contribution for collecting and interpreting data. This work was supported by EU FP7 project DIABAT (HEALTH-F2-2011-278373), Netherlands Organization for Scientific Research (NWO) (TOP 91209037), Dutch TKI Urban Energy project DYNKA (TEUE117G3L6U), and Netherlands Organization for Health Research and Development (ZonMW)/Dutch Diabetes Research Foundation (95105007).

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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