INDOOR CLIMATE

AND

ADAPTIVE THERMAL COMFORT

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PREFACE

In the past 40 years the authors of this book conducted numerous investigations into the indoor environmental quality of buildings. This was usually in response to discomfort complaints and health symptoms from occupants, for example too high or low temperatures, drafts, stuffy and stale air, headaches, fatigue or eye and respiratory irritations. In the beginning of the 1980's, there were few methods and techniques available for conducting indoor climate investigations. Working for the Occupational Health Service of the Dutch Government[1] at the time we had to develop systems to be able to perform long-term measurements to collect data to get an impression of the physical and chemical composition of the indoor environment in buildings. After a few years, it became clear that measurements were useful, but also had their limitations because the measurements and the available standards and guidelines could not always explain the occupants' discomfort and symptoms in the indoor environment.

This insight led to the development of a research methodology, based on Post Occupancy Evaluation (Leaman & Bordass, 2001) to systematically map occupants' perceptions and then explain them on the basis of scientific, statistical knowledge about the relationship between building characteristics and health and comfort experiences of building users. The methodology became known as the Building-in-use method (Vischer, 1989; Kurvers & Leyten, 1992) and was later further developed as a diagnostic method for dealing with discomfort and health symptoms related to the indoor environment (Leyten & Kurvers, 2007). During these studies, we noticed that occupants in buildings with closed, glass façades and extensive air-conditioning systems experienced more discomfort and health symptoms than occupants in buildings with openable windows and simpler climate systems. This observation was increasingly confirmed by scientific field studies and this phenomenon became widely known as the Sick Building Syndrome (Burge, 2004). To explain the comfort and health symptoms, we later developed the concept of *robustness of indoor climate* (Leyten & Kurvers, 2006). This is explained in more detail in Chapter 5. By studying the indoor environment in buildings, we were also regularly consulted on building planning and renovation projects. It struck us that often limited scientific knowledge on the influence of indoor environments on people's comfort and health is used in design and consulting practice. With this book, we aim to narrow this gap by addressing the disciplines responsible for the design of the indoor climate in buildings: developers, architects, building physicists, HVAC-consultants, contractors, facility managers, health and safety professionals and, above all, students. The main subject of this book is thermal comfort. Other facets of indoor environment, such as air quality, lighting and acoustics are also important, but are only addressed here indirectly when relevant.

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[1] In Dutch: Rijks Geneeskundige Dienst

CONTENTS

INTRODUCTION

The main challenge for the building industry is to create buildings in which occupants feel comfortable and healthy and that use little energy. Buildings should, by design, use as much natural energy as possible for most of the day and year and are heated or cooled only when really necessary, using energy from renewable sources (Olesen, 2018). With outdated models of human thermal comfort this inevitable ambition will not be achieved and therefore architects, developers and their consultants must understand and be able to apply the principles of *adaptive* thermal comfort.

Over the centuries, temperatures that people find pleasant or comfortable have changed considerably. Since the 1940s, for example, the average winter temperature in homes has increased by about 1°C per decade (Nicol et al., 2012). This is due to developments in building methods and building materials, as well as a different way of heating. And also changes in clothing play a role. As a result of cultural influences, fashion and the use of new textile materials, the physical properties of clothing, such as thermal insulation and moisture transport, have changed.

Everyone experiences situations where you feel too cold or too hot. Sometimes you prefer to sit in the sun and warm up a bit when you are cold or like to feel a nice cool breeze when it is hot. At home or at work, when you feel cold, you put on a sweater or try to change the temperature by opening or closing a window or adjusting the thermostat to be comfortable again. This "being comfortable" is called *thermal comfort* in technical jargon. The formal definition is: "Thermal comfort is that state of mind which expresses satisfaction with the thermal environment and is determined by subjective evaluation" (EN 16798-1, 2019). This definition originates from the air conditioning industry and is measured with a thermal sensation scale in climate chamber research and field studies (see Table 2.1 and Table 2.2). However, comfort is a broader concept and has a different meaning in different climates and cultures. In a hot climate, a cooler situation can lead to more comfort, whereas in a cold climate an open fire, for example, may give comfort. Other words for comfort also have a broader meaning, such as *behaaglijk* in Dutch, *hygge* in Danish or *gemütlich* in German. In some Arab and Asian countries, *rahat* means cool, cosy or protective and is used when it has cooled down after a hot period (Roaf & Nicol, 2019).

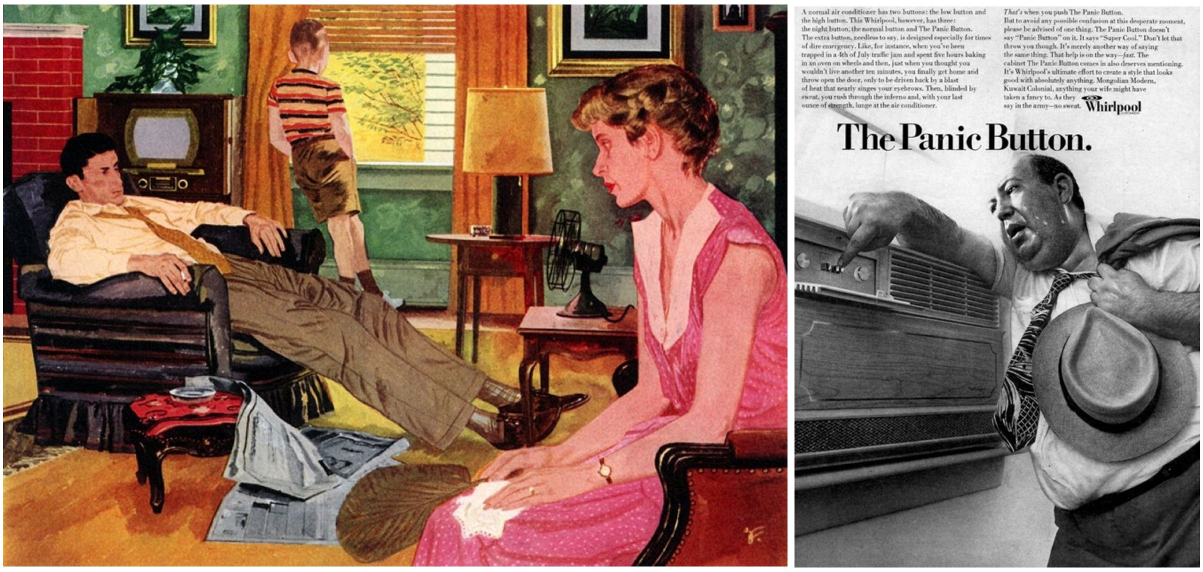
The temperature level in buildings is important because the built environment is responsible for more than 35% of global energy consumption (UN, 2017). In addition, in certain types of buildings, the way the indoor climate is controlled can lead to structural and long-term dissatisfaction with the thermal environment and have negative effects on the health, morale, performance and absenteeism of employees (Leyten, 2006). Thermal comfort is not achieved by one "ideal" temperature for everyone, but has proven to vary among occupants. Now that we live in a time when buildings must become more energy efficient and sustainable, it is very important to understand what temperatures people experience as pleasant, acceptable and stimulating. The warming climate poses an additional challenge because there is a real risk that buildings with energy saving measures in place aimed at the heating season will become too warm in hot summers. If this leads to the installation of air conditioning, the cure is worse than the disease. Therefore, it is important that standards and guidelines for thermal comfort are in line with the latest scientific insights. Energy-efficient buildings and innovative solutions are necessary, but they must be based on a contemporary and scientifically founded vision of thermal comfort.

This book is not a list of numbers and guidelines to be met by the indoor climate, but rather highlights the background to thermal comfort so that it can be better understood and standards and guidelines can be nuanced and adapted. Also, this book explains that thermal comfort is achieved when people, when they are too cold or too hot, take various measures to make themselves comfortable again. They will do this by adjusting the building, e.g. opening windows or doors, using fans or blinds and/or by adapting themselves to the environment, e.g. by changing clothes, drinking cold or hot drinks or exercising less. This approach to adaptive thermal comfort differs from how traditional thermal comfort is seen: as a *product* delivered by the building and especially its technical systems, and with which occupants should be satisfied if the temperature remains as constant as possible at a predetermined value.

1 THE IMPORTANCE OF A GOOD INDOOR CLIMATE

In the course of history, man learned to design buildings in which extreme variations in the outdoor climate were taken into account in order to achieve a pleasant indoor climate. Many different, innovative building designs were developed with natural climate solutions adapted to the local climate. For example, by using heavy structures to buffer heat in the structure or by using open facades to let in cooling breezes. In other climates, wind catchers on buildings provide a cooling airflow inside, and air flows over tanks of water cause evaporation to cool the air. All with the aim of making the indoor climate more pleasant than the outdoor conditions, which can be extreme in some parts of the world.

From the end of the eighteenth century, knowledge in areas such as biology and physics increased and natural air-conditioning techniques were further perfected (Short, 2018). From the end of the nineteenth century, a revolution took place: technology developed very rapidly and advanced mechanical air-conditioning techniques emerged that could not only heat, but also cool, humidify and dehumidify air. Rooms could be kept at a specific temperature and humidity, largely independently of the external climate. Energy consumption was irrelevant because of the massive and cheap production of oil. At the beginning of the twentieth century, Willis Carrier developed a system to keep the temperature and humidity in a printing house within certain limits, which significantly reduced machine down-time and allowed more newspapers to be printed. A few years later, the first cinema in New York was equipped with air cooling, based on Carrier's invention. The number of visitors rose spectacularly and within a short time, hundreds of cinemas in the United States were equipped with air-conditioning. Subsequently, more and more department stores, offices, schools and even homes were air-conditioned. Air-conditioning developed into a global industry with huge marketing budgets that influenced consumers (Figure 1.1).



A normal air conditioner has two buttons: the low button and the high button. This Whirlpool, however, has three: the night button, the normal button and The Panic Button. The extra button, needless to say, is designed especially for times of dire emergency. Like, for instance, when you've been trapped in a 4th of July traffic jam and spent five hours baking in an oven on wheels and then, just when you thought you wouldn't live another ten minutes, you finally get home and throw open the door, only to be driven back by a blast of heat that nearly singes your eyebrows. Then, blinded by sweat, you rush through the inferno and, with your last ounce of strength, lunge at the air conditioner.

That's when you push The Panic Button. But to avoid any possible confusion at this desperate moment, please be advised of one thing. The Panic Button doesn't say "Panic Button" on it. It says "Super Cool." Don't let that throw you though. It's merely another way of saying the same thing. That help is on the way—*fast*. The cabinet The Panic Button comes in also deserves mentioning. It's Whirlpool's ultimate effort to create a style that looks good with absolutely anything. Mongolian Modern, Kuwait Colonial, anything your wife might have taken a fancy to. As they say in the army—no sweat.

Figure 1.1: Examples of advertisements of the air conditioning industry around 1960 in the United States, where air conditioning was presented as a primary necessity of life.
Source: www.pinterest.com/Vintage HVAC Ads.

The purpose of heating, ventilating and air conditioning (HVAC) systems is to support the building functions. The form, the structural characteristics, the building physics and the orientation determine, together with the prevailing outdoor climate and the indoor climate requirements, which systems are needed in a building. This means that for a given outdoor climate and comfort requirements, air conditioning becomes more important the less architectural and building physics properties are utilized. Examples of successful and specific applications are air conditioning in cars and trains, where building physics measures are not sufficient to bring the temperature to a comfortable and safe level. Also, in department stores, for example, which have a high internal heat load due to lighting, equipment and customers, or in microelectronics factories, where the manufacturing process requires narrow indoor climate tolerances, air conditioning can often be necessary.

Besides the many useful applications of air conditioning, there are downsides that have far-reaching consequences. The knowledge that architects have accumulated over the centuries to design naturally conditioned buildings has largely disappeared, because architects can now focus solely on “creating aesthetic forms” (Short, 2018). Necessary building physics principles and solutions were no longer integrated into designs, so that comfortable temperatures could only be achieved by energy-intensive air conditioning systems. Millions of people worldwide were thus made dependent on air conditioning (Lundgren-Kownacki, 2018). However, there is increasing evidence that air conditioning compromises the physiological adaptation mechanism in humans (Yu, 2012) and also impairs behavioral and psychological adaptation (Rijal et al., 2009). In addition to the huge implications for energy consumption, CO_2 emissions and the contribution to climate change, there have been other consequences. Recent heat waves in the United States have caused more deaths than heat waves in previous decades. People often stayed indoors, relying on air conditioning, rather than using their evolutionarily evolved physical adaptability and behavior to cool off in the shade in parks, swimming areas and other natural cooling opportunities. The lack of useable openable windows meant that buildings could not be cooled at night by cooler outside air. The large peaks in energy demand led to power outages, air conditioning failures and consequently very high indoor temperatures, resulting in high mortality rates (Chappells & Shove, 2003; Lundgren-Kownacki, 2018).

In recent decades, much research has been conducted into how building users experience their indoor climate. In the periodic Benchmark of the Centre for People and Buildings, for example, which is based on 138 case studies in the Netherlands at 52 different organizations with over 23,000 respondents, measured in the period 2007 to 2016, 40% of the building users were dissatisfied with the indoor climate (CfPB, 2017). In an analysis of 351 buildings with over 52,000 occupants in the United States, 53% of the occupants appeared dissatisfied with the temperature. Buildings certified with a sustainability certificate or label for “health, productivity and liveability” (e.g., LEED, BREEAM, WELL) did not perform better than non-certified buildings in this analysis (Karmann, et al., 2018). An analysis of 11,243 responses from occupants of 93 LEED-certified office buildings in the U.S. and Canada found that no relationship existed between LEED rating and occupant satisfaction with the indoor environment (Altomonte et al., 2019). Among the reasons cited by the researchers are that personal influence has significant potential for increased comfort, improved energy performance, and increased satisfaction with the indoor environment, and that better metrics for achieving IEQ points are needed to form reliable indicators of user satisfaction.

A review article by Leyten (2006) describes research in 331 buildings in various countries in Europe and the United States. By means of measurements, technical building surveys and subjective responses of 31,500 employees, correlations were found between the comfort and health of employees on the one hand and the characteristics of the buildings on the other. Cooling, humidification and recirculation of the supply air, the absence of usable openable windows, insufficient possibilities to adjust temperature and ventilation by the occupants themselves and working in large open plan offices were risk factors for occupant dissatisfaction and health symptoms.

The risk factors are mainly found in buildings where the solar gain through the transparent façade is so high, that the indoor climate has to be controlled by means of air conditioning. As a result, the indoor climate is highly disconnected from the outdoor climate and the users have little influence on the temperature. In the American database of the Center for the Built Environment, with more than 370 buildings and 43,000 subjective responses from occupants about the indoor climate, the users gave their opinions about thermal comfort, air quality, lighting, acoustics and room layout, among other things (Brager & Baker, 2008). Only 11% of all buildings met the thermal comfort standard of at least 80% satisfaction. Mixed-mode buildings, which switch to cooling only when outside temperatures are high and featured operable windows, were then compared with the rest of the buildings (mostly with conventional air conditioning). Figure 1.2 shows that the occupants in mixed-mode buildings are on average more satisfied with the indoor thermal climate than those in air-conditioned buildings. This is largely due to the fact that the indoor climate is more variable and that occupants in this type of buildings have more opportunities to control the indoor climate.

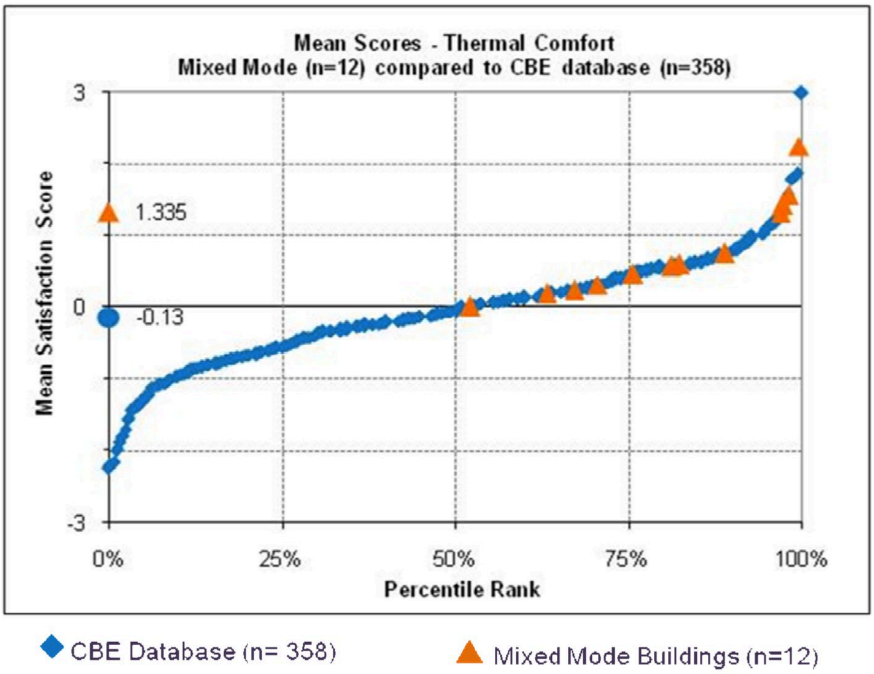


Figure 1.2: The assessed mean satisfaction with thermal comfort per building, expressed on a 7-point scale (-3 = very dissatisfied to 3 = very satisfied) in the database of the Center for the Built Environment. Source: Brager & Baker, 2008.

In a study of 95 office buildings in the United States (Mendell, 2009), it was found that in summer the observed indoor temperatures were below the lower limit of the recommended

summer range in ASHRAE Standard 55 in more than half of the cases. In winter, the recommended ranges were both under and over exceeded (
Figure 1.3). Moreover, the mean indoor temperature was lower in summer than in winter. Since people are dressed more lightly in summer than in winter, this must lead to comfort problems, especially since such low temperatures are only possible in air-conditioned buildings and, as explained in Section 4.2, users of air-conditioned buildings are less inclined to adjust their clothing insulation. Furthermore, it was found that in summer, more health issues, such as headaches, fatigue and nose and throat symptoms occurred when the measured temperatures were lower than the comfort range. In winter, on the other hand, temperatures higher than the recommended upper limit led to more symptoms. Thus, more health symptoms occurred when there was too much cooling in summer and too much heating in winter. That this also leads to unnecessary energy consumption is obvious.

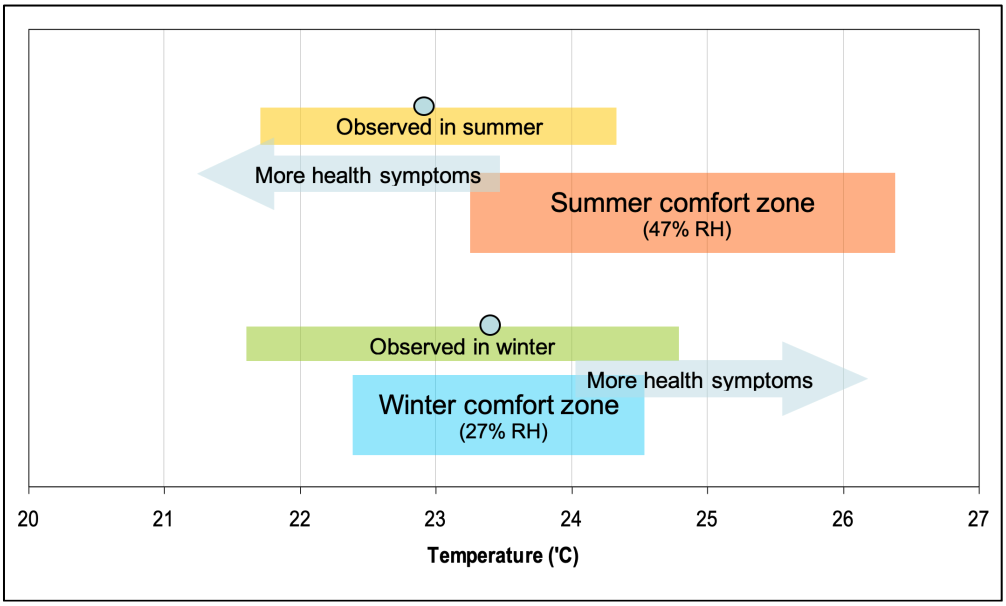


Figure 1.3: Measured temperatures and health symptoms related to the comfort intervals in ASHRAE-55 in summer and winter in 95 office buildings in the US. Source: After Mendell, 2009.

The question is why this official ASHRAE standard is often departed from in practice. A possible explanation for the low temperatures in summer is that it is a widespread view in the air-conditioning industry that employee performance is at its maximum at a temperature of around 22°C and that above and below that performance drops (Wargocki et al, 2006, 2007). Chapter 10 of this book explains that this view is incorrect (Parkinson, de Dear and Brager, 2020). However, it does not explain why higher temperatures occur in winter than in summer and even higher than the ASHRAE comfort range. A possible explanation for this is that maintaining extra-low temperatures in summer and extra-high temperatures in winter is seen by some companies, incorrectly, as a status symbol.

The human body needs to be kept at a core temperature of about 37°C as much as possible, and this is achieved to a large extent by autonomous physiological processes, such as vasoconstriction and vasodilatation to regulate the heat exchange with the environment, evaporating sweat when we are hot or shivering when we get cold. When we feel too cold or too hot, it is actually a warning sign of an eventual health threat.

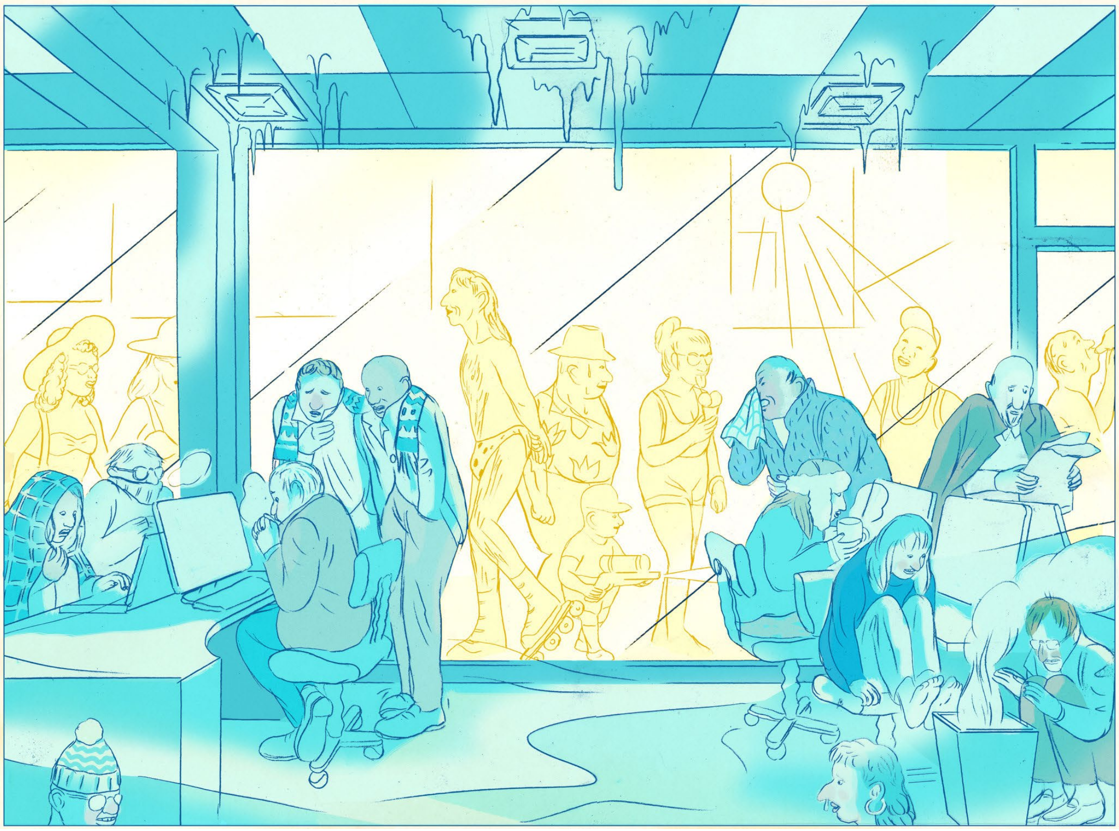


Figure 1.4: Enduring Summer's Deep Freeze.
Source: Olivier Schrauwen in Enduring Summer's Deep Freeze by Kate Murphy, New York Times, July 5, 2015.

It is therefore an evolutionarily formed warning mechanism to ensure that we take measures to avoid (prolonged) discomfort. This adaptability has enabled humans to live in large parts of the world, in deserts (up to around +50°C) and around the North Pole (down to around -50°C). This sometimes requires very drastic measures regarding clothing and housing. It therefore seems paradoxical that precisely in buildings with full climate control occupants experience discomfort. Providing a thermally comfortable indoor climate does not mean that we must strive for a temperature level within a narrow bandwidth; on the contrary. Humans have a close relationship with nature and the climate due to their evolutionary adaptability. In winter, he or she expects a lower indoor temperature than in high summer, so he or she will put on warmer clothes. This expectation is based on experience of the relationship between outdoor and indoor temperatures. Variation in temperature can even give a feeling of pleasure. For example, when we are cold it can be very pleasant to sit temporarily in the sun, or near a stove that we would normally find much too hot (de Dear, 2011). In a warm environment, a cool breeze can be wonderful, while the same breeze can be irritating and uncomfortable when we are cold. This phenomenon is called alliesthesia and will be discussed further in Section 4.6. Variation in temperature also appears to be healthy for the heart and blood vessels and can help against obesity and diabetes (van Marken Lichtenbelt, 2017).

In 1948, the World Health Organisation (WHO) defined health as “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”. With the invention of antibiotics, it was thought at the time that such a state could be achieved for everyone in the world. Now, more than 70 years later, far fewer people are indeed dying of all kinds of infectious diseases, but because we are getting much older, other chronic diseases have taken their place. According to the old definition, few people are healthy today. Therefore, after years of research and consultation, the WHO has proposed a new definition (Huber et al., 2011). It is not diseases, abnormalities or deficiencies that determine whether or not we are healthy, but the resilience and adaptability to take control of our lives as much as possible. The new concept is formulated as follows: “Health is the ability to adapt and self-manage, in the face of social, physical and emotional challenges” (Huber et al., 2016). The approach to thermal comfort as an adaptive process thus fits in well with the WHO's renewed view of health.

In recent decennia, medical science has been able to establish clearer links between regular high levels of physical activity and cardiovascular health (Stoops, 2004) and brain fitness (Scherder, 2017). Regular exercise is a critical factor for a healthy cardiovascular system. During exercise, a certain degree of discomfort is experienced, but after exercise, the production of endorphins provides a calm and satisfied feeling. The cardiovascular and thermoregulatory systems are closely related. During exercise, the released body heat is regulated by the thermoregulation system and the cardiovascular system is activated. There is agreement in medical science that the thermoregulatory system needs to be exercised for better health, as also shown in research on heat shock protein (Yu, et al., 2012, see Section 4.3). Many cultures have traditions of alternating hot and/or humid conditions with ice-cold immersion baths, such as the Greek and Roman baths, the sauna and the hammam in the Middle East. People have experienced these extreme temperature changes as pleasant and beneficial for centuries. In many buildings, however, we condition our interior spaces within narrow limits with the effect of exercising our thermoregulatory system as little as possible.

When a person gets cold, the body may start to shiver (this happens autonomously), which increases the metabolism and warms the person again. But even when you are a little cold, the body produces heat without shivering. The tissue that is responsible for heat production in these circumstances is brown fat. Regular exposure to cold increases the production of brown fat. In this way the body can adapt to cold conditions. What is initially experienced as uncomfortably cold becomes more acceptable over time (Van Marken Lichtenbelt, 2016). People who do not produce brown fat or have a relatively high amount of white fat appear to be less healthy. Brown fat also has a beneficial effect on the prevention of obesity. In type 2 diabetes, the hormone insulin has too little effect on the muscles, causing them to absorb too little sugar and too much sugar to enter the bloodstream. Medication is usually used to lower blood sugar levels. Research has shown that a regular stay in a cooler environment has a beneficial effect on the sugar absorption of muscles, so that medication can be reduced (Van Marken Lichtenbelt, 2017).

1.1 DEFINITIONS OF BUILDING TYPES

In the foregoing, air-conditioned buildings and mixed mode buildings have already been mentioned, but in reality, there are various mixed forms of building and installation types. In the remainder of this book, when interpreting research on the differences in comfort experienced in different types of buildings, it is important to make a clear distinction between building types and how they are conditioned. This section will therefore first discuss the different building types.

In studies on adaptive thermal comfort, *air-conditioned* buildings refer to buildings with central air conditioning. The air is extracted at a central point, usually on the roof or top floor, filtered, heated, cooled, often humidified and sometimes dehumidified, and ducted through the building to the various rooms. Sometimes the air is recirculated to save energy, but nowadays part of the energy is recovered by passing the exhaust and supply air through a heat exchanger. In the (work)spaces, there are usually appliances in various shapes and designs for heating and cooling to control the temperature at the room level.

The indoor temperature is controlled using sensors, valves, pumps, motors and computer software. Many air-conditioned buildings have a layout with deep open plan work spaces. Sometimes there is a possibility for the users to control the temperatures per work space, but this possibility often proves ineffective in practice due to the size and depth of the work spaces and the presence of many people per workspace. Often there are also no or limited possibilities to open the windows, so adapting the environment to personal needs are limited. The indoor climate is largely decoupled from the outdoor climate, so that the indoor temperature does not or only marginally follows the outdoor temperature.

The term *naturally ventilated* buildings, or *free running* buildings, refers in the studies to buildings without mechanical (air) cooling in operation. The term naturally ventilated focuses on the supply of fresh outside air through openable windows, ventilation grilles in the facade or other structural facilities. The exhaust takes place by means of cross ventilation or passive or active central extraction. The windows can be operated effectively by the occupants to ventilate whenever needed and to influence the temperature, air movement and supply of fresh air. The term free running emphasises that there is no heating or cooling in operation at certain times of the day or year. The term *climate-responsive* is also sometimes used, which indicates that the building acts as a filter for the outdoor climate and a balance is established between excluding undesirable and admitting desirable climatic influences (Looman, 2017). The indoor temperature varies with the outdoor temperature and is controlled by building physics solutions such as shading, heat accumulation in the building mass combined with night ventilation. The emphasis is more on the application of (innovative) passive climate control techniques. In practice, these terms basically describe the same kind of building.

The term *mixed-mode* buildings is used in the literature in two ways: in the first major field study (de Dear, Brager & Cooper, 1997 hereafter RP-884 study) this term is used for fully air-conditioned buildings with windows that can be opened. These types of buildings were rare in this database. In this study, these buildings most closely resemble air-conditioned buildings. In a second large field study conducted in Europe (Nicol & McCartney, 2000, hereafter SCATs study) and in recent publications (Parkinson, de Dear & Brager, 2020), mixed-mode buildings are referred to as buildings that are free running for a large part of the time up to a certain temperature and are mechanically cooled to some extent above that temperature.

Mixed-mode ventilation is also referred to as *hybrid ventilation*, both natural and mechanical ventilation are used with the basic principle: natural if possible, mechanical if necessary. There is always a mode or circumstance in which natural ventilation is used. For the mechanical part, two variants can be distinguished. The first consists exclusively of a mechanical exhaust to create underpressure, whereby supply takes place via windows, grilles and specific openings. The second variant uses balanced ventilation, which may include filtering, heating, heat recovery, cooling and/or humidification (Van Bruggen, 2016). Most of the time, natural ventilation takes place and, above a certain temperature, mechanical ventilation, possibly with cooling of the supply air, comes into play.

When cooling is provided, hybrid ventilation most closely resembles buildings referred to in international publications as mixed-mode. Natural ventilation is always leading in hybrid buildings through the use of openable windows, dedicated ventilation openings and other provisions to achieve thermal draught (passive exhaust), supplemented by solutions for passive or free cooling, external shading, utilisation of thermal mass in combination with night ventilation and the use of modern control systems and sensors (TVVL, 2017). Most of the time, such buildings are free-running and below and above a certain indoor temperature, heating or cooling is provided. However, this must be done in such a way that through various forms of adaptation, thermal comfort can be achieved for and by the occupants (see chapter 4).

2 THE QUEST FOR COMFORTABLE TEMPERATURES

2.1 INTRODUCTION

What temperatures do people find pleasant or comfortable? The answer may surprise some: somewhere between 14°C and 32°C. It all depends on where you live, what clothes you wear, what you do, what you are used to and what you expect. Sometimes you might hear the phrase "set the thermostat to 22°C, that's a good temperature for most people". This idea stems from research carried out in the 1960s and 1970s, mainly in climate chambers. The test subjects, mostly from Europe and the United States, wore the same clothes, performed the same tasks, spent only a few hours in the climate chamber, had no contact with the outside world, were often unable to set temperatures themselves and, in most cases, knew what the purpose of the research was. They were focused on answering questions about their sense of warmth, also known as thermal sensation. There was no influence of previous experiences, no work stress and there were no colleagues. In fact, the test subjects were in an abstraction of reality. The result was a fairly narrow bandwidth of about 3.5°C within which people would be "satisfied" (Fanger, 1970).

In contrast, studies of thermal comfort under everyday conditions show that comfortable temperatures can vary over a wide range. This depends not only on the physical environment, but also on personal, social, cultural, geographical and climatic factors. Moreover, individual preferences do not appear to be stable, but are subject to change. This means that thermal comfort cannot be achieved in practice by offering a constant temperature to a group of people in an open plan office, for example, even if it falls within the narrow bandwidth of around 22°C.

Thermal comfort has been studied since the 1930s in both climate chambers and in real environments (field studies). The results of climate chamber research became popular in the 1970s and, until fairly recently, formed the basis of standards and guidelines that were leading in how buildings were designed and air-conditioned. From around 1990, field research gained momentum, partly because measuring equipment became smaller, smarter and cheaper. The results led to the start of the revision of standards and guidelines.

2.2 HUMAN THERMOREGULATION AND HEAT TRANSPORT

The physiological and physical aspects of human thermoregulation are outlined below, followed by a discussion of analytical climate chamber models.

HEAT PRODUCTION

The human body can only function properly (chemical processes such as enzyme, protein, hormone production) if the core of the body (the vital organs) is kept within narrow temperature limits. During metabolism, food is burned with the help of oxygen from respiration and converted into energy. Under normal circumstances, most of this energy consists of heat; a relatively small part is converted into mechanical energy (physical exercise). Metabolism (M) is expressed in W/m^2 or in Met (1 Met is 58.16 W/m^2A_{Du}, equivalent to a person sitting down). The m^2A_{Du} is the body surface area, determined by the Dubois formula and depends on body height and build. Usually 1.8 m^2 is used, which means that an average person produces about 110 Watt of heat at rest. When a person is performing physical work (W in W/m^2), energy is required. This mechanical work is obtained from the metabolic energy production (M in W/m^2). The amount of energy that remains (the major part) is released as heat (H in W/m^2):

$$H = M - W$$

With this mechanical work, the mechanical efficiency η is relevant:

$$\eta = W / M$$

Mechanical power therefore represents a percentage of the total metabolic energy. η is close to 0 for most exertion and rises slowly to 0.1 for activity (physical work) and around 0.2 for very intensive activity (e.g., climbing a mountain). The metabolic rate is determined by measuring oxygen consumption, recording heart rate or using extensive tables. Measurement is the most accurate, but often difficult to realise in a working environment. Determining metabolism using tables is simple but inaccurate and requires considerable experience. The metabolism varies over time and is strongly influenced by breaks, eating and drinking, mental effort and stress.

HEAT TRANSPORT

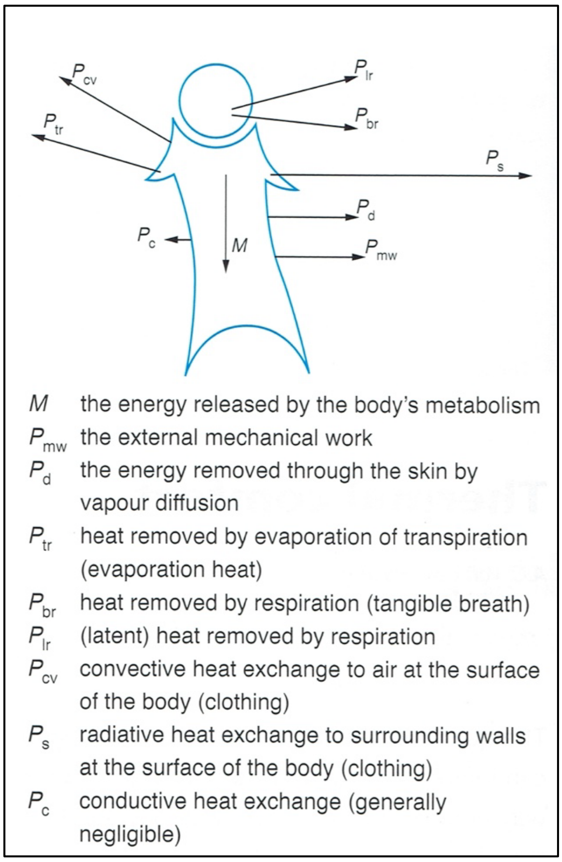
A naked body at rest will be thermally neutral at an ambient temperature of about 28°C (Mcintyre, 1980). In other words, the body is in thermal equilibrium, the skin temperature is experienced as pleasant (approximately 34°C) and there is no sweat production. Heat is transported from the core of the body to the skin surface by means of blood flow and, to a lesser extent, by conduction in the tissues. At the skin surface, the heat is then transferred to the environment. When the body is in danger of losing too much heat, for example in a cold environment and/or when heat production is low, vasoconstriction occurs, which means that less blood flows to the skin surface and the skin temperature drops. When the body is in danger of becoming too warm, in a warm environment and/or with a high metabolism, vasodilation occurs, causing the skin temperature to increase and more heat to be transferred to the environment. When the body, due to exertion or a high ambient temperature, has to give up more heat, sweating occurs after some delay and the pulse and respiratory rate increase. After repeated exposure to higher temperatures (from a few days to a few weeks), acclimatisation occurs: sweating starts earlier and in greater amounts, which lowers the skin temperature and reduces the heart and respiratory rate.

THERMOREGULATION

The main inputs for the thermoregulatory system are skin temperature and core temperature. The control centre is located in the hypothalamus in the brain, the anterior part regulates when the body gets too warm, the posterior part controls when there is a threat of cooling down. The anterior hypothalamus functions as a sensor and regulator which means that when the temperature of the anterior hypothalamus rises above its set point, nerve impulses are emitted to stimulate vasodilation and sweating. When the body is unable to dissipate sufficient heat despite maximum sweating, thermoregulation becomes disturbed and the core temperature rises, putting the body's functions at risk. The posterior hypothalamus defends the body against cooling down. It does not “feel” temperature itself but receives data from skin sensors and then activates vasoconstriction and shivering.

2.3 PHYSICAL MECHANISMS

In the previous section we saw that the body tries to keep its (core) temperature constant by controlling the heat flow to the skin. The skin surface in turn exchanges heat with the environment by means of radiation, convection, evaporation and conduction (Figure 2.1). Heat exchange with the environment through conduction is usually negligible. It occurs in practice only where the skin comes into contact with materials (bare feet, hands, forearms). Skin temperature is influenced by a combination of the abovementioned physical aspects. The heat exchange is significantly influenced by the thermal insulation and water vapour permeability of the clothing.



M	the energy released by the body's metabolism
P_{mw}	the external mechanical work
P_d	the energy removed through the skin by vapour diffusion
P_{tr}	heat removed by evaporation of transpiration (evaporation heat)
P_{br}	heat removed by respiration (tangible breath)
P_{lr}	(latent) heat removed by respiration
P_{cv}	convective heat exchange to air at the surface of the body (clothing)
P_s	radiative heat exchange to surrounding walls at the surface of the body (clothing)
P_c	conductive heat exchange (generally negligible)

Figure 2.1: Energy exchange of the human body with the environment.
Source: Van der Linden, 2016.

RADIATION

By means of thermal radiation, the body exchanges heat with all the objects surrounding it, for example walls, windows, the sun and heating radiators.
The degree of radiation depends on:

- The temperature difference of the heat exchanging surfaces;
- The distance between the exchanging surfaces and the angle at which they face each other;
- The emission coefficient of the radiating surface.

Radiation is expressed in terms of the mean radiant temperature t_{mrt} (°C), which can be defined as: the temperature of a uniform environment at which a person would exchange the same amount of heat by radiation as in the actual environment.

CONVECTION

Usually the skin temperature (or in practice the surface temperature of the clothing) of a person is higher than the air temperature. The layer of air surrounding a person is warmed up and blown away by the air movement present (draught, wind) and replaced by cooler air. This is called forced convection. If there is no air movement (air speed $v \leq 0.10$m/s) the warmed-up air will rise due to its lower specific weight and be replaced by cooler air. This is called free convection (see also Section 4.8).

EVAPORATION

The production and evaporation of sweat is the most effective heat dissipation mechanism, especially in warm environments. At ambient temperatures higher than the mean skin temperature, humans rely primarily on sweat evaporation to dissipate heat. Two “steps” can be distinguished here: the physiological sweat regulation mechanism and the physical evaporation process from the skin into the environment. When there is sweat on the skin, evaporation requires heat, which is extracted from the skin and therefore cools it. Dripping sweat therefore has no cooling effect. In addition to evaporation, water vapour diffuses through the skin. In contrast to sweating, the degree of diffusion depends mainly on the physical environment. Finally, heat loss occurs through respiration of air heated and humidified in the lungs. Sensible heat loss is heat released by airflow, radiation or conduction. Latent heat loss is body cooling by evaporation of water through respiration and sweating.

CLOTHING

Clothing influences both heat emission through thermal insulation and moisture evaporation from the body and consequently skin temperature and skin moisture, which to a large extent determine a person's thermal sensation. Therefore, by varying the clothing, people can influence their thermal comfort within wide limits. Clothing influences evaporation in two ways. It is an additional resistance to water vapour diffusion and if the clothing absorbs sweat, less sweat evaporates onto the skin and also extracts less latent heat from the skin, thus partially negating the cooling effect. This is why, for example, sportswear is made of vapour-permeable fabrics that absorb little moisture. The thermal resistance I_{clo} is expressed in clo units. One clo is the thermal insulation of clothing to keep a seated person thermally neutral at a temperature of 21°C and equals $0.155\text{m}^2\text{K/W}$.

2.4 RESEARCH IN CLIMATE CHAMBERS

The advantage of climate chambers is that the physical conditions can be closely monitored and extensive measurements on humans can be taken. This makes it possible to study in detail the physiological responses, such as skin blood flow, vasodilation and vasoconstriction, which regulate the transport of heat between the body and the environment. By also recording the subjective feeling of heat and cold during the experiments, insight is gained into how people experience a particular thermal environment. The Danish researcher P.O. Fanger became widely known for his research into thermal comfort in climate chambers. He analysed the data of 1296 students, 128 in Denmark, and 720 and 448 respectively from previous research in the United States (Fanger, 1970). The model he developed is based on the heat equilibrium model and thermoregulation of the human body. Based on this thermophysiological model, Fanger developed an equation that predicts the mean thermal sensation expressed on the ASHRAE thermal sensation scale (Table 2.1). He called this the

PMV (Predicted Mean Vote). Using this equation, the PMV, i.e., the thermal sensation of an average person, can be calculated on the basis of air temperature, mean radiant temperature, air speed, humidity, metabolism and clothing insulation.

Various computer programs can be found online with which the PMV can be calculated, for example http://comfort.cbe.berkeley.edu/. With such a tool, the various parameters can be varied and the sensitivity of the PMV value to those parameters can be studied. For example, the PMV increases (the body warms up) when the air temperature, the radiant temperature, the clothing insulation or the metabolism increases or the air velocity decreases. Conversely, the PMV becomes lower at lower air and radiant temperature, if air velocity increases (air flow cools the body), clothing insulation decreases or metabolism decreases (less physical activity produces less body heat). The influence of humidity is usually limited in indoor environments (Section 8.5) and only becomes noticeable at higher temperatures and higher humidity when the body starts to produce sweat that evaporates from the skin and, due to the high humidity, is more difficult to evaporate, making it harder for the skin to cool.

Table 2.1: The ASHRAE scale for assessing thermal sensation. Source: ASHRAE, 2015.

Thermal sensation	*Vote*
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

By assuming that the subjects who voted -2 (cool), -3 (cold), +2 (warm) and +3 (hot) were “dissatisfied”, the theoretical percentage of dissatisfied could be calculated, the PPD (Predicted Percentage of Dissatisfied), see Figure 2.2.

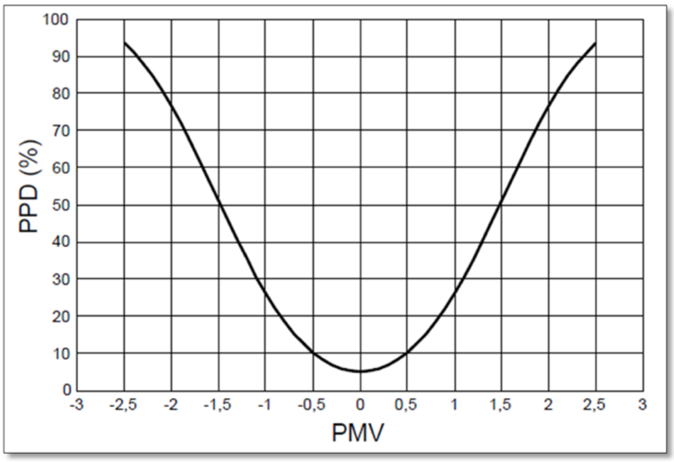


Figure 2.2: Relationship between the PMV index and the PPD index in climate chambers. The percentage of dissatisfied people is lowest at a PMV of 0. This percentage increases with a higher or lower PMV. Source: Fanger, 1970.

Another widely used index to quantify thermal comfort, and partly comparable with the PMV, is the Standard Effective Temperature (SET). This index is based on the more detailed Pierce Two-Node Model[2] (Gagge et al, 1970, 1986). This model focuses more on thermoregulation and comfort under warm conditions where people sweat. The SET is defined as "an imaginary thermally uniform environment with an air temperature equal to the mean radiant temperature, a relative humidity of 50% and an air speed of less than 0.1 m/s, in which the total heat loss from the skin of an imaginary person with an activity level of 1 Met and a clothing insulation of 0.6 clo is the same as that of a person in a real environment with real clothing and activity level". The SET is thus a function of activity level and clothing as well as the physical variables of the environment. So a person sitting down in light clothing at a low airspeed and an air temperature of 24°C at 50% humidity has a SET of 24°C. If this person were to take off his clothes, the SET would be 20°C, because the skin temperature is now the same as that of a lightly dressed person in a real environment of 20°C (McIntyre, 1980). The SET is used in psychrometric diagrams instead of the air temperature in order to show the effect of the other physical variables that influence comfort (further information on psychrometric diagrams is given in Section 8.4). In addition to Fanger's comfort equation and the Pierce Two-Node Model, there are several other, more detailed, models for research on human thermoregulation (Huizenga, Hui & Arens, 2001; Kingma et al., 2012; Schweiker et al., 2018).

It is interesting to compare the PMV and SET. The ASHRAE RP-884 database (see Section 2.5 and Chapter 3) makes this possible, as both use all six main variables to calculate the index (Humphreys, Nicol & Roaf, 2016). Each row in the database gave a calculated value of PMV and of SET based on the same measured environmental data and therefore eliminating the effect of measurement error. Figure 2.3 shows the scatter diagram of PMV and SET.

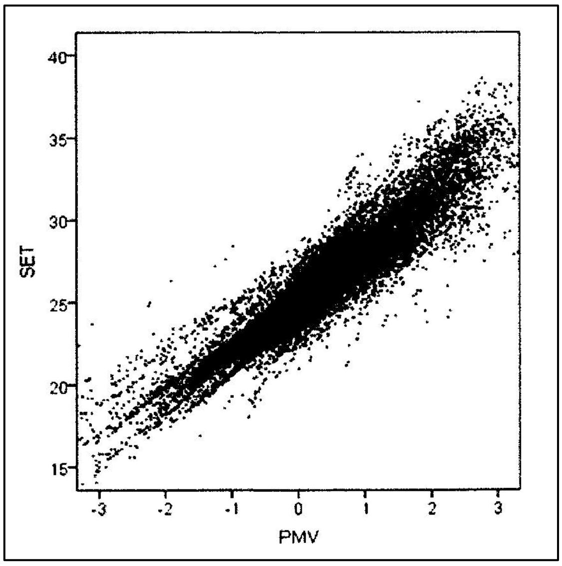


Figure 2.3: Comparison of SET and PMV in the ASRAE RP-884 database.
Source: Humphreys, Nicol & Roaf, 2016.

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[2] The Pierce two-node model is a more complex model than the Fanger comfort equation and is composed of two concentric cylinders, one for the core of the body and one for the skin (Doherty & Arens, 1988).

If the indices are consistent with each other, there would be no scatter, only a single line or curve connecting the two. However, a value of PMV does not give an exact corresponding value for SET. The difference is significant, up to a few degrees. The PMV or SET, or both, seem to contain significant errors, and their practical applicability is therefore questionable, as we will elaborate further in Chapters 3, 7 and 8.

The PMV model in particular became popular because an elegant formula can be used to calculate the expected thermal comfort, based on physical assumptions. This is attractive for heating, ventilation and air conditioning (HVAC) engineers, because calculating thermal comfort with the help of a formula is more familiar to them than having to take behavioural, psychological and social influences into account which are determined by building design and building physics parameters. The PMV/PPD model became the basis for standards and guidelines from the 1970s, which prescribe temperature limits for buildings and are still used today to design the indoor climate of buildings in large parts of the world with very different climate zones and cultures. Air conditioning technology allows the same indoor climate to be created anywhere in the world, in very different climates (Short, 2017) Thus, to this day, almost identical buildings are being created, from Dar es Salaam to Chicago and from Paris to Seoul (Figure 2.4). It goes without saying that a high price is paid for this in the form of energy consumption.

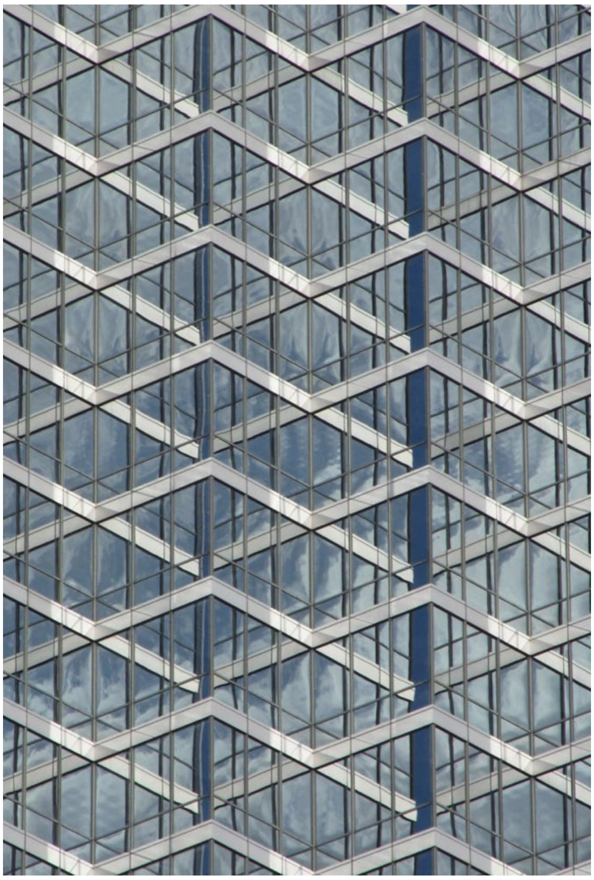

Figure 2.4: Building with glass facade in Madrid, Stockholm of Tokyo?
Source: Publicdomainpictures.net.

Another factor in the popularity of climate chamber research has been that the responses of test persons in a carefully controlled environment have been considered scientifically more reliable than the responses of occupants in field studies, where all kinds of confounding factors may play a role. This overlooked the fact that the artificial conditions in the climate chamber are most likely not representative of normal living or working environments, and that the results of climate chamber studies therefore have lower ecological validity[3], as shown below. The PMV model became commonplace in practice, but over time its limitations became increasingly apparent. Initially anecdotally by researchers who observed differences between thermal appreciation of people in buildings and the PMV predictions (Kurvers, 1986) and later by careful re-analysis of existing field studies (de Dear, Brager & Cooper, 1997; McCartney, 2002; Nicol & Humphreys, 2005). The PMV model has been found to predict thermal sensation well only in situations that closely resemble the conditions in climatic chambers, usually buildings with a closed façade and full air conditioning. Field studies showed that in naturally ventilated buildings and mechanically ventilated buildings without cooling, the PMV model overestimates thermal sensation and dissatisfaction at higher temperatures. The PMV model predicts that people are too hot, while in reality they are not. For example, a reanalysis of 8 field studies with a total of 66,500 observations (Figure 2.5), shows how much the actual judgements deviate from the PMV (Humphreys et al., 2016).

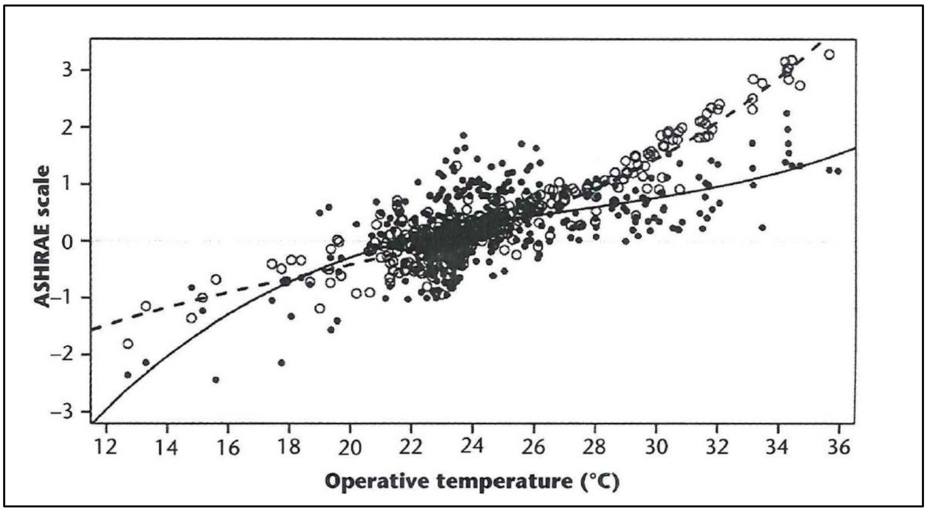

Figure 2.5: The calculated PMV (open points and dotted line) compared to the actual judgements (closed points and solid line) in 8 field studies with 66,500 observations. When people feel warmer than neutral in a warm environment, the PMV overestimates how warm they feel and thus the discomfort. Source: Humphreys et al., 2016.

2.5 FIELD STUDIES

Even before the Second World War, field studies on the relationship between the thermal environment and human perception were conducted in various parts of the world. The first major study dates from 1936 and was conducted in Great Britain in twelve factories where 3085 women worked (Bedford, 1936). Temperatures were measured and questionnaires

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[3] Ecological validity is the extent to which the measurement results are representative of everyday practice and therefore do not apply only within the test environment.

were used to assess whether the women were thermally comfortable. A seven-category scale, the Bedford scale, was used to indicate how warm or cold the workers were at a given time (Table 2.2). The mean comfort temperature appeared to be 18°C. This may seem on the cool side, but people in those days were dressed rather warmer and the investigated persons were doing light work.

Table 2.2: The Bedford scale for recording thermal sensation. Category 4 was later also referred to as "neutral" (Note: Although this scale also has seven categories, it differs in the phrasing of the categories from the ASHRAE scale used later. One similarity is that in both scales the middle three categories are considered comfortable). Source: Webb, 1959.

Thermal sensation	*Vote*
1	Much too cool
2	Too cool
3	Comfortably cool
4	Comfortable and neither cool or warm
5	Comfortably warm
6	Too warm
7	Much too warm

In the 1950s, more field research was done in workshops and offices, in Singapore, Iraq, India and Great Britain (Webb, 1959). For this purpose, the first data loggers for automatic recording of data were built (Figure 2.6). Webb found that the occupants of these buildings were comfortable at temperatures that were most common in the buildings during the relevant season. In these studies, temperatures ranged from 16°C in winter to 30°C in summer. Webb concluded that people adapted to the mean temperatures to which they were exposed over a long period of time. It was also found that thermal comfort was also related to the outdoor temperature on the day of the measurements and that the temperature at a given moment did not in itself say much about thermal comfort, but rather the deviation from the mean temperature during that period (Humphreys et al., 2016). The greater the deviation from the mean indoor temperature, the less comfortable the workers were.

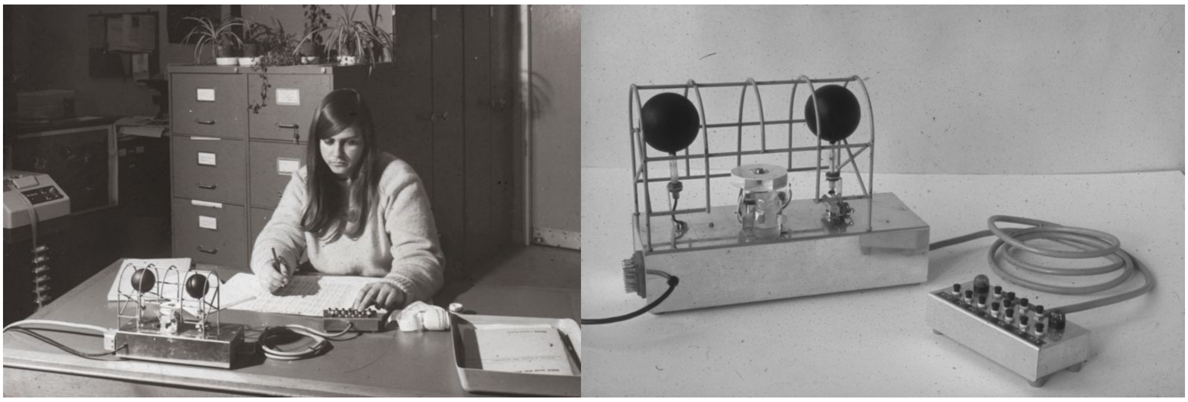

Figure 2.6: The data logger for measuring indoor temperatures, humidity and recording comfort votes on the 7-point scale. Source: Humphreys et al., 2016.

In the early 1970s, a large number of studies conducted in different parts of the world during the period 1938-1974 were combined and reanalysed (Humphreys, 1975).
Figure 2.7 shows that during the season when the buildings were not heated or cooled, the free running mode, the neutral temperatures were strongly and linearly correlated with the outdoor temperature. The bandwidth of the buildings in the period that they are heated and/or cooled is greater and less strongly correlated with the outside temperature. The curvilinear correlation is caused by the fact that below a mean outdoor temperature of 0°C, neutral temperatures tend to rise again. There are only five observations here, so they could be outliers[4], but it could also indicate that at sub-zero outdoor temperatures there is a need to be extra warm inside.

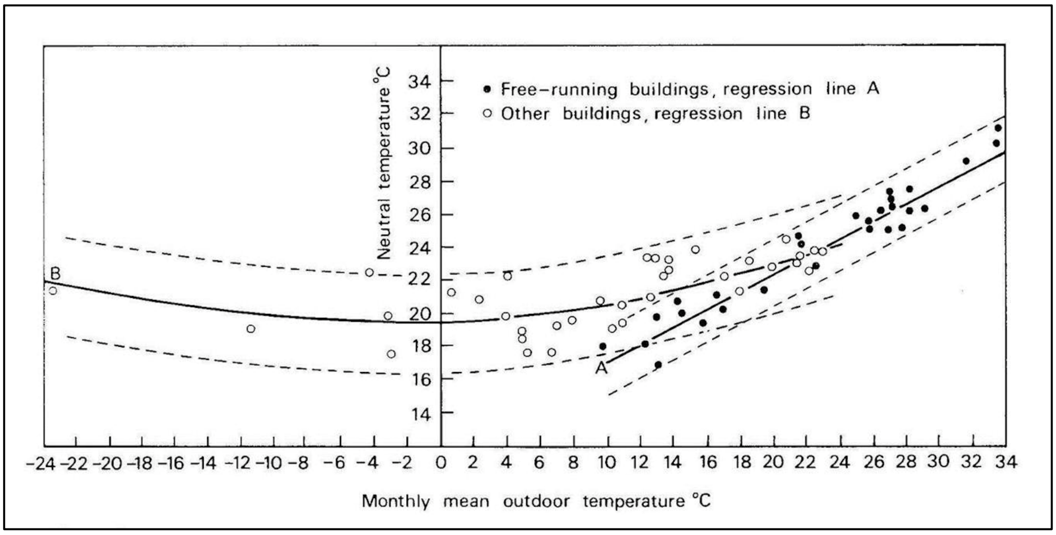

Figure 2.7: The indoor comfort temperature varies with the mean monthly temperature. For free running buildings the relationship is stronger than for buildings with heating and/or cooling. The solid lines are the averages of the values and 95% of the values lie between the dashed lines. Source: Humphreys, 1978.

The strong relationship between the outdoor temperature and the comfort temperature indoors in free-running buildings originates from the influence of the outdoor temperature on the indoor temperature. The warmer it gets outside, the warmer it gets inside and the occupants gradually get used to this, adjusting their clothing and opening and closing windows to achieve a temperature that is comfortable for them at that moment. It can also be seen that in heated/cooled buildings the neutral temperatures are mostly in a limited range: around 17°C to 24°C. In free-running buildings, even if the indoor temperature is influenced to some extent by building physics parameters such as thermal mass, glass percentage and insulation, the indoor temperature and therefore also the neutral temperature is strongly related to the outdoor temperature as line A in
Figure 2.7 shows. In buildings that are heated or cooled during a certain period, the indoor temperature is more strongly decoupled from the outdoor temperature and therefore the neutral indoor temperature is also less strongly related to the outdoor temperature and there will also be a larger bandwidth around the regression line, as shown by line B in

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[4] An outlier is a data point that deviates (strongly) from the rest of the data. The problem with outliers is that they can strongly distort the data. However, correcting for outliers can also distort research results.

Figure 2.7. The accuracies of these relationships could be significantly improved with a better indicator for the outdoor temperature. At the time these studies were conducted, only mean monthly temperatures were available. In the following chapters it will become clear that a better indicator for outdoor temperatures also provides more accurate predictions of comfort temperature. The above shows that thermal comfort can be seen as a self-regulating system in humans (Figure 2.8).

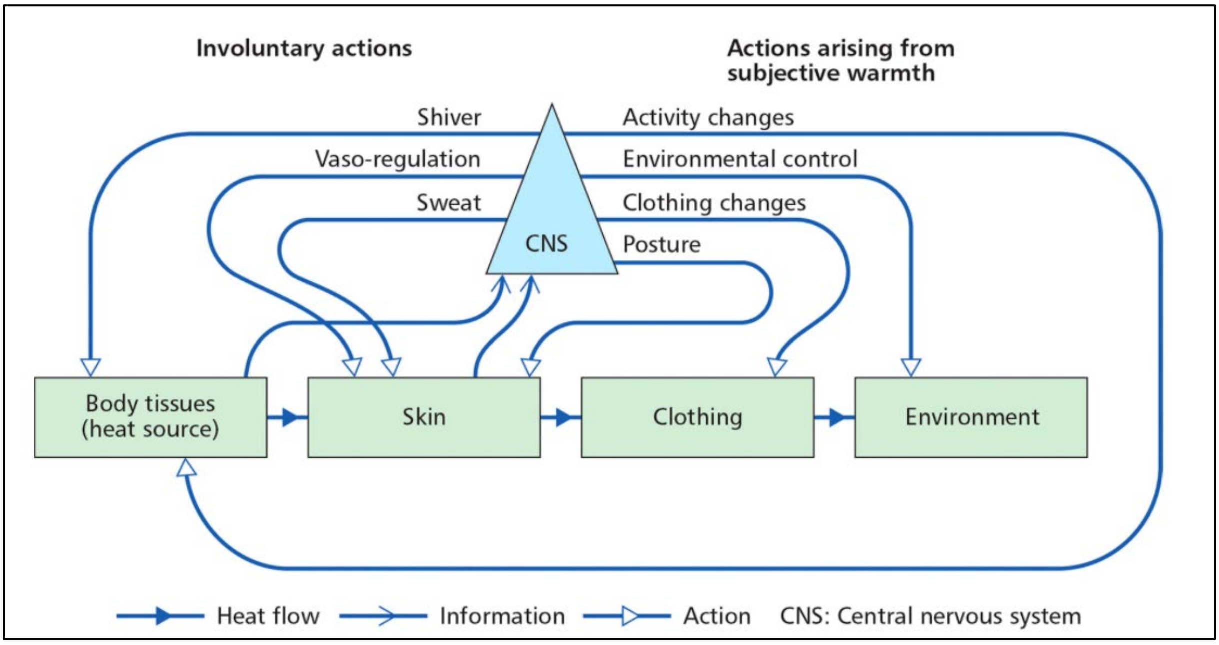

Figure 2.8: The human thermoregulation system. Source: Nicol & Roaf, 2017.

It consists of conscious and unconscious control loops. In the unconscious loops, the skin and the core of the body, where the heat is produced, provide information to the central nervous system so that action can be taken in the form of shivering or sweating and vasodilation or vasoconstriction, to keep the core temperature at around 37°C. Based on the subjective feeling of warmth, conscious control circuits behaviourally adjust the heat balance by adjusting the activity level and/or the clothing and/or, for example, opening a window. Especially these behavioural adjustments are essential for achieving thermal comfort. These data and models were very valuable for the design of buildings, but were mostly forgotten at the end of the 1970s when research in climate chambers became more fashionable.

3 MORE FIELD STUDIES

3.1 INTRODUCTION

Due to the many investigations in buildings in use, doubts about the validity of the PMV/PPD model grew over time. This eventually led to the creation of new databases of a large number of building surveys. The first was a study by ASHRAE in buildings in different parts of the world, called the RP-884 study (de Dear, Brager & Cooper, 1997). This study discussed the differences between air-conditioned buildings and naturally ventilated buildings and was followed by a study of European buildings, called the SCATs[5] study (Nicol & McCartney, 2000). Here a distinction was made between a heated and cooled *mode* and a free running *mode*. This refers to the condition in which the indoor climate is conditioned at a given moment, cooled/heated or not cooled/heated.

3.2 ASHRAE ADAPTIVE THERMAL COMFORT FIELD STUDY

The doubts about the validity of the PMV/PPD model prompted ASHRAE[6] to commission a re-analysis of existing field studies and to examine the extent to which standards and guidelines need to be adapted on the basis of the evolving insights into adaptive thermal comfort. The research was carried out in 160 buildings in various parts of the world (including the United States, Canada, the United Kingdom, South-East Asia and Australia) at different times of the year. For each building survey, occupants were asked to vote on the 7-point ASHRAE scale (hereafter referred to as thermal sensation vote, TSV) and relevant physical parameters, such as operative temperature and air velocity, were measured simultaneously for each occupant location. The metabolism and the insulation value of the clothing (including the insulation of the office chair) were also estimated. The relationship between the TSV and the operative temperature was established in a regression equation[7]. The operative temperature at which, according to the regression equation, the TSV equals 0, is the neutral temperature (also called: the comfort temperature) for the building in question. This is the variable on the y-axis in, for example, Figure 2.7, Figure 3.1 and Figure 3.2.

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[5] Smart Controls And Thermal Comfort

[6] American Society of Heating, Refrigerating and Air Conditioning Engineers.

[7] A regression analysis is a statistical analysis method for estimating the relationship between variables. In RP-884 it is applied on two levels.

- First, per building the relation of the thermal sensation vote (tsv) with the indoor operative temperature is established. The indoor temperature is the independent variable, the tvs is the dependent variable. Based on a regression line through the scatter plot, the neutral or comfort temperature per building is established, namely the indoor temperature where tsv=0.
- Next, over the whole group of buildings the relation of the neutral indoor temperature per building with the outdoor temperature is established. The outdoor temperature is the independent variable and the neutral temperature is the dependent variable. The results are figures 3.1 and 3.2.

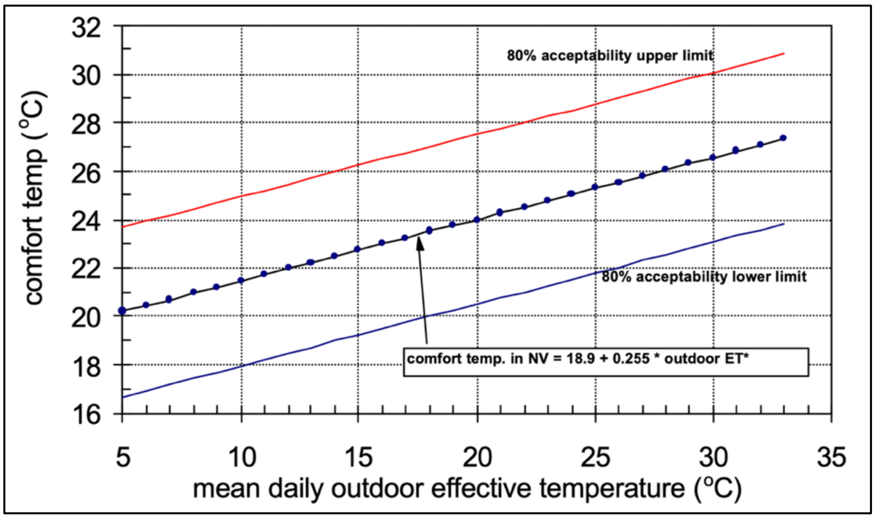

Figure 3.1: Comfort temperature in relation to outdoor temperature in non-cooled buildings with natural ventilation in RP-884. The red and blue lines indicate respectively the upper and lower limits of the range within which the thermal environment is acceptable for 80% of the occupants. Source: de Dear et al, 1997.

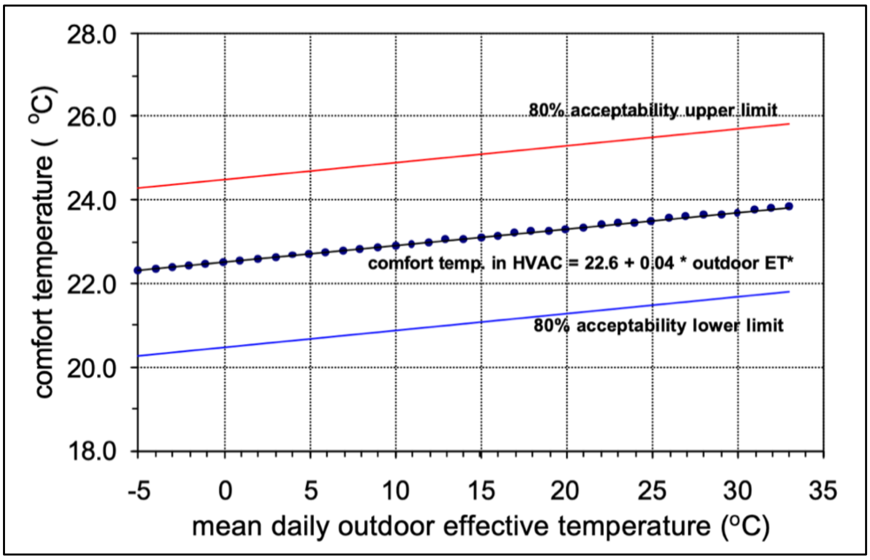

Figure 3.2: Comfort temperature in relation to outdoor temperature in buildings with central air conditioning in RP-884. The red and blue lines indicate respectively the upper and lower limits of the area within which the thermal environment is acceptable for 80% of the occupants. Source: de Dear et al, 1997.

Next, in RP-884, the relationship between the neutral temperature and the mean effective outdoor temperature in the month in question is calculated. In the latest version of the ASHRAE standard, the mean outdoor temperature has been replaced by the prevailing[8] outdoor temperature (ASHRAE 55, 2017). This results, for example, in the middle lines in Figure 3.1 and Figure 3.2. Finally, a bandwidth is shown around these lines, within which the

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[8] The prevailing outdoor temperature is determined by calculating the average daily temperature of a minimum of 7 and a maximum of 30 successive days preceding the day in question. The daily temperature is determined by taking the arithmetic mean of the dry air temperature of the 24-hour day. For further information refer to ANSI/ASHRAE Standard 55-2017.

thermal environment is acceptable for 80% of the occupants. Two assumptions are made here, namely that a vote on one of the three middle categories of the ASHRAE scale means the thermal environment is acceptable and that the distribution of votes on the ASHRAE scale within each building is sufficiently similar to the distribution of the PPD function in the PMV model to assume that a vote on the ASHRAE scale of +0.85 or -0.85 corresponds to 80% overall acceptability (20% dissatisfied). These are for example the lower and upper lines in Figure 3.1 and Figure 3.2. In the same way, limits for 90% acceptability can be calculated. These Figures show that:

- Comfort temperatures are related to the mean outdoor temperature: the warmer it is outside, the higher the comfort temperature indoors. Building users get accustomed to and adapt to temperatures that vary along with the outside temperature;
- The comfort temperature in naturally ventilated, uncooled buildings is more closely related to the outside temperature than in air-conditioned buildings.

3.3 EUROPEAN ADAPTIVE THERMAL COMFORT FIELD STUDY

A second major study was commissioned by the EU with the aim of reducing energy use in air-conditioned buildings and encouraging the use of naturally ventilated, free-running buildings through the development of control systems based on adaptive comfort. This so-called SCATs study consists of building surveys carried out several times over a year in 26 office buildings in France, Greece, Portugal, Sweden and the UK (McCartney, 2002; Nicol & Humphreys, 2005). On a number of points, this study makes different assumptions from RP-884. Firstly, no regression equations per building are used to determine the neutral temperature. Instead, the relationship between the TSV and the operative temperature is assumed to have a fixed regression coefficient, called the Griffiths constant, named after its creator. The higher this regression coefficient, the stronger the relationship between the neutral temperature and the TSV. This constant cannot be derived directly from the data because observed regression coefficients are lower than actual values due to confounding factors. These can be:

- Measurement errors in determining the operative temperature: there will always be some degree of measurement error;
- Errors in the equation used to calculate the operative temperature: the optimal index for the ambient temperature may be slightly different from the operative temperature;
- Behavioural adaptation: when the indoor temperature varies over a wider range, occupants are more likely to adjust their clothing insulation, so the observed regression coefficient is lower than the actual value;
- Psychological adaptation: occupants accustomed to a wider range of indoor temperatures may be less sensitive to changes in temperature than those accustomed to a narrower range, so that with a wider range of indoor temperatures the observed regression coefficient is lower than the actual value.

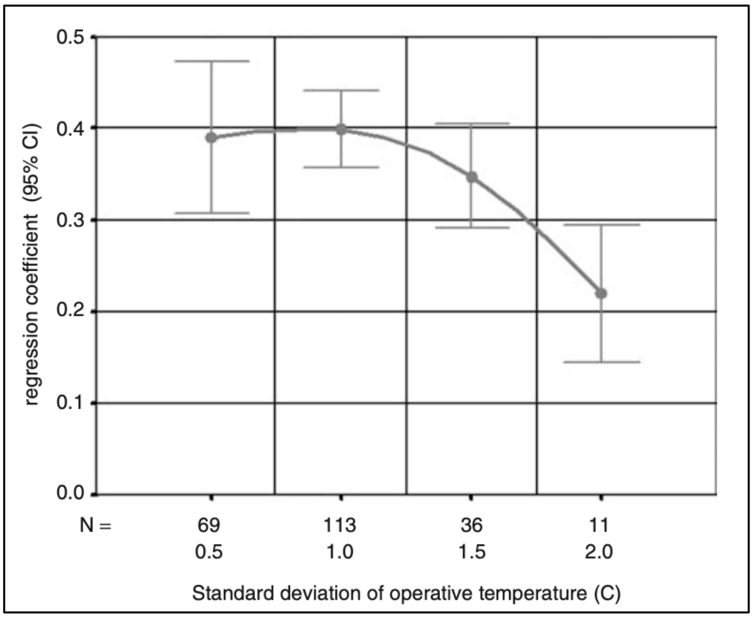

Figure 3.3: Mean values of regression coefficients and standard deviation of operative temperature in RP-884 and SCATs databases. *Sources: Nicol & Humphreys, 2005.*

Figure 3.3 shows the relationship between the observed regression coefficient and the standard deviation (statistical measure of scatter) of the indoor operative temperature. The curve shows a maximum of about 0.4 with a standard deviation of the indoor temperature of about 1.0. Below this, the regression coefficient is slightly lower, which is probably due to measurement errors and errors in the equation used, which count more heavily when the indoor temperature spread is low. Above that, the greater the distribution of indoor temperatures, the lower the regression coefficient, which is probably due to behavioural adaptation and possibly also psychological adaptation. As there is also likely to be some reduction in the observed regression coefficient of 0.4 due to confounding factors, a regression coefficient of 0.5 is chosen in the SCATs study. With this fixed regression coefficient, the neutral temperature can be calculated from any combination of a TSV and an operative temperature by the following equation:

$$\text{Neutral temperature} = \text{operative temperature} - \text{TSV} / 0.5 \qquad (1)$$

Next, the relationship between the neutral temperature and the outdoor temperature is determined. In RP-884, the mean of the daytime and night-time temperatures for the month in question is used. The SCATs study, on the other hand, uses *the running mean outdoor temperature,* RMOT, in the equation below: T_{rm}. This is determined as follows:

$$T_{rm} = (1- \alpha) \,.\, (T_{od-1} + \alpha .\, T_{od-2} + \alpha^2 T_{od-3} + \alpha^3 T_{od-4} + ...)$$

where:

T_{rm} =running mean outdoor temperature;
T_{od-1} = Mean of maximum and minimum outdoor temperature yesterday;
T_{od-2} = Mean of maximum and minimum outdoor temperature day before yesterday;
T_{od-3} = Mean of maximum and minimum outdoor temperature day before day before yesterday;
T_{od-4} = etc.

α is a constant that defines the speed at which the running mean responds to the outside temperature. Usually, a value of 0.8 is used. This equation implies that the Mean comfort temperatures in buildings can be determined on the basis of an Mean outdoor temperature of the past few days, with the most recent days being weighted most strongly. The reason for this is that the SCATs study shows that the influence of the outdoor temperature on the expectations of the occupants and on the choice of the clothing is determined by the days immediately preceding the day in question, with the most recent days weighted the strongest. Finally, as in RP-884, a range is given within which the indoor temperature must fall to ensure that enough occupants feel comfortable. In RP-884 this was derived from the PPD equation in the PMV model, in the SCATs study it is done on the basis of an observed relationship between deviation of actual temperature from neutral temperature and the percentage of occupants who feel comfortable (Figure 6.1). This then leads to temperature limits as shown in Figure 6.2. The SCATs study distinguished between *free running* on the one hand and *heated and cooled* conditions on the other, which yielded different relationships (Figure 3.4).

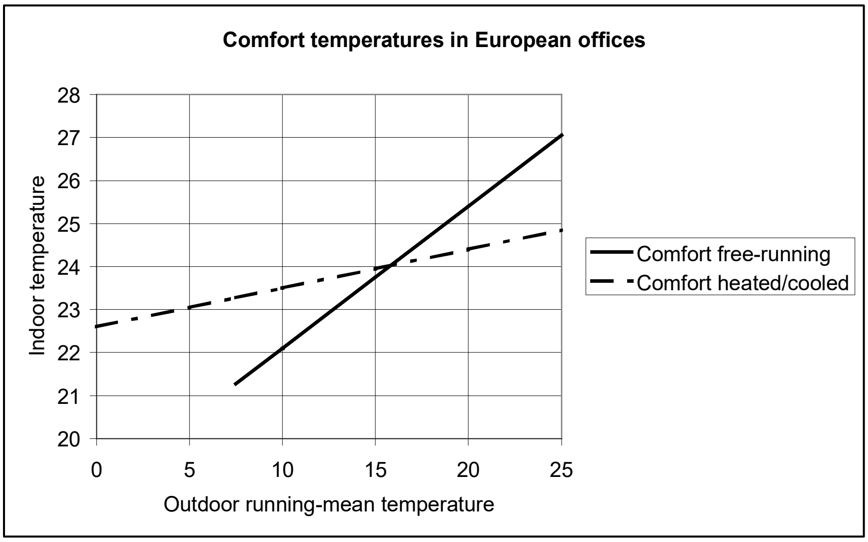

Figure 3.4: Mean indoor comfort temperatures for free running (solid lines) and heated and cooled buildings (dashed line) depending on the running mean outdoor temperature (SCATs study). *Source: Nicol & Humphreys, 2005.*

Formally, the standards based on the RP-884 and the SCATs studies should not be compared because there are so many differences in the way they were developed. However, it is informative to do so for the following reasons. The locations where both surveys were conducted are largely different, but there is also overlap. Furthermore, the differentiation in climate between the locations in RP-884 should also make this study sufficiently representative for Europe. Calculating neutral temperatures per building based on the data for that building, as in RP-884, or deriving a constant regression coefficient from the total data, as in the SCATs study, are both legitimate methods. Establishing temperature limits based on the PPD equation in the PMV model, as in RP-884, or based on an observed relationship, as in the SCATs study, are also both legitimate methods. The only point where the difference in approach does matter is the measure of outdoor temperature, which is more appropriate in the SCATs study than in RP-884. When the bandwidths of RP-884 and SCATs are compared it becomes apparent that the difference is small, especially in the upper limits for 80% satisfaction. Both upper limits are almost parallel and have a difference in the allowable operative temperature of up to 1K. The great similarity between the standards based on RP-884 and the SCATs study, respectively, confirms the validity of the results of both studies and the standardisation based on them. The main reason for choosing the European standard based on the SCATs study is not only that this study is more representative for the European situation, but also because of the better measure of the outside temperature: the running mean outdoor temperature (RMOT).

In Figure 3.5, the neutral or comfort temperatures of each building studied are within a certain range. The distance to the mean regression line is not a measurement error, but are the actual comfort temperatures (Humphreys & Nicol, 2018). This means that different mean indoor comfort temperatures are found for each outdoor temperature and that there are therefore local differences in the relationship between outdoor and indoor comfort temperatures. Thus, in different climates and buildings there are different relationships between outdoor temperature and comfort temperature, but they are all within the range shown in Figure 3.5.

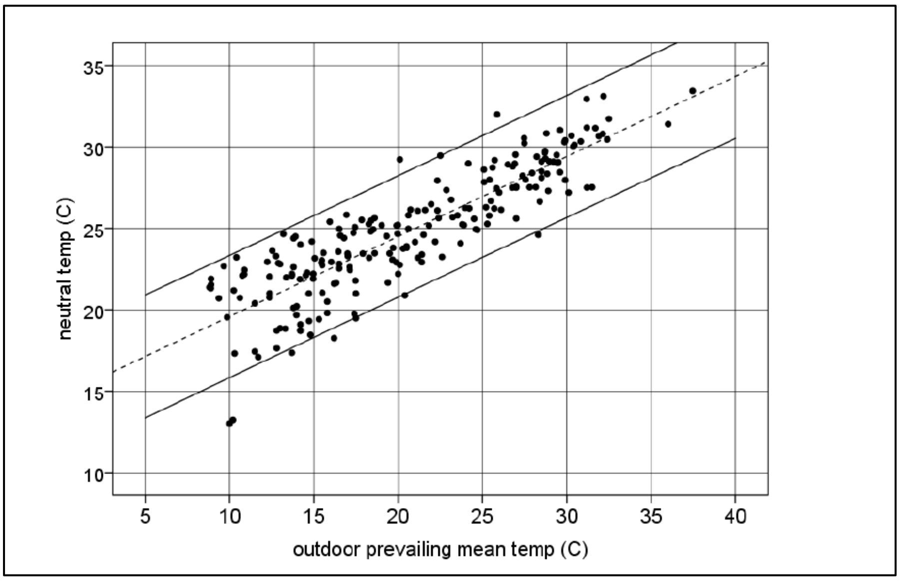

Figure 3.5: The relationship between the neutral temperature and the prevailing outdoor temperature based on the RP-884 and SCATs databases. Each point is a separate survey.
Source: Nicol & Humphreys, 2005.

For example, the SCATs data provide the normative relationship for European buildings and similar climates and cultures, but this may differ from, for example, India (Manu et al., 2016) and southern Brazil (Rupp et al., 2018a). Furthermore, most research has been conducted in offices and little is known about thermal comfort and adaptive behaviour in homes, schools and healthcare facilities. It is therefore of great importance that such research is conducted in different climate zones and types of buildings to further perfect the adaptive model. A first initiative in this direction is described in Chapter 8.

Figure 3.6 compares the comfort temperatures predicted by the PMV model with the observed comfort temperatures for the naturally ventilated buildings. The PMV model is somewhat adaptive, as one can take into account the differences in clothing insulation over the seasons, so that at least part of the behavioural adaptation is taken into account. Therefore, there is a certain relationship between the outdoor temperature and the calculated neutral indoor temperature (the red line in Figure 3.6). However, in naturally ventilated (non-cooled) environments, the PMV model does not appear to predict thermal comfort well. For outdoor temperatures above 20°C it predicts a lower comfort temperature than is observed, which corresponds to the PMV model's overestimation of thermal comfort mentioned earlier (Figure 2.7). For outdoor temperatures below 20°C it predicts a higher comfort temperature than is observed (Figure 2.7). This is because in free running environments the temperature that people subconsciously expect is dependent on the temperatures of the past few days. As a result, in free running environments comfort temperatures are in fact more closely related to outside temperatures than the PMV model shows (de Dear & Brager, 2002), as illustrated by the blue line in Figure 3.6.

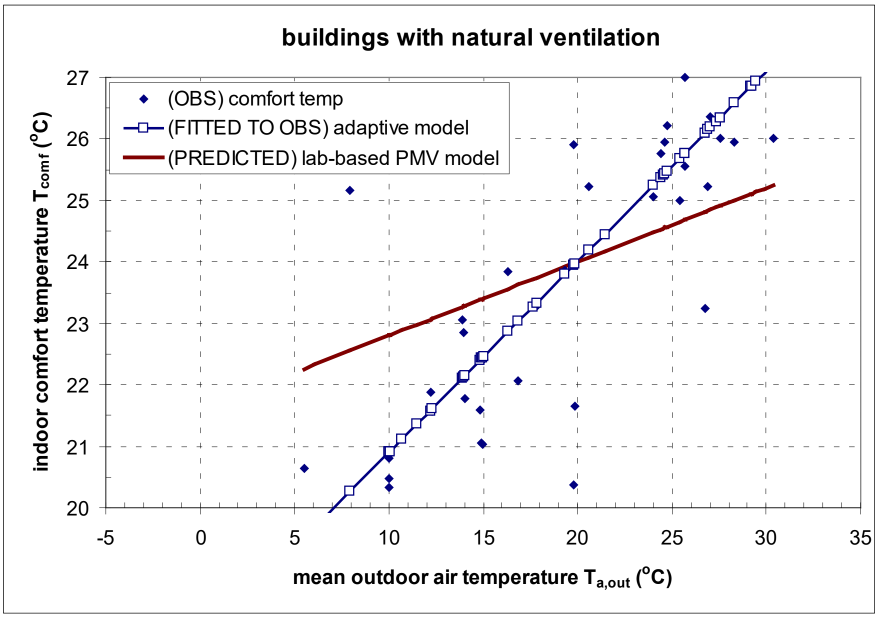

Figure 3.6: Comfort temperatures predicted by the PMV model (PREDICTED) compared to observed comfort temperatures (OBS) in naturally ventilated buildings and the calculated relationship between the observed comfort temperature and the Mean monthly outdoor temperature for naturally ventilated buildings (FITTED TO OBS).
Source: Nicol & Humphreys, 2005.

4 THERMAL ADAPTATION

4.1 INTRODUCTION

Although most people today spend more than 90% of their time indoors (living, working, travelling), humans are, from an evolutionary point of view, "outdoor animals" (Baker, 2004). The first humanoids lived outside, without clothing and without a hut. By seeking shelter in caves and under trees, sitting in the sun to warm up and later in time making clothes and creating campfires, humans adapted to weather conditions and climatic variations. Three and a half million years later, just before the Industrial Revolution, our ancestors still lived outside most of the day. They worked the land, sowed, harvested, irrigated, drained, fished, hunted, cut trees, built huts, houses, and they did it all largely outdoors. People had extensive knowledge of temperature, wind, clouds and rain. In many places in the world, architecture was developed that took the local climate into account to make the indoor climate in homes and other buildings as comfortable as possible. Examples include windcatchers in ancient Persia that bring airflow inside the building to provide cooling, patios in southern Spain, located between tall buildings for shade and with lots of greenery that lowers the temperature through evaporation. In other areas, thick clay walls were used to buffer heat in combination with small windows. In tropical humid regions, houses were built with huge overhanging roofs for shade and open walls to allow wind flowing through the building. There are wonderful examples of this "vernacular architecture", although regrettably the principles have largely been forgotten or are not applied. Fortunately, nowadays we begin to see applications of these building methods again, combined with modern building materials.

From the Industrial Revolution to the present, a negligible moment on the evolutionary time scale, people have increasingly worked and lived indoors. Until the middle of the last century, there was often a close relationship between indoor and outdoor climates. People were used to indoor temperatures of 10°C or even lower in severe winters, and in summer it was sometimes warmer inside than outside. With the invention of air conditioning at the beginning of the twentieth century and through increasingly better building techniques, it became possible to make the indoor climate virtually independent of the outdoor climate. All over the world, in the most diverse climates, the same kind of buildings with an identical indoor climate appeared. In recent years, however, research has increasingly shown that people actually feel more comfortable and healthier in an indoor climate that to some extent naturally varies with the outdoor climate. This is most likely due to the fact that we as a species have been used to these variations for tens of thousands of years. But what exactly does this adaptation mean? People in buildings have various options for adapting to the thermal environment. A distinction can be made here between behavioural, physiological and psychological adaptation, with interaction between the first and third form of adaptation.

4.2 BEHAVIOURAL ADAPTATION

Satisfaction with the indoor climate is strongly influenced by the possibilities users have to influence the factors that determine their feelings of warmth and to adjust them to their wishes (Figure 2.8). The most important of these are increasing or decreasing air speed and air temperature by opening or closing windows or doors or using a ceiling or table fan and adjusting clothing insulation by changing clothes. Other behavioural adaptations include seeking the warmth of the sun or finding shade, doing more or less exercise (higher or lower metabolic heat production), drinking hot or cold drinks and sitting in a warmer or cooler place within the building.

In naturally ventilated, free running and hybrid buildings, which in most cases have openable windows, the users can vary the air velocity and temperature by controlling the windows. In air-conditioned buildings with a closed façade, this possibility is either non-existent or very limited[9]. The RP-884 study shows that in naturally ventilated buildings the relationship between measured air velocity and indoor temperature is stronger than in air-conditioned buildings. In naturally ventilated buildings, 53% of the variance[10] in air velocities measured at the workplace is explained by differences in the indoor temperature. In air-conditioned buildings this is only 34%. In naturally ventilated buildings, users are therefore more active in controlling their heat balance by varying the air speed than in air-conditioned buildings. It also appears that in naturally ventilated buildings the relationship between clothing insulation and indoor temperature is stronger than in air-conditioned buildings. In naturally ventilated buildings, 66% of the variance in clothing insulation is explained by differences in indoor temperature. In air-conditioned buildings this is only 18%. The occupants are more active in controlling their heat balance by varying the clothing insulation than in air-conditioned buildings. The difference is even greater than for air velocity. People naturally have the ability to adapt to changing temperatures through behaviour, which keeps them comfortable. In a conditioned environment, where the climate system is designed to manage the temperature, the occupants often do not need to and cannot do anything for their thermal comfort and behavioural adaptation is, as it were, discouraged. In psychology, this is called learned helplessness (Carlsen, 2010).

4.3 PHYSIOLOGICAL ADAPTATION

As explained in paragraph 2.2, the core temperature of the human body must be kept at around 37°C. When the core temperature is in danger of deviating from this, involuntary physiological reactions follow (Figure 2.8). The most important of these are vasoconstriction and shivering when the temperature is too low and vasodilation and sweating when the temperature is too high (vasoconstriction and vasodilation occur before behavioural adaptation). People who spend long periods of time in an air-conditioned environment lose

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[9] Some fully air-conditioned buildings have some form of operable windows. This is often done to meet the wishes of the client or occupants, but the design is sometimes insufficiently well thought-out to be able to speak of effective openable windows.

[10] The variance is a measure of variability. The explained variance (R^2) indicates the extent to which one variable influences the other and varies between 0% (no influence at all) and 100% (complete correlation). The explained variance is equal to the square of the correlation (r) between the variables. The correlation is a measure of the relationship between two variables and ranges from 1.0 (complete correlation) via 0.0 (no correlation at all) to -1.0 (complete opposite correlation). Because the correlation has a value between +1.0 and -1.0, the numerical value of the explained variance is always lower than that of the correlation. Looking only at the correlation can lead to an instinctive overestimation of the relationship. For example, a correlation of 0.30 may seem substantial, but the explained variance is no higher than 9%. Correlations must be above about 0.50 to arrive at a substantial explained variance. Examples:
When $r=0.50$, $R^2=25\%$;
When $r=0.70$, $R^2=49\%$.

some of the body's physiological ability to adapt adequately to temperature changes, especially higher temperatures. This was shown in a laboratory study comparing two groups of subjects (Yu et al., 2012). One group consisted of persons who spent more than 10 hours per day during the previous summer in an air-conditioned environment (usually the work environment), hereafter referred to as the AC group. The other group consisted of persons who spent less than 2 hours per day during the previous summer in an air-conditioned environment, hereafter referred to as the NV (naturally ventilated) group. The individuals in both groups were subjected to heat shock by moving them from a room with a temperature of 26°C to a room with a temperature of 36°C. Thermal sensation was also asked. At the moderate temperature, both groups reported the same thermal sensation and comfort level. But at the high temperature, the AC group felt warmer and less comfortable than the NV group. To explain this, several physiological measurements were taken that are indicative of how the body responds to heat shock, including skin temperature and sweat volume. The blood level of heat shock protein 70 (HSP70) was also measured. This protein has a protective function against heat stress. It appeared that each of these parameters partly explained why the NV group felt more comfortable and less warm at higher temperatures:

- At the moderate temperature, the NV group had a higher skin temperature than the AC group. During exposure to the high temperature, the skin temperature of both the NV group and the AC group increased, but the skin temperature for the NV group remained higher than that of the AC group. This indicates a better physiological adaptation of the NV group to the high temperature.
- At the higher temperature, the NV group were sweating more than the AC group, which meant that more body heat was being transferred to the environment by sweat evaporation in the NV group. This also indicates a better physiological adaptation of the NV group to the higher temperature.
- Heat shock exposure had no effect on HSP70 levels in either group. But at both temperatures, the HSP70 levels of the NV group were about one and a half times higher than those of the AC group.

4.4 PSYCHOLOGICAL ADAPTATION

Although behavioural and physiological adaptation bring the body heat balance closer to a neutral heat balance, it does not always bring it completely to neutral. Nevertheless, building users can still feel comfortable. This is possible because, based on past experience, they have expectations of higher and lower temperatures occurring in certain situations. RP-884 shows that the spread of acceptable temperatures is largely related to the distribution of measured temperatures in each individual building. This indicates that when users expect a greater range of temperatures based on past experience, they also find a greater range of temperatures acceptable. Conversely, if due to previous experience, users expect a constant temperature, the range of temperatures considered acceptable is narrowed accordingly. It is important to note that getting used to a wider range only works if the range is related to the external temperature in a way that the occupants can understand, as is the case in free running, non-cooled buildings. If the indoor temperatures are not related to the outdoor temperatures, but are caused by random variations in the operation of the air-conditioning system, the acceptability of temperature variations decreases. Expectations thus depend on the type of building. If occupants have experiences of both naturally ventilated and air-conditioned buildings, they will also expect and accept higher temperatures in summer in naturally ventilated buildings. Wagner et al. (2006) show how sophisticated the expectations of occupants are. It turns out that occupants of naturally ventilated buildings accept higher temperatures in the afternoon than in the morning in summer (Figure 4.1). A temperature of 25.5 °C in the morning is still experienced as somewhat warm by most occupants, while in the afternoon the same temperature is experienced as just right. This is because occupants expect higher temperatures in the afternoon than in the morning.

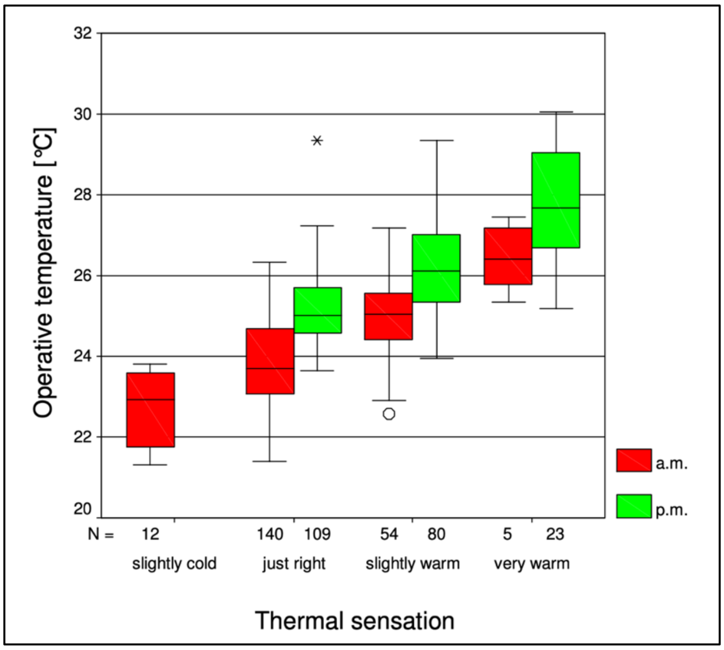

Figure 4.1: Thermal sensation votes in relation to operative temperature. The red boxes show the mean and the 50% bandwidth of the votes in the morning, the green boxes of the votes in the afternoon. Source: Wagner et al., 2006.

The importance of user expectations is further underlined by the fact that in semi-outdoor environments, for example a covered outdoor terrace or an indoor space that is open to the outdoors, people accept a much wider range of ambient temperatures than in indoor environments (Nakano & Tanabe, 2003a). They are also more active in adjusting their clothing (Nakano & Tanabe, 2003b). Although users in semi-outdoor environments can influence the insulating value of their clothing and perhaps have some influence on air velocity and radiation temperature by sitting in a different position, their influence on air temperature is almost negligible. The greater tolerance is therefore largely due to the adjusted expectation of users in semi-outdoor environments combined with the adjustment of their clothing.

4.5 THE INTERACTION BETWEEN BEHAVIOURAL AND PSYCHOLOGICAL ADAPTATION

Indoor environmental quality is important for overall building user satisfaction and thermal comfort is the most important indoor environmental factor, but thermal comfort is experienced differently in different types of buildings. Research into marketing strategies distinguishes between basic factors, bonus factors and proportional factors. Basic factors are factors which consumers take for granted and which are therefore minimum requirements. For these factors, the fulfilment of extra-high requirements does not lead to a higher degree of satisfaction with the product as a whole, but when the minimum requirements are not met, this will lead to dissatisfaction. Thus, the negative effect on overall satisfaction of a poor performance of a basic factor is greater than the positive effect of an extra good performance. Bonus factors are properties that are not expected by consumers. Not meeting these characteristics will not lead to dissatisfaction with the product as a whole. However, if one or more bonus factors are met, user satisfaction with the product will increase. So the positive effect on overall satisfaction of a good performance of a bonus factor is greater than the negative effect of a poor performance of that bonus factor. With proportional factors, the effect on consumer satisfaction is proportionally distributed. When these factors perform well, consumers are satisfied with the product as a whole; when they perform poorly, consumers are dissatisfied (Figure 4.2).

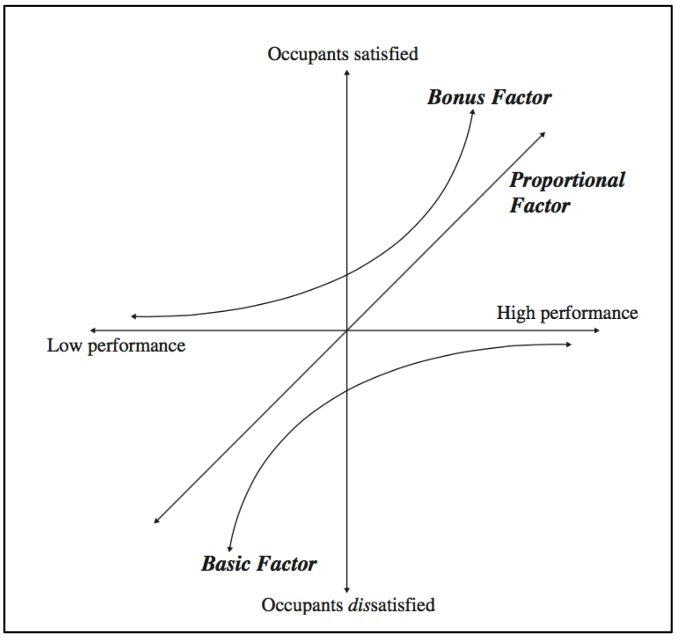

Figure 4.2: Model for marketing strategies applicable to indoor environment satisfaction.
Source: Kim & de Dear, 2012.

The applicability of this classification to the indoor environment was investigated by Kim & de Dear (2012). They used a dataset in which the ratings of individual indoor environment factors and the rating of the indoor environment as a whole were available for users of various office buildings. It was also known whether the buildings were air-conditioned, naturally ventilated or mixed mode (mixed mode is defined in this study as air-conditioned buildings with windows that can be opened, as also used in the analyses of RP-884). The study shows that thermal comfort is a basic factor in air-conditioned buildings, a proportional factor in mixed-mode buildings and a bonus factor in naturally ventilated buildings.

Acceptable thermal comfort is a minimum requirement for people in air-conditioned buildings. They do not notice the indoor climate if it meets their expectations. If the thermal comfort in these buildings does not meet expectations, this has a negative impact on overall satisfaction with the indoor environment. In naturally ventilated buildings, expectations are not as high. Thermal discomfort does not lead to a negative rating of the indoor environment as a whole. But if the thermal indoor climate is perceived as good, this contributes to a positive appreciation of the indoor environment as a whole. In mixed-mode buildings, thermal comfort leads to a higher rating of the indoor environment as a whole and thermal discomfort to a lower rating. The fact that thermal comfort is a bonus factor in naturally ventilated buildings is due to the combination of the influence that users have on the thermal indoor climate, making them feel co-responsible for their own thermal comfort, and the understanding that in naturally ventilated buildings the indoor temperature varies with the outdoor temperature. Furthermore, occupants in naturally ventilated buildings appear to pay more attention to local weather conditions. This affects their expectations, allowing them to anticipate indoor temperatures to a certain extent and make adjustments accordingly. In air-conditioned buildings, occupants have less influence on air temperature and air velocity than in naturally ventilated buildings. Moreover, they have largely lost the ability to control their heat balance by adjusting their clothing insulation (Carlsen, 2010). They also pay less attention to local weather conditions. Based on experiences with the current building, or with air-conditioned buildings in the past, they expect the building to provide a comfortable temperature. They do not feel responsible for their own thermal comfort. Therefore, in air-conditioned buildings, thermal comfort is a basic factor.

Interestingly, the study by Kim & de Dear found that noise levels is a basic factor in air-conditioned buildings and a bonus factor in naturally ventilated buildings. This factor has different meanings in air-conditioned and naturally ventilated buildings. In general, there are three types of noise sources in an office space:

- Noise from outside, in naturally ventilated buildings this is mainly determined by traffic noise and how far the windows are opened;
- Noise from the air handling and ventilation system;
- Noise from colleagues and office equipment.

In air-conditioned buildings, the closed façade means that noise from outside will not determine the noise level, unless the sound insulation of the façade is inadequate or the noise level is very high. There will be noise from the air handling system, depending on the way the air is supplied. In fully air-conditioned buildings with an open plan layout, there will often be noise from colleagues in adjacent desks. The noise of the air handling system, where the degree of nuisance depends on the noise level, cannot be influenced by the occupants. If the noise is perceived as annoying for a long period, it can also lead to symptoms such as headaches, fatigue and loss of concentration. The annoyance caused by the noise of colleagues and office equipment in the room in question is not determined by the noise level (Nemecek, 1980). Annoyance is more severe the greater the intelligibility and informational content, and the lesser the localisability, predictability and perceived necessity. These matters cannot be influenced by users either. Annoyance caused by noise from colleagues and office equipment can also lead to symptoms such as headaches, fatigue and loss of concentration (Cohen & Weinstein, 1982). It is therefore understandable that noise is a basic factor in air-conditioned buildings. If noise is experienced as a nuisance, it also leads to symptoms that negatively influence the quantity and quality of work (Vroon et al., 1990). The perceived quality of the indoor environment as a whole will also decline.

In naturally ventilated buildings, noise is usually mainly from outside when windows are open and the noise level depends on the position of the windows. Noise caused by the air-conditioning system is rare in passively conditioned buildings. Also, because such buildings are usually designed as smaller office spaces or room offices, noise from colleagues and office equipment is less likely to be a problem. Naturally ventilated buildings offer the occupants optimum possibilities for balancing the positive and negative effects of opening windows. At one moment, people will open the window (further) to obtain more cooling. They will then accept the higher noise level from outside, which is quite possible because they feel responsible for it and because dissatisfaction with the noise level does not lead to dissatisfaction with the indoor environment as a whole. Noise is a bonus factor in this type of building. At other times, for example when extra concentration is needed for a certain period of time, you can close the window (or set it to a very small aperture, if possible). If it gets a bit warmer as a result, people will accept that too, because thermal comfort is also a bonus factor. The decision is also your own decision. A good compromise between thermal comfort and noise level can also be found by adjusting the open window to an intermediate position. This also emphasises the importance of being able to set windows to different positions.

The importance of adaptive options and how to use them is often not recognised. This is especially true for high performance buildings that incorporate passive building strategies, which require the active involvement of the occupants, which is typical for achieving energy saving and occupant comfort targets. A study in 8 high performance buildings in de U.S. found that there was a significant difference between those who had received effective training and those who had not (Day & Gunderson, 2015). Those who indicated they had received effective training were significantly more satisfied with their office environment than those who had not received training. Moreover, people who did not understand how to operate their controls can, in a sense, be equated with people who did not have access to building controls at all.

4.6 ALLIESTHESIA

The word alliesthesia originates in Greek (allios=altered; esthsia=feeling) and describes that certain sensory stimuli can induce a pleasant or unpleasant feeling, depending on a person's internal state. Although over a long period of time a neutral thermal sensation is often experienced as most comfortable for the body as a whole, localised cooling or warming of the body over a short period of time can be very pleasant. For example, when the body's core temperature, which, as mentioned, must remain constant as much as possible for physiological processes to function properly, becomes lower than the setpoint, warming of a peripheral part of the body will bring the core temperature closer to the setpoint and this will be experienced as pleasant. This pleasurable experience also occurs when the core temperature exceeds the setpoint and a peripheral part of the body is cooled. This is called *positive alliesthesia*, which can also be called *thermal delight*. But when a part of the body cools down or warms up and the difference between the core temperature and the setpoint therefore increases, it will be experienced as unpleasant. This is called *negative alliesthesia*. Alliesthesia does not only occur when experiencing temperature, but also, for example, when experiencing thirst. The body needs a certain level of water. When this is too low, for example due to not drinking enough or because the kidneys produce too much urine, the body sends signals to the brain that evoke a feeling of thirst and the desire to drink something. When something is consumed, even if it is only a glass of water, it evokes a feeling of pleasure. It is similar with temperature. If someone is feeling cold after a cold winter walk, it can be particularly pleasant to sit down by an open fire, even if the heat exposure is so great that we would experience it as too hot under normal circumstances. The feeling of thermal discomfort is reduced by overcompensation, because it returns the core temperature to the set point faster. Another example we all know: during a very hot day, a cool breeze on your face is experienced as very pleasant, because it brings the core temperature back towards setpoint. Another example to illustrate that it can also be about small peripheral parts of the body: if you are cold, a cup of hot drink in your hands leads to thermal pleasure; if you are warm, a can of cold drink in your hands or briefly on your forehead leads to thermal pleasure.

Thermal pleasure can even be enhanced when different thermal factors have an opposite effect at the same time. Visitors to a restaurant, for example, often prefer the terrace or a semi-outdoor environment to sitting indoors, even if the indoor environment better meets the indoor climate requirements. Apparently, people find it, to a certain extent, more pleasant to feel solar radiation and wind at the same time. In such situations, people unconsciously seek to stimulate the senses. This is also shown in a study conducted in a restaurant with a normal air-conditioned indoor environment and a semi-outdoor environment without air conditioning with a glass roof and an open connection to the outdoors (Shimoda et al., 2003). The reasons given by respondents who chose the semi-outdoor environment included: openness (32%), fresh air (12%), sunlight (8%), lack of air conditioning (7%) and wind (5%). The research by Nakano and Tanabe (2003b) and Shimoda et al. (2003) shows that more than 80% of the occupants of a semi-outdoor environment chose this of their own free choice. It is also striking that Nakano and Tanabe (2003a) show that people spend much less time in a semi-outdoor environment than in an indoor environment. Nakano and Tanabe (2003b) indicate that the time spent in a semi-outdoor environment is usually no more than one hour. People usually only need such conditions for a short period of time. Apparently, a neutral thermal sensation and positive alliesthesia are complementary; if the core temperature is at or close to the setpoint, people prefer a thermal neutral sensation, if the core temperature deviates too much from the setpoint they look for forms of positive alliesthesia. Positive alliesthesia is only possible if the occupant of the space has sufficient possibilities to adapt the thermal environment, for example, to (temporarily) open a window or change its position, to (temporarily) set a table fan to an extra high setting, or to (partially) raise an outdoor sunshade in order to feel more solar radiation. The regular occurrence of positive alliesthesia in addition to a generally neutral thermal sensation leads to thermal delight and increased satisfaction with the indoor thermal environment. The absence of positive alliesthesia, as in the case of a temperature controlled within narrow limits, is experienced as *thermal boredom* (de Dear, 2009, 2010, 2011).

4.7 THE STRICT TEMPERATURE LIMITS PARADOX

In air-conditioned buildings, what one might call the *strict temperature limits paradox* occurs. The narrower the limits within which the indoor temperature is maintained, the more the occupants lose the ability to keep themselves comfortable through their own behaviour, especially adapting their clothing insulation, and the more their bodies lose the ability to physiologically adapt to higher temperatures. If, as is inevitable in these buildings with more complex systems, occasional deviations from the set temperature occur that are not related to the outside temperature, this will lead to discomfort and dissatisfaction. This is supported by Li et al. (2019) who conclude from their research results that “Occupants becoming accustomed to, or even demanding, tighter temperature tolerances might explain why tight temperature ranges do not necessarily improve thermal comfort”. The likelihood of these occasional deviations is higher when the robustness (see Chapter 5) of the building and its installations is low, as is often the case when complex HVAC technology is employed to keep the temperature within narrow limit limits. The narrow temperature limits paradox also involves the fact that a temperature that is controlled within narrow limits and where possibilities for influencing the temperature are limited can lead to thermal boredom. This can result in dissatisfaction with the indoor thermal environment, which will be expressed as “too hot”, “too cold” or “varying temperatures”, while this is not reflected in temperature measurements. A related explanation that goes one step further is the following: Vroon et al. (1990) describes a phenomenon from general psychology: *sensory deprivation*. When test subjects are placed in a situation with as little sensory stimulation as possible, by laying them in a lukewarm bath in a room without light or sound, they eventually start to hallucinate. By analogy, Vroon et al. (1990) hypothesised that a thermally very stable environment, in which insufficient sensory stimuli are perceived, leads to the experience of high, low or changing temperatures that are not actually there, ultimately resulting in discomfort.

It is still the standard view among some designers that varying temperatures, such as those found in naturally ventilated buildings, place an undesirable burden on users and are not comfortable or even healthy. In air-conditioned buildings, controlling the temperature within narrow limits removes this burden, leading to greater comfort and health, so the reasoning goes. However, the reverse appears to be true: the temperature differences that occur in a well-designed naturally ventilated building are a healthy burden for the organism, while the tightly controlled temperature in air-conditioned buildings is an unhealthy underload for the organism.

4.8 ADAPTATION AND AIR MOVEMENT

In the adaptive thermal comfort models, the effect of air velocity on thermal comfort is not explicitly visible, whereas this parameter can have an influence under certain conditions. Air velocity can have a cooling effect in warm conditions, but can be experienced as an annoying draught in a cool environment. Influencing the air velocity is an important possibility in the adaptation process between occupant and building. Field studies show that twice as many building users would prefer *more* air movement than *less* air movement (Toftum, 2003; Zhang et al., 2007). Influencing air velocities is a means of achieving a thermally acceptable situation and also contributes to improving perceived air quality (Melikov, 2012). Building users look for opportunities to influence air velocities by, for example, opening windows or using fans (ceiling, table or standing).

Initially, research into air velocities was carried out in climate chambers and focused on the influence of mechanical ventilation on the sensation of draught. One of the first studies took place in a climate chamber, where subjects were exposed for two and a half hours to fluctuating air speeds from a mechanical ventilation system (Fanger, 1986). The turbulence of the air speed was characterised by the turbulence intensity, defined as the standard deviation (spread) of the air speed divided by the mean air speed. In a follow-up study, a model was developed that predicts the percentage of dissatisfied as a function of air temperature, Mean air speed and turbulence intensity (Fanger et.al., 1988). Figure 4.3 shows this relationship (Brüel & Kjær, 1988). This became the basis of the draught-risk model, which was incorporated into the EN-ISO 7730 (2005) and ASHRAE-55 (2017) standards.

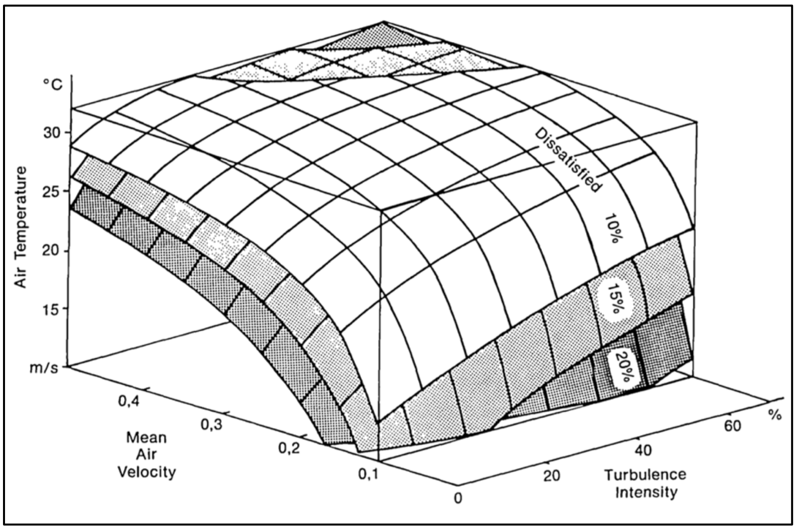

Figure 4.3: A 3-dimensional representation of the draught risk model. The surfaces shown correspond to 10, 15 and 20% dissatisfied. The axes are turbulence intensity, mean air velocity and air temperature. Source: Brüel & Kjær, 1988.

However, air velocities coming from open windows or ventilation grilles are experienced differently from air velocities coming from a ventilation system, because the air turbulences are different in character. In naturally ventilated and mixed-mode buildings, air velocities are generally higher than in air-conditioned buildings, especially in conditions with temperatures above 26°C. Figure 4.4 illustrates this, as it shows a stronger relationship between air temperature and air velocity in naturally ventilated buildings (Parkinson, de Dear & Brager, 2020).

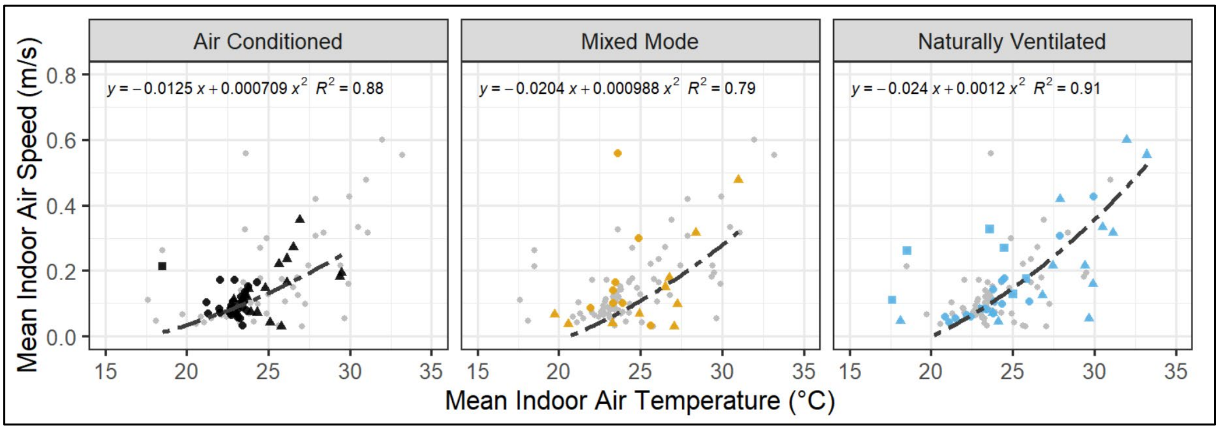

Figure 4.4: The Mean air velocity for three building types. The shape of the points indicates the region: circle=Europe and USA; triangle=Asia; square=other.
Source: Parkinson, de Dear & Brager, 2020.

When a person is in a warm or cold environment, it is not the "temperature" that is felt, but we notice a change in the nerve endings in our skin, the thermoreceptors. The combined effect of air and radiant temperature and air speed on our skin sends signals to our brain (Zang, 2003). Hot and cold environments are felt differently because the skin contains separate heat and cold receptors (de Dear, 2010). Air speed changes with a frequency between 0.2 Hz and 1.0 Hz have a strong cooling effect, with frequencies between 0.3 and 0.5 Hz being perceived as an unpleasant draught (Madsen, 1984; Huang et al., 2012).

Because air movements originating from windows, facade grilles or fans are different in character from air movement caused by a ventilation system, it is also informative to study air velocities in the frequency domain (Djamila, 2014). For this purpose, the *power spectral density* (PSD) is determined, which indicates how the energy of the air velocity is distributed in relation to the frequency of fluctuations caused by eddies in a turbulent air flow (Quang, 2006). Natural air currents have more energy in the low frequencies and are perceived as more pleasant. Air currents caused by a ventilation system have more energy in the high frequencies and this is perceived as more unpleasant. To visualise the differences in characteristics between airflows, the β-value is used, which is the slope of the logarithmic power density spectrum E(f). The higher the β-value, the greater the power in the low frequencies, and the larger the eddies that are characteristic of natural airflow. Figure 4.5 gives examples of β-values of natural and mechanical airflows, showing that natural airflows have a higher β-value than mechanical ones. Airflows with higher β-values are perceived as more pleasant and the optimum range is around 1.40 to 1.80, values that are mainly found with natural airflows. This supports the findings that people prefer natural airflows to airflows from mechanical ventilation systems (Kang et al., 2013).

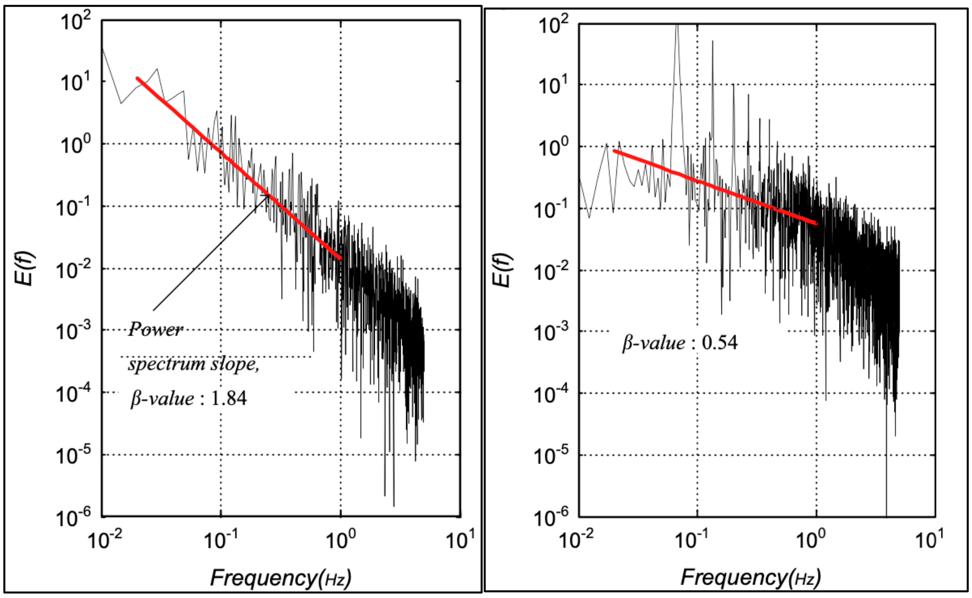

Figure 4.5: Representation of spectral power density distribution and β-values for natural (left) and mechanical air currents (right). The horizontal axis shows the logarithmic frequency and the vertical axis the logarithmic spectral power density E(f). A high β-value is characteristic of natural air currents, while mechanically generated air currents have a low β-value. *Source: Kang et al., 2013.*

If ceiling fans or tabletop fans are used in warm conditions, an air velocity of approximately 0.6m/s is optimal if the control of the fan is shared by several people and an air velocity up to approximately 0.8m/s is acceptable if the fan is operated individually (Zhai et al., 2017; Cândido et al., 2010). At air velocities higher than approximately 0.9m/s, there is a risk of paper lying on desks being blown away. EN 16798-1 (2019) also permits increased air velocities, if these can be controlled by building users. Figure 4.6 shows that an air speed of, for example, 0.8m/s corresponds to an increase in comfort temperature of approximately 2.8°C. Or in other words, with a good fan it feels as if the temperature is about 2.8°C lower.

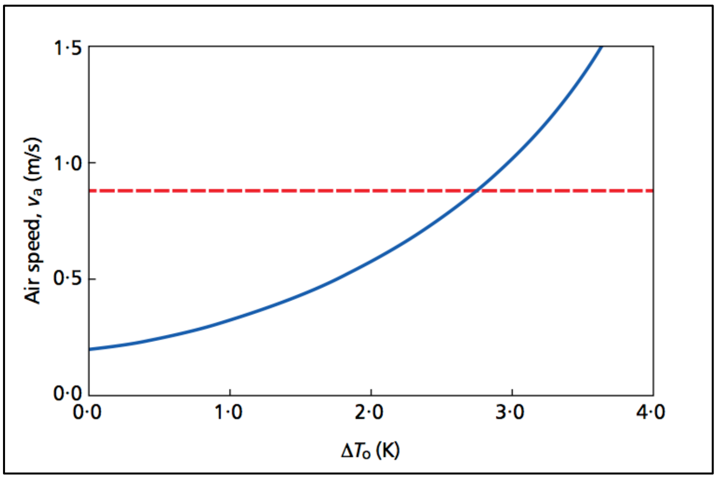

Figure 4.6: Allowable air velocities (V_a) in relation to the increased operative comfort temperature (To), when building users have control of e.g., a ceiling fan or windows that can be opened. The red dotted line is a practical limit value, above this value paper starts blowing off desks. Source: EN 16798-1, 2019.

5 INDOOR CLIMATE ROBUSTNESS

5.1 INTRODUCTION

International field studies into the causes discomfort and building related heath symptoms in hundreds of office buildings show that occupants in certain building types are more satisfied than occupants in other building types. The studies show that the following risk factors lead to significantly more discomfort and health symptoms (Leyten and Kurvers, 2006):

- Cooling of the supply air;
- Humidification of the supply air;
- Recirculation of room air[11];
- The absence of openable windows;
- Insufficient possibilities for the occupants to adjust the temperature;
- Working in large open plan offices.

Our own studies in office buildings in the Netherlands also show the following risk factors, which are closely linked to the above factors:

- Controlling the indoor temperature within narrow limits;
- No openable windows or windows that, although openable, are not practically usable by the occupants at their own choice;
- Insufficient thermal mass to store excessive heat;
- Large areas of glass in the facade trap too much solar heat;
- Lack of controllable external sun shading;

The last two often occur in combination.

Various causes for the poor performance of buildings are mentioned in the literature. Examples are that more complex air handling systems contain more potential sources of chemical and microbiological indoor air contaminants in filtering, cooling and humidifying sections (Weschler, 2004; Clausen et al., 2011). Furthermore, it is reported that more complex systems are more susceptible to failure due to inadequate maintenance (defective parts of installations are often discovered only after a long time), inadequate commissioning of the building systems, altered use compared to the design, or cutbacks during the construction phase that cause the resulting situation to no longer function as intended in the design.

In buildings where the occupants perceive the indoor climate as uncomfortable, the energy consumption is often higher than anticipated during the design process (Turner, 2008; Van den Ham, 2009). These are often buildings with (complex) HVAC systems. Buildings are also being realized that aim to meet a high sustainability ambition and strive for an energy-efficient design, but where the emphasis is on innovative technical installations and less on building physics, architectural and passive design. What many of these designs have in common is that little consideration is given to the outdoor climate, for example through

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[11] Recirculation is not officially used much anymore in the Netherlands, but the authors of this book have investigated buildings with some regularity, where the air handling system did recirculate air, both as a deliberate setting, to save energy, as well as unintended settings caused by malfunctions of systems.

limited thermal mass and glass façades with a high level of solar radiation and no external sun blinds.

5.2 THE CONCEPT OF ROBUSTNESS

In order to explain the relationship between building characteristics and the discomfort and health symptoms of occupants, this chapter describes the concept of *indoor climate robustness* (Leyten and Kurvers, 2006, 2011). A robust system is a system where the output is relatively insensitive to variations or uncertainties of the input. The term robustness is used in computer science, statistics and economics, among others. Robustness should not be confused with *resilience*, which is “the ability to bounce back after disruption”. Unlike robustness, which is proactive, resilience is reactive, following incidents in which system performance has already been affected.

The robustness of the indoor climate of an office building, including the architectural properties and its air handling systems, is defined as the degree to which the realised indoor climate of the building meets its design goals regarding comfort, health and energy consumption during the operational phase. Buildings differ in their robustness: some meet their design goals better than others. Designs that appear to perform flawlessly at the design stage in simulation calculations and test chamber studies may systematically perform less well in practice. This is part of the explanation for the large differences in occupant satisfaction between different types of buildings mentioned in Section 1.1. Robust climate design indicates that the indoor climate and energy use in daily use meet the design objective: an indoor climate that is as comfortable and healthy as possible, with the lowest and most predictable energy use. In the following sections, a number of mechanisms are mentioned that can increase the robustness of the building and its systems, or, in other words, reduce the risks of comfort and health complaints and high energy consumption. It will also become clear that some mechanisms overlap to some extent.

5.3 ROBUSTNESS AND TECHNICAL FUNCTIONING OF BUILDINGS

There is a tendency that buildings and climate systems become more and more complex, because of increasing demands on the quality of thermal comfort, reducing energy and the application of renewable energy. The quality of thermal comfort is often based on incorrect assumptions what thermal comfort actually is and how to achieve this (see Chapter 7). The integration of ICT in the built environment increases the possibilities for detailed control and gathering of information about the building, but also make it more complex and difficult to understand it during the design and operational phase. But also for the occupants if the operation is not straightforward.

PASSIVE INSTEAD OF ACTIVE SOLUTIONS

A strategy for achieving both a good indoor environment and low energy use is recommended by Roulet (2006): control the indoor environment as far as possible by passive means, and use active means only to adjust the indoor environment if necessary. Examples of this strategy are controlling the sources of indoor air pollutants instead of using increased ventilation and controlling the temperature by managing heat sources and applying passive building physics principles instead of opting for mechanical cooling. These two examples are further explained below.

CONTROL OF SOURCES OF INDOOR AIR POLLUTION

The control of pollution sources has priority over increased ventilation or personal protection (CEN, 1998). From a purely theoretical point of view, this is not obvious. If the objective is to limit exposure to a certain maximum, one might assume that this can be achieved just as well by increased ventilation or personal protection as by source control. But from a robustness point of view, there are good reasons to prefer source control. The most obvious reason is that if the source is removed one can be very certain that no exposure is taking place. This is in contrast to increased ventilation where exposure remains possible in practice due to problems such as underestimation of source strength, inadequate ventilation rates or inadequate ventilation effectiveness.

CONTROL OF HEAT SOURCES BY PASSIVE BUILDING PHYSICS PRINCIPLES

The strategy of using as many passive means as possible to control the indoor environment and using active means only to fine-tune the indoor environment where necessary also applies to indoor temperature control. In parts of the world, this strategy is used for winter temperature control. The standard is to increase the thermal insulation of the façade as much as possible to minimise the need for active heating. Following the same strategy in summer would mean minimising the solar heat load and internal heat sources and maximising the use of thermally effective building mass to eliminate or reduce the need for active cooling. This strategy has not been widely accepted; on the contrary, it has become common practice to accept high solar heat loads by omitting external shading, usually due to cost considerations or architectural reasons. In addition, a low thermally effective mass is often chosen to allow for flexible layout. All this leads to a higher cooling demand, requiring more extensive HVAC systems.

INSENSITIVITY TO DEVIATIONS FROM DESIGN ASSUMPTIONS

Certain building designs are sensitive to (minor) deviations from design assumptions. An example is induction units, where it is very important that the properties of the unit are accurately tuned to the properties of the room. An incorrect adjustment can lead to distortion of the flow pattern and thus, for example, to too high air velocities in the occupied zone. It is our experience that such mismatches occur regularly in practice. If, during the construction process, a different air supply grille is chosen or a different ceiling structure is used, the flow pattern may be disturbed. Technically simpler heating and ventilation systems are less sensitive to such changes and therefore more robust[12].

FEASIBLE MAINTENANCE REQUIREMENTS

Some designs require more maintenance than others. To contrast two extremes: a larger heat-accumulating building mass, for example by using thermally open ceilings, to limit temperature excursions through passive cooling, is a robust measure. Once installed, it requires hardly any maintenance. Another robust choice is to reduce the window area to limit solar heat gain. On the other hand, the cooling section and variable volume boxes, for example, require periodic maintenance. Particularly high maintenance requirements are imposed by devices where moisture can lead to bacterial growth, such as spray humidifiers (ASHRAE Handbook, 2016). Such devices reduce the robustness of the HVAC system. The

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[12] Constant air volume controllers, for example, are less critical during commissioning, which means that severely disrupted air balances are less likely to occur.

robustness can be further reduced by components such as the condensation drains of induction units, which can be contaminated with bacteria (Byrd, 1996; Menzies et al., 2003; Asikanen et al., 2006). Such facilities are scattered throughout the building, which significantly reduces the likelihood that they will all be properly maintained. In general, passive solutions require less maintenance and are therefore more robust than more complex mechanical systems, and centralised systems are more robust than decentralised ones.

SEPARATION OF HEATING AND VENTILATION

If heating and ventilation are integrated in some way, they seem to be more prone to malfunction than systems where heating and ventilation are separated as much as possible. For example, with induction units, reducing the air supply to avoid drafts or noise can also reduce the heating or cooling capacity. Another example is variable volume systems, where controlling the air supply for the purpose of keeping the indoor temperature constant can lead to insufficient fresh air supply and therefore inadequate air quality.

NO TIME-VARYING FLOW RATE

One of the conclusions of the European IAQ Audit (Bluyssen, 1995) was that in systems with recirculated exhaust air, the actual amount of recirculated air was often higher or lower than the specified amount. This poses the risk that with recirculation, the fresh air supply is actually lower than intended. This not only highlights the risks of recirculation, but also reminds us that, in practice, supply air volumes are not controlled as precisely as we like to think. In other words, controlling supply air volumes reduces robustness.

A system that can function reliably in practice in, for example, schools and homes is CO_2-controlled ventilation. The air is supplied via (pressure-controlled, draught-free) grilles in the facade and discharged centrally via a CO_2-controlled mechanical ventilation unit. It is of course essential that the CO_2 sensor functions correctly.

5.4 ROBUSTNESS AND INTERACTION BETWEEN OCCUPANT AND BUILDING

TRANSPARENCY AND CONTROL FOR OCCUPANTS

An air handling system is transparent when the occupants can acquire a certain basic understanding of how the system works just by looking at it and using it, and when they can see for themselves when the system is not working properly and to some extent know what is wrong with it. Examples of this are:

- Most people have a basic understanding of how heating radiators work. Malfunctions of radiators can be noticed by occupants: the radiator does not warm up, the thermostat knob cannot be turned, or it does not seem to affect the temperature;
- The operation of an openable window is also understandable for most people. One can immediately see how far it is open, as well as whether or not different positions can be set. If opening windows cause draughts, it is usually easy to identify which windows are affected;
- If an exterior sunshade is not working properly, occupants will notice this immediately and building management can take action.
- With complex climate systems, it is sometimes difficult even for experts to get an idea of what is causing occupants' discomfort.

OCCUPANT CONTROL

Transparent and effective user control of the indoor environment increases robustness for two reasons:

- It allows occupants to adapt the indoor environment to their own preferences and to variations over time;
- Within certain limits, it allows the occupant to compensate for any deficiencies in the functioning of the building and the HVAC system.

BALANCING POSITIVE AND NEGATIVE IMPACTS THROUGH OCCUPANT CONTROL

Control options are especially effective for users if they can balance the various positive and negative consequences of their interventions (Clausen & Wyon, 2006). An example of this is described in Section 4.5 where it was found that in naturally ventilated buildings, when using windows to open, users can always make a trade-off between the need for cooling by airflow and fresh air on the one hand and reducing noise from outside on the other because in these buildings both thermal comfort and noise levels are bonus factors.

NATURAL USER BEHAVIOUR LEADS TO IMPROVEMENT OF THE INDOOR ENVIRONMENT

If users can control their environment, for example by regulating the temperature or opening windows, and if the number of workplaces per room is not too large, the natural behaviour of users will lead to an optimal situation for most users. An example of a situation where the natural behaviour of the users leads to a worse situation for themselves and/or for others is when there are draught problems due to the mechanical air supply. In some cases, users therefore tape over ventilation grilles, reducing the ventilation from that particular grille, with a risk of inadequate air quality, and increasing the air velocities at other grilles, which can lead to more draught complaints there.

THE ENVIRONMENTAL GESTALT PROMOTES ACCEPTANCE

The environmental Gestalt[13] encompasses the entire context of the indoor environment and the user experiences in these areas (de Dear, 2004). Formulated in this way, this may seem too abstract, but it can be defined in terms of transparency and control of the indoor environment and the concept of fairness. An environmental Gestalt promotes acceptance if the following conditions are simultaneously met (Leyten, Kurvers & van den Eijnde, 2009):

- Deviations from a comfortable situation can be feasibly reduced or compensated for by occupants with limited negative side effects for themselves or others. This includes the ability to influence the environment and choices about personal factors such as activity and clothing. If there are negative side effects, the possibilities for influence should enable occupants to weigh up the positive and negative consequences of choices;
- The remaining deviations from a comfortable situation are then understandable to the occupant through the transparent functioning of the building and its systems;
- The remaining deviations from a comfortable situation are considered fair by the occupants on the basis of insight through transparency and a feeling of co-responsibility

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[13] Gestalt is originally a German word and the term stands for “an overall picture”, where the whole is more than the sum of the constituent parts. E.g., a table is more than four bars and a plank, and the human personality is more than the sum of its individual describable and measurable characteristics. The psychology of perception assumes that man experiences more than the sum of the individual sensory stimuli (Source: Wikipedia).

for the working environment that arises from the occupants' ability to influence the situation.

ADDITIONAL CONDITIONS THAT PROMOTE ACCEPTANCE

A lack of privacy and views can contribute to dissatisfaction. Good privacy and good views improve user well-being and reduce stress. Workers with more routine work need at least as much privacy as those with creative work because they already have little influence on the work they do. A good view includes a visible skyline and the ability to see distant objects, vegetation and weather conditions (Vroon et al., 1990). That taking complaints seriously by management increases acceptance is something we have seen in complaint assessment surveys we have conducted and follows from the social psychological fairness theory (Whitley et al., 1995). Privacy and views are determined by the building design and the resulting possibilities for arranging the workspace layout.

5.5 THE INDIVIDUAL OFFICE ROOM AS A ROBUST AND ACCEPTING ENVIRONMENTAL GESTALT

Since the 1960s, the layout of offices has changed from smaller cellular office rooms with 1 to 4 workplaces to larger spaces, which are usually referred to as open-plan or landscape offices. In recent years, new office concepts have been introduced such as flex spaces, mixed offices, combination offices or eco landscape offices. The aim is a flexible office design with additional claimed benefits such as better communication, better social interaction and more responsibility and freedom for employees. In addition to the advantages of open-plan offices, such as saving space through a greater density of people and more flexible (re)arrangement, also better cooperation, communication and a related improvement in productivity are suggested. However, there is no scientific basis for this. On the contrary, research by various disciplines, such as architecture, engineering and psychology, show negative effects of open-plan offices on the perception of the office environment (Vroon et al., 1990; Pejtersen et al., 2006). The negative effects are felt in various aspects, such as general dissatisfaction with the office environment, decreased concentration and loss of privacy (Sundstrom et al., 1982; Leaman & Bordass, 1999; Kaarlela-Tuomaala et al., 2009). Many researchers consider open plan offices to be one of the main underlying causes of symptoms of sick building syndrome, such as headaches, fatigue, difficulty concentrating, eye irritation and respiratory complaints (Klitzman & Stelman, 2006; Pejtersen et al., 2006; Wittersey et al., 2004). Noise nuissance causes concentration difficulties, dissatisfaction and reduced privacy (Danielsson & Bodin, 2009; de Croon et al., 2005).

The development of large databases containing results of occupant surveys is making it possible to carry out increasingly reliable analyses. In order to investigate whether the claimed advantages of open plan offices (better communication and cooperation) also exist in practice and outweigh the reported disadvantages (concentration problems, noise disturbances and health symptoms), the results of 303 offices with 42,764 responses were analysed (Kim & De Dear, 2013). This study shows that none of the claimed advantages of open plan offices are based on fact. On the contrary, satisfaction with “interaction between office occupants” were found to be higher in enclosed private offices. The negative effects of noise nuisance and lack of privacy outweighed the claimed “ease of interaction” in open-plan offices. Satisfaction with the office environment was highest in enclosed private offices. More field studies show that physical symptoms and dissatisfaction with the indoor environment occur more frequently as the number of workstations per workspace increases

(Leyten & Kurvers, 2007). These results are supported by Pejtersen et al. (2006), who show that the more workstations per workroom, the greater the number of complaints about thermal comfort, indoor air quality, noise, fatigue, headaches and concentration difficulties occur (see Figure 5.1).

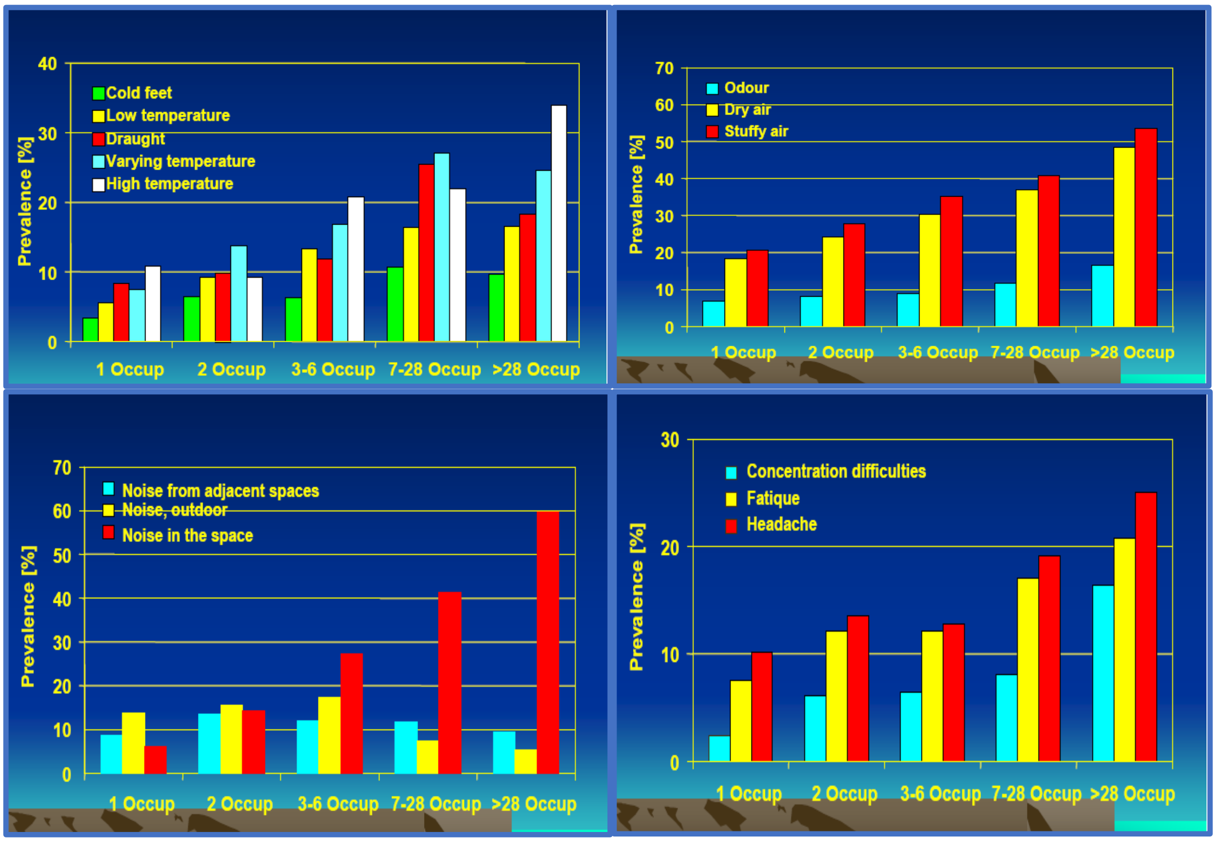

Figure 5.1: Correlation between the number of workstations per workspace and dissatisfaction with the thermal environment (top left), dissatisfaction with the air quality (top right), dissatisfaction with the acoustic environment (bottom left) and concentration problems, fatigue and headaches (bottom right). Source: Pejtersen et al., 2006.

This can be explained within the building robustness hypothesis: in the enclosed private offices, most of the above-mentioned robustness mechanisms apply, and they all work in the right direction:

- Due to its limited dimensions, especially its limited depth, and its high surface/volume ratio, enclosed private offices can be equipped with a less complex heating and ventilation system with higher robustness;
- If every room is equipped with windows that can be opened and temperature control for the winter period, this will ensure maximum transparency and control by the occupants. An illustration of this is a study in 8 office buildings in The Netherlands (Kurvers, Van der Linden & Boerstra, 2002) which shows that the perceived ability to open windows decreases as the size of the office spaces increases. The percentage of people who can open the window as needed decreases from 79% in single rooms to 27% in rooms with more than four people (Figure 5.2);

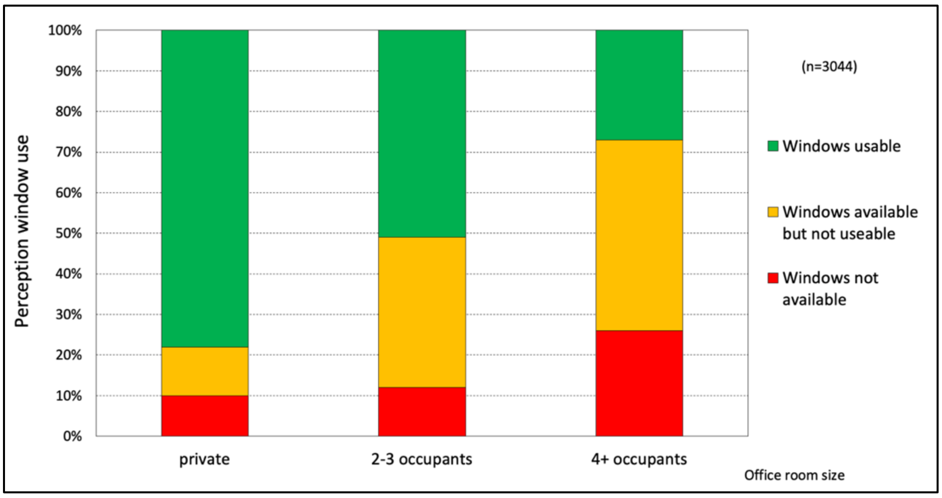

Figure 5.2: Experienced ability and usability to open windows in relation to group size, in 8 office buildings in The Netherlands. Source: Kurvers, Van der Linden & Boerstra, 2002.

- The presence of openable windows instead of mechanical cooling will increase the acceptability of higher temperatures in summer and make the application of adaptive thermal comfort standards more feasible. It also makes thermal comfort a bonus factor (See Section 4.5)
- A small office room encourages users who share a space to be considerate of each other, for example when making telephone calls. This also includes the acceptability of temporary disturbance as the reason and necessity are understood;
- The small office space has a positive effect on social relationships in general. This has been demonstrated by research into the social effects of open plan offices in the 1960s and 1970s (Vroon et al., 1990; Pejtersen et al., 2006);
- Compared to open plan offices, small room offices reduce noise nuisance from the workspace, give more privacy to the users and generally provide a better view of the outside, as the desk is usually closer to the window. All of this will enhance the acceptability of the working environment as a whole.

6 THERMAL COMFORT IN STANDARDS AND GUIDELINES

6.1 INTRODUCTION

Initially, from the 1970s onwards, standards and guidelines for thermal comfort were based on research in climate chambers, particularly on the PMV/PPD model. Based on renewed field research since the turn of the century, standards have been extended to include guidelines for naturally ventilated, non-cooled buildings. In the following paragraphs, the standards are briefly addressed and the problems that the current standards and their classifications can lead to are discussed. Finally, a method to interpret the results of temperature simulations or measurements is described.

6.2 EN-ISO 7730 STANDARD

The EN-ISO 7730 standard "Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria" (EN-ISO 7730, 2005) is an analytical method based on the Fanger climate chamber study (Section 2.4). As an example, Table 6.1 shows some design temperatures from EN-ISO 7730. It is assumed here that the mean radiant temperature is virtually the same as the air temperature.

Table 6.1: Design temperatures for summer and winter for two different activity levels in EN-ISO 7730. For summer a clothing insulation value of 0.5 clo and for winter 1.0 clo is taken. A turbulence intensity of 40% is used for the air speed (mixed ventilation).
Source: EN-ISO 7730, 2005.

Type of building/space	Activity (W/m²)	Category	PPD (%)	Operative temperature (°C)		Maximum mean air velocity (m/s)	
				Summer 0,5 clo	Winter 1,0 clo	Summer 0,5 clo	Winter 1,0 clo
Single office Landscape office Conference room Auditorium Cafeteria/restaurant Classroom	70	A	< 6	24,5 ± 1,0	22,0 ± 1,0	0,12	0,10
		B	< 10	24,5 ± 1,5	22,0 ± 2,0	0,19	0,16
		C	< 15	24,5 ± 2,5	22,0 ± 3,0	0,24	0,21
Department store	93	A	< 6	23,0 ± 1,0	19,0 ± 1,5	0,16	0,13
		B	< 10	23,0 ± 2,0	19,0 ± 3,0	0,20	0,15
		C	< 15	23,0 ± 3,0	19,0 ± 4,0	0,23	0,18

The table distinguishes between three indoor climate categories, assuming that category A provides more comfort than categories B and C, while category B provides more comfort than category C. Originally, EN-ISO 7730 was intended for all types of buildings. The results of field studies have now shown that this standard is not valid for naturally ventilated, non-cooled environments. However, this standard can still be used for the design of air-conditioned environments.

6.3 EN 16798-1 STANDARD

European standard EN 16798-1 “Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6” (EN 16798-1, 2019) is based on both the conventional PMV/PPD model and the adaptive model (based on the SCATs database). The PMV/PPD model is still considered the leading model. Section 6.1.1 of EN 16798-1 states: “*Criteria for the thermal environment in heated and/or mechanical cooled buildings shall be based on the thermal comfort indices PMV-PPD (EN ISO 7730), with assumed typical levels of activity and typical values of thermal insulation for clothing (winter and summer)*”. EN 16798-1 distinguishes four comfort categories (Table 6.2). According to this standard “*the categories are related to the level of expectations the occupants may have. A normal level would be “medium”. A higher level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but may decrease comfort. Selection of the category is building, zone or room specific, and the needs of special occupant groups such as elderly people (low metabolic rate and impaired control of body temperature) shall be considered. For this group of people it is recommended to use category I requirements*”.

Table 6.2: Comfort categories for design of mechanically heated and cooled buildings.
Source: EN-16798-1, 2019.

Category	Predicted Percentage of Dissatisfied PPD (%)	Predicted Mean Vote PMV	Level of expectation
I	<6	-0,2<PMV<+0,2	High
II	<10	-0,5<PMV<+0,5	Medium (Normal)
III	<15	-0,7<PMV<+0,7	Moderate
IV	<25	-1,0<PMV<+1,0	Low

In Section B2.2 of EN 16798-1 recommended ranges of indoor operative temperatures are presented for buildings without mechanical cooling systems as function of the outdoor running mean temperature (Figure 6.2). This alternative method only applies for office buildings and other buildings of similar type (e.g., residential buildings) used mainly for human occupancy with mainly sedentary activities, where there is easy access to operable windows and occupants can freely adapt their clothing to the indoor and/or outdoor thermal conditions, where thermal conditions are regulated primarily by the occupants through opening and closing of openings (windows) in the building envelope. The adaptive comfort limits (Figure 6.2) are considered in this part of the standard as an *alternative* method that can be used under specified conditions.

The bandwidths of the different categories are determined according to the relationship of the percentage of people who are not comfortable with the deviation from the neutral temperature, as shown in Figure 6.1. The running mean external temperature[14] is determined as described in the explanation of the SCATs study in Section 3.3.

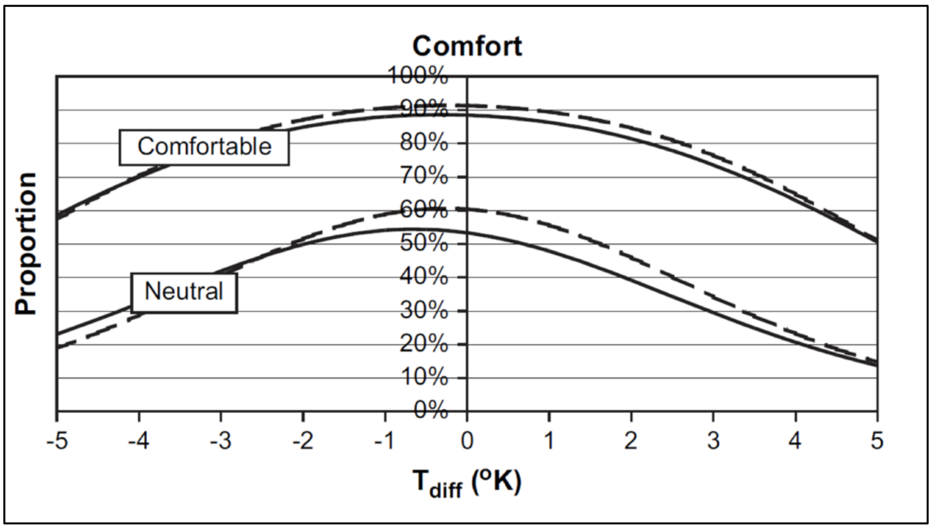

Figure 6.1: Percentage of people who feel comfortable and neutral respectively for free-running (solid line) and air-conditioned (dashed line) buildings, depending on deviation from Mean neutral temperature. Source: Nicol & Wilson, 2010.

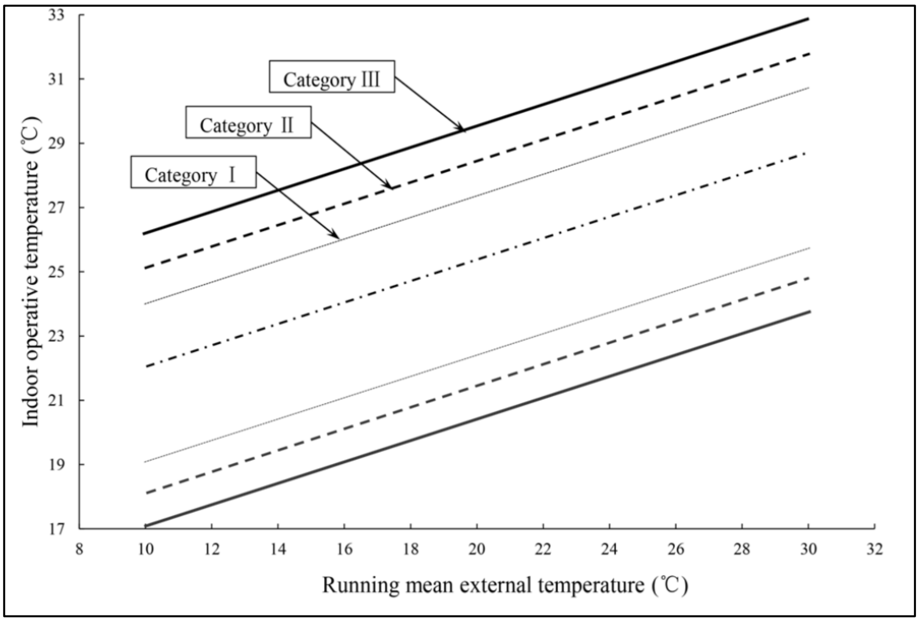

Figure 6.2: Default design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature. Source: EN 16798-1, 2019.

6.4 ASHRAE STANDARD 55

In the American ASHRAE Standard 55, “Thermal Environmental Conditions for Human Occupancy” (ASHRAE, 2017), the adaptive model is also an optional method, in addition to the PMV/PPD method, which can only be applied under the following conditions:

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[14] In literature and standards, the terms external temperature and outdoor temperature are used interchangeably.

- No mechanical cooling is installed;
- The metabolism of the occupants is between 1.0 and 1.3 Met;
- Occupants are free to adjust their clothing to the indoor and/or outdoor conditions within a range of at least 0.5 to 1.0 clo;
- The prevailing outdoor temperature is higher than 10°C and lower than 33.5°C.

The limit values for the adaptive standard are shown in Figure 6.3, where two categories are distinguished:

- 90% or more acceptability;
- 80% or more acceptability.

The limit values are derived from the results of RP884 (see Section 3.2). The limit values for 80% acceptability correspond to those in Figure 3.1.

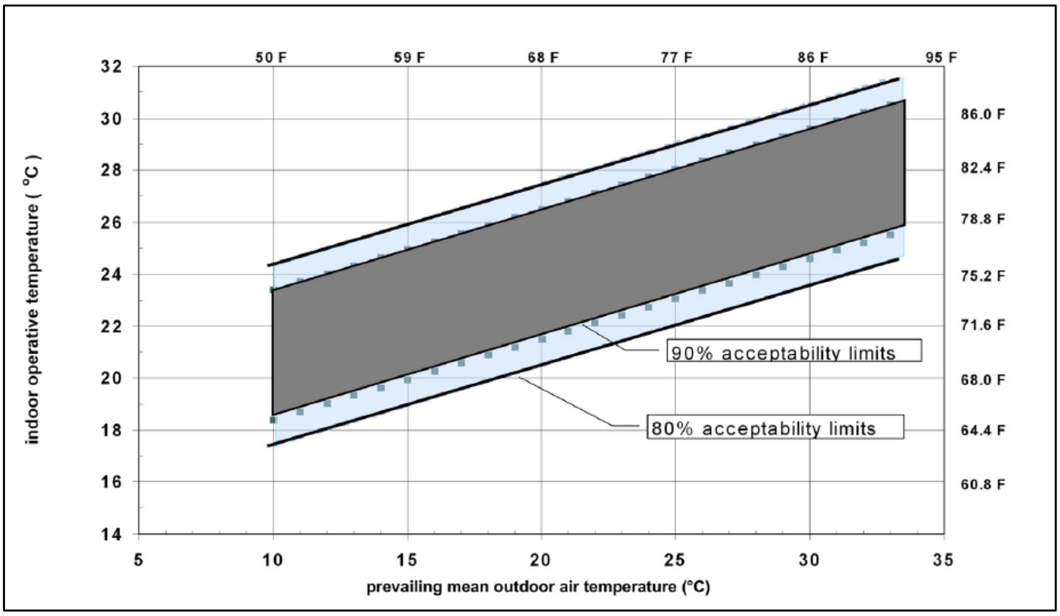


Figure 6.3: The adaptive ASHRAE standard 55 for naturally ventilated rooms as a function of the prevailing outdoor temperature. Source: ASHRAE, 2017.

6.5 ASSESSMENT OF TEMPERATURE EXCEEDANCE

When simulating the thermal behaviour of buildings, in practice the results of temperature simulations for fully air-conditioned buildings are assessed on the basis of temperature exceedances or weighted temperature exceedances. This allows a certain degree of exceeding of the fixed limits in the standards, with the aim that a design is not rejected on the basis of a few exceedances limited in time and scope. Testing is very important, especially in light of the warming climate and because the results of building simulations have far-reaching consequences for energy use and indoor climate quality. Below is a proposal, taken from the adaptive approach in CIBSE TM52 (CIBSE, 2013), on how to interpret exceedances in non-cooled or moderately cooled buildings. Finally, three criteria are given for possible exceedances. If all three criteria are met simultaneously, the design need not be rejected, despite the exceedances. The lines indicating the comfort range (category II in EN 16798-1) should not be interpreted as sharp boundaries. The bandwidth is the percentage of acceptability or discomfort as a function of the deviation from the Mean neutral or comfort temperature. So even within the bandwidth there is always some degree of discomfort due to differences between people. It is in the nature of distributions that discomfort is gradual and therefore has no precise or sharp boundary. A little below or above the boundary line therefore has little effect on the degree of comfort.

The results of temperature simulations are sensitive to differences in, for example, inaccuracies in input parameters of building physics and installation properties, differences in weather data, differences in simulation software and differences in occupancy hours. This can lead to calculated temperature distributions in which a part of the temperatures is just inside or just outside the boundary. In practise this situation is often interpreted in black and white: within the bandwidth there is no discomfort and outside it there is and the situation is therefore rejected. However, in reality the standard indicates from which boundary a certain degree of discomfort is exceeded. Therefore, a method has been developed by CIBSE (CIBSE, 2013) to test temperature discomfort calculations against adaptive limits. It is important to understand that discomfort is not a function of temperature, but of the deviation from the comfort temperature. Figure 6.4 shows that the percentage of people who feel discomfort varies with the deviation from comfort temperature.

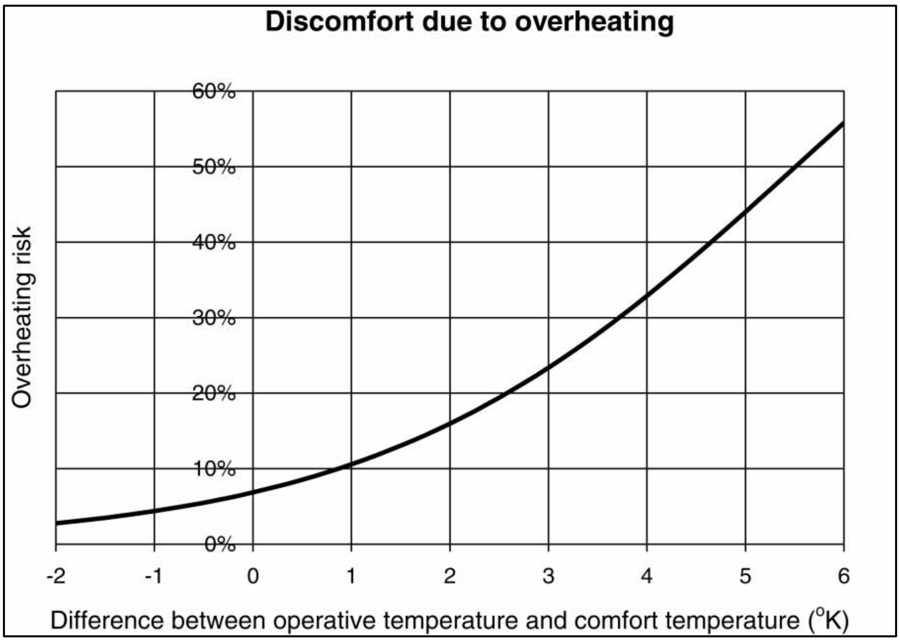


Figure 6.4: The increase in thermal hot discomfort, depending on the difference between the comfort temperature and the operative temperature. This shows that there is also discomfort at the design temperature and that there is no sharp boundary. *Source: CIBSE, 2013.*

In the CIBSE standard, the results of building temperature simulations are assessed against the following criteria:

- Category II of EN 16798-1 (EN 16798-1, 2019). The upper limit of the comfort zone is determined from:

$$T_{max} = 0.33\ T_{rm} + 21.8$$

where T_{max} is the maximum accepted temperature (°C). For T_{rm} see Section 2.5.

- Conditions are then set for ΔT, the difference between the calculated or measured operative temperature T_{op} and the maximum acceptable temperature T_{max}:

$$\Delta T = T_{\mathrm{op}} - T_{\mathrm{max}}$$

ΔT is rounded to whole degrees (e.g., ΔT between 0.5 and 1.5 becomes 1°C).

As stated above, due to the nature of the calculations, not all calculated temperatures can fall within the range and therefore additional conditions are imposed:

1. The number of hours H_{e} that ΔT is greater than or equal to 1°C during the period May - September shall not exceed 3% of the total number of hours of occupancy per year.

2. In addition to a limit on the *number* of hours, there is also a criterion for the *degree* of exceedance.

   Per day, the weighted excess W_e shall not exceed 6:

$$W_{\mathrm{e}} = (\Sigma\, h_{\mathrm{e}})\ x\ \mathrm{WF}$$

$$= (h_{\mathrm{e0}}\ \mathrm{x}\ 0) + (h_{\mathrm{e1}}\ \mathrm{x}\ 1) + (h_{\mathrm{e2}}\ \mathrm{x}\ 2) + (h_{e3}\ \mathrm{x}\ 3)$$

where weighting factor WF = 0 if $\Delta T \leq 0$, otherwise WF = ΔT and h_{ey} is the time (h) when WF = y.

Example: In a temperature simulation, a temperature is calculated every half hour during an 8-hour occupation. There are 16 values, of which ten are $\Delta \mathrm{T} = 0$ or negative (WF = 0), three are $\Delta \mathrm{T} = 1$ (WF = 1), two are $\Delta \mathrm{T} = 2$ and one is $\Delta \mathrm{T} = 3$ (WF=3), so:

$$\mathrm{W_e} = \tfrac{1}{2}\ [(10 \text{ x } 0) + (3 \text{ x } 1) + (2 \text{ x } 2) + (1 \text{ x } 3)] = 5$$

(the condition is fulfilled)

3. Finally, an absolute maximum is set for the operative indoor temperature of:

$$\Delta T \leq 4°\mathrm{C}$$

Above this value, no normal adaptive measures to restore thermal comfort are possible. Condition 3 is a protection against possible future heat waves (Section 6.6). The values for $H_{\mathrm{e}} \leq$ 3% and $W_e \leq 6$ are based on practical studies and for a detailed description and justification of this method, please refer to CIBSE (2013).

Figure 6.5 give examples of temperature simulations in 2 naturally ventilated buildings, where in building A, although there is some excess of the adaptive limit, criteria 1, 2 and 3 are still met. In building B, the exceedances are even slightly larger but conditions 1 and 2 are no longer met.

(For more information concerning CIBSE TM52 Thermal comfort analysis see: https://energy-test.co.uk/thermal-comfort-analysis/).

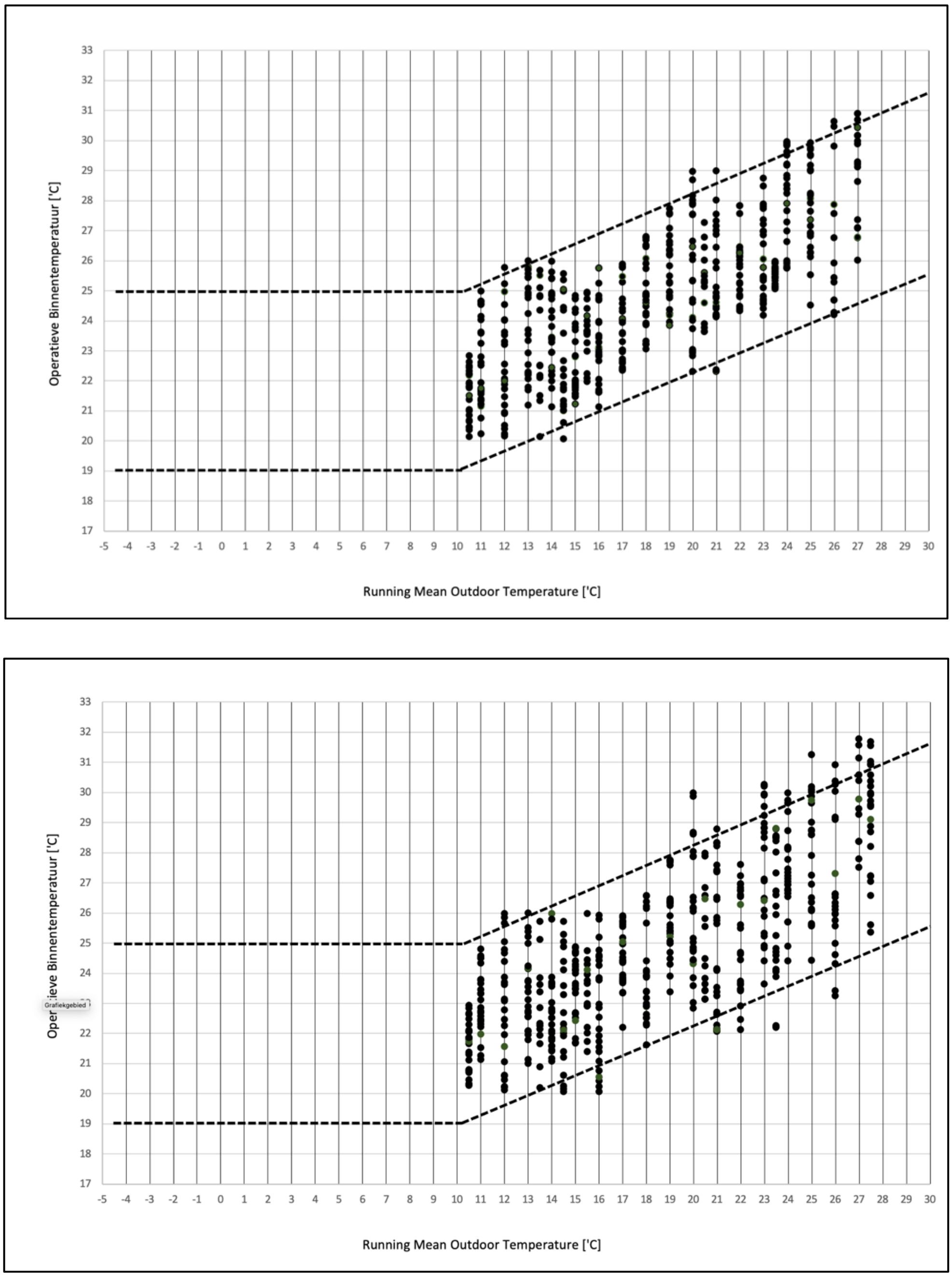


*Figure 6.5: Examples of temperature simulations in naturally ventilated buildings. Above building "A": Criteria 1, 2 and 3 are met. Below building "B": Criteria 1 and 2 are **not** met.*

6.6 HEAT WAVES

A heat wave is a period of at least five days with temperatures of 25 degrees or more. On at least three days a tropical temperature of 30 degrees or more must be reached. The number of official heatwaves in the Netherlands since 1901 at De Bilt is 29. Over the period 1901-2000 the counter stood at 16 heatwaves in total, which corresponds to an Mean of once every six years. In this century there have already been 13 heat waves. This number has been reached in a period of just over twenty years. This means that, on average, we are now faced with a heat wave once every eighteen months. In other words, two out of every three years we experience a period of heat.

According to the climate scenarios of the Royal Dutch Meteorological Institute (KNMI), we can expect around 7 to 13 tropical days in the year 2050. At the moment (2020), there are 5 tropical days per year. In both 2018 and 2019, there were two official heat waves. In 2020 one heat wave was recorded. In this century, the longest period without a heat wave was seven years. No official heat wave was recorded between July 2006 and July 2013. In the previous century, there was no official heatwave for 28 years between July 1948 and June 1976. A heat wave was a rare occurrence and an entire generation grew up without it. Nowadays, it is quite normal for a heat wave to occur in summer. Not only is the number of heat waves increasing, the number of warm summer days and tropical days is also rising. At the beginning of the last century, during the climate period 1901-1930, a mean of 66 warm days with a temperature of at least 20 degrees was recorded in a year. On 13 of those days, the temperature rose to 25 degrees or more and on an average of 1 day it became tropically warm with values of 30 degrees or more. In the period 1961-1990, a slight increase was visible. The number of warm days with temperatures of 20 degrees or more was 71, the number of summery days 19 and the number of tropical days 2. Over the period 1991-2020, the annual number of warm days is no less than 93. On 28 of those days the temperature was at least 25 degrees and on an average of 5 days per year the mercury rose to 30 degrees or more (KNMI, 2020). The implications for building design will be discussed in Section 11.6.

7 INDOOR CLIMATE CATEGORIES IN STANDARDS

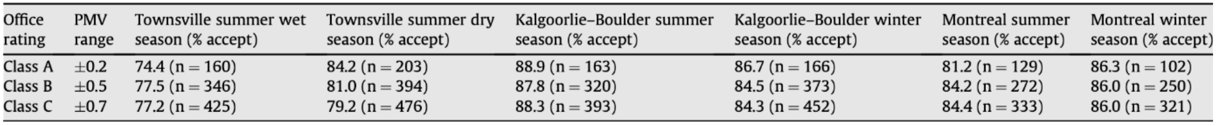
7.1 INTRODUCTION

Both the standard based on the PMV model (Table 6.1 and Table 6.2) and the adaptive indoor climate standards (Figure 6.2 and Figure 6.3) give ranges within which a certain percentage of occupants find the temperature acceptable or comfortable. These ranges are divided into categories or classes (A, B, C or I, II, III, IV). A narrower range is referred to in the standards as a “higher level of expectation, ambition or quality”. This suggests that a narrower bandwidth will provide a better indoor climate in practice. In the certification method for a sustainably built environment BREEAM-NL (2014), for example, even explicit distinctions are made between a “good” and an “excellent” indoor climate, with the excellent indoor climate falling within a narrower bandwidth. It is appropriate to recall that the bandwidths represent a percentage of 80% or 90% acceptability that is an average of a database of a large number of buildings. A single building can have a different distribution within this bandwidth. In most cases, a narrower bandwidth does lead to a higher energy use, but whether it also leads to a more comfortable indoor climate in practice is questionable. Below, both empirical and theoretical arguments are given as to why indoor climate categories are problematic.

7.2 EMPIRICAL OBJECTIONS TO INDOOR CLIMATE CATEGORIES

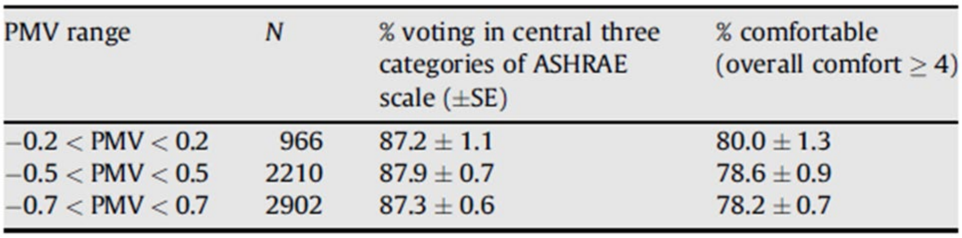
In general, more energy is required to achieve a narrower temperature bandwidth. The question that arises here is therefore: does this extra amount of energy also lead to a more comfortable indoor climate in practice? This has been investigated in the databases of 45 office buildings around the world (RP-884) and the European database (SCATs) of 26 office buildings of various types in 5 European countries (Arens, 2010). Air temperature, radiant temperature, air velocity and humidity were measured in the buildings, and the clothing insulation and metabolism values were determined, so that PMV values could be calculated. In addition, the subjective comfort of the occupants was determined via questionnaires. The results are given in Table 7.1 and Table 7.2. In both tables, the three indoor climate categories according to the PMV/PPD model correspond to 90%, 80% and 70% acceptability, respectively.

Table 7.1: Comparison of calculated PMV ranges, A: 90%, B: 80% and C: 70% with actual acceptability (RP-884 database). *Source: Arens et al., 2010.*



Office rating	PMV range	Townsville summer wet season (% accept)	Townsville summer dry season (% accept)	Kalgoorlie–Boulder summer season (% accept)	Kalgoorlie–Boulder winter season (% accept)	Montreal summer season (% accept)	Montreal winter season (% accept)
Class A	±0.2	74.4 (n = 160)	84.2 (n = 203)	88.9 (n = 163)	86.7 (n = 166)	81.2 (n = 129)	86.3 (n = 102)
Class B	±0.5	77.5 (n = 346)	81.0 (n = 394)	87.8 (n = 320)	84.5 (n = 373)	84.2 (n = 272)	86.0 (n = 250)
Class C	±0.7	77.2 (n = 425)	79.2 (n = 476)	88.3 (n = 393)	84.3 (n = 452)	84.4 (n = 333)	86.0 (n = 321)

Table 7.2: Comparison of calculated PMV ranges, A: 90%, B: 80% and C: 70% with actual acceptability (SCATs database). The percentages of building users voting “somewhat cool”, “neutral”, “somewhat warm” (third column) and “comfortable” (fourth column).
Source: Arens et al., 2010.



PMV range	N	% voting in central three categories of ASHRAE scale (±SE)	% comfortable (overall comfort ≥ 4)
$-0.2 < PMV < 0.2$	966	87.2 ± 1.1	80.0 ± 1.3
$-0.5 < PMV < 0.5$	2210	87.9 ± 0.7	78.6 ± 0.9
$-0.7 < PMV < 0.7$	2902	87.3 ± 0.6	78.2 ± 0.7

It is clear that a narrower range determined by measurements and calculated PMV/PPD ranges is not perceived by occupants as more comfortable or acceptable in real-life conditions. Sometimes there are no differences at all, in other cases a narrower PMV range leads to slightly more satisfaction, in yet other cases a narrower PMV range leads to less satisfaction. None of the differences are statistically significant. One reason is that the measurement uncertainties of the variables to calculate the PMV are as large as the differences between the ranges of the 3 categories (Alfano, et al., 2011). Thus, there is no empirical support for the idea that a higher climate class, with a narrower PMV or temperature limit on paper, also leads to more comfort or satisfaction in reality. This will be discussed in more detail in the following sections.

7.3 THEORETICAL OBJECTIONS TO INDOOR CLIMATE CATEGORIES

The adaptive standard EN 16798-1 defines the indoor climate categories as levels of “expectation”. The narrower the temperature bandwidth, the higher the level of expectation and the higher the indoor climate class, with the implication that there will also be more satisfied occupants. The question is whose and what level of expectation is involved. Given the role that the indoor climate standard plays in the design process, it could be about the level of expectation of the developer, the architect, the HVAC consultant or the management of the company housed in the building. At some time in the process a certain level of expectation is chosen. For example, the developer may choose an air-conditioned building in climate category A (or I), because he or she thinks it will get a higher building certification and will therefore be easier to rent out. Or the management of an organisation might choose to rent such a building to ensure that there are no or few complaints about the indoor climate from staff. However, it is most logical to assume that what is meant here is the users' expectation level. If users actually have different expectation levels, it is not obvious that these are defined in terms of the narrowness of the temperature bandwidth or in constancy of temperature. If we look only at the users, independent of the building, it is obvious that most users have roughly the same expectation level: a thermally comfortable environment for most of the time. If we include the type of building involved, there are differences in expectation levels. The study by Kim & de Dear (2012) discussed in Section 4.5 shows that occupants of air-conditioned buildings have a different expectation pattern of the thermal environment than occupants of naturally ventilated buildings.

For the occupants of air-conditioned buildings, thermal comfort is a basic factor. They expect it to meet high standards and, if the indoor climate does not meet these, they are more likely to be dissatisfied with the building as a whole. In addition, they expect a comfortable thermal environment and they expect to have to do little themselves, for example by changing their clothes or adjusting the temperature (if at all possible). For users of naturally ventilated buildings, thermal comfort is a bonus factor; if the indoor climate has shortcomings, this does not lead to dissatisfaction with the building as a whole, and if the indoor climate is acceptable, the users are additionally satisfied. They also feel jointly responsible for their own thermal comfort, because they can influence it through the use of openable windows and blinds and by adjusting their clothing insulation.

Chapters 1 and 4 have shown that the high expectations that clients or employers have of air-conditioned, category A buildings are often not met in practice, because the dependence on (complex) installations increases the risk of discomfort and physical symptoms, as this type of building has a low robustness (Chapter 5). Buildings with natural or hybrid ventilation with a high degree of control perform better and provide realistic user expectations.

The use of two types of standards alongside each other, namely a standard based on the PMV/PPD model and an adaptive standard, in combination with the current classification into climate categories, can lead to so-called perverse incentives. When, during the design process, a choice is made for the type of building and the envisaged indoor climate quality, and the client requires in any case a “good indoor climate” and therefore opts for category A, it may happen that the temperature simulations show that, given the physical design properties, the outdoor climate and the location, a building with adequate natural ventilation meets category B, but does not (just) meet category A. This can then be a reason for the client to decide to apply the PMV/PPD standard and therefore to choose a category A air-conditioned building, especially if the standard used gives the impression that adaptive comfort is only an *alternative*. There is a good chance that the air-conditioned category A building will in reality lead to more dissatisfaction about the indoor climate and more physical symptoms than the naturally ventilated category B building.

Another perverse incentive comes from the fact that, in addition to a “high level of expectation”, category A is also recommended for vulnerable groups, such as the sick, young children and the elderly. In many cases, this means that mechanical rather than building-physical and passive solutions will be used to comply with category A, which actually increases the risk of air quality complaints, possibly including headaches, fatigue, difficulty concentrating, irritation of the eyes, throat and nose, which is particularly undesirable for vulnerable groups. For these groups, natural air supply through the façade can be an interesting alternative to mechanical supply, because there may be a lower risk of contamination by pathogenic microorganisms than air supplied through filters, ventilation ducts and terminal units, which may not be properly maintained (Van den Engel & Kurvers, 2017). Moreover, different vulnerable groups cannot be treated in the same way. Chapter 9 describes that the elderly and children experience the thermal environment differently and that there are also individual differences within these groups. A normally good building can be assumed to have a satisfaction rate of 80%. Research shows not only that narrower temperature limits do not lead to more satisfaction, but also that a satisfaction rate higher than about 80% is not feasible in practice (Arens et al., 2010; Li et al., 2019).

7.4 CLASSIFICATION BASED ON ADAPTIVE OPPORTUNITIES

Because of the problems with indoor climate categories, it has also been suggested to classify the indoor climate according to the adaptive possibilities for the users (Boerstra, 2010). One of the first attempts can be found in RP-884. There, the following adaptive possibilities are defined:

- Openable Windows;
- Exterior doors;
- Interior doors;
- Thermostats;
- Curtains/light blinds;
- Local heating appliances;
- Local fans (ceiling or table-top).

Furthermore, for a subgroup of respondents whose overall score for the adaptive opportunities in their building and their score for individual adaptive opportunities was known, an index of personal adaptive opportunities was determined. From this data an index of Mean personal influence per building was derived. The relationship between this index and several measures of thermal perceptions within a building was then calculated, including the relationship with thermal satisfaction. None of these correlations is statistically significant. Apparently, simply determining whether an adaptive capability is present is not sufficient to predict thermal satisfaction.

A better approach is to base a personal or building control index not only on the presence of the adaptive opportunities, but also on their *usability* and *effectiveness*, based on assessments by actual occupants. A good example of this is given in Boerstra (2016). In questionnaires used to investigate the causes of complaints in specific office buildings, the questions asked included:

- The presence of a temperature control system;
- If present, the effectiveness of the temperature control;
- The presence of a window that can be opened;
- If present, the opportunity to adjust the openable window at ones own will.

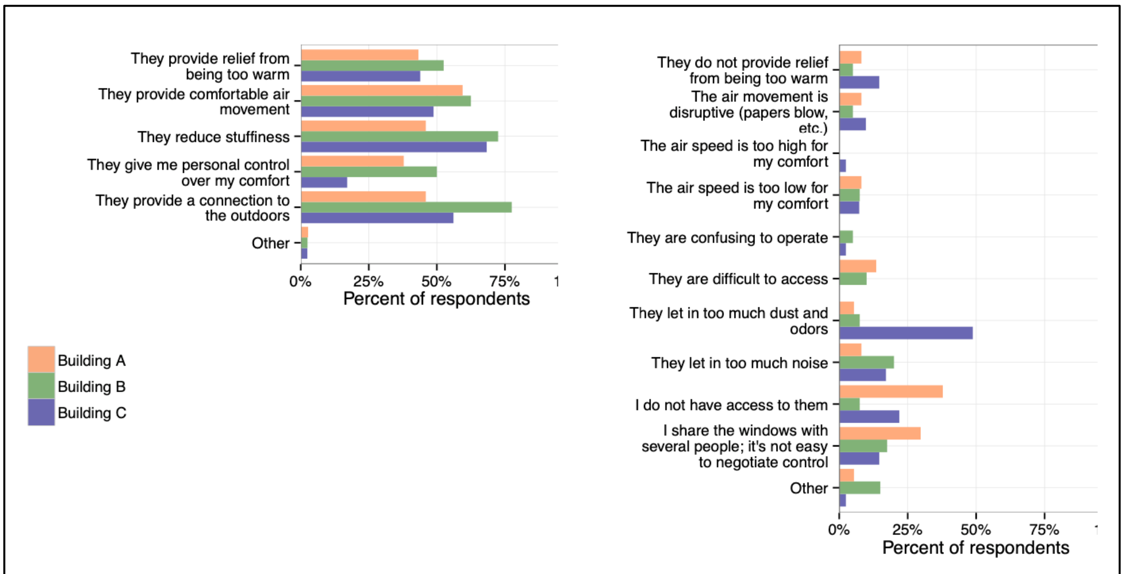
Based on these questions, a control index can be formed that has a statistically significant relationship with, among others, a composite measure of comfort, as indicated by the occupants, and a measure of building-related physical symptoms, also as indicated by the occupants. In particular, the relationship between this control index and the number of building-related symptoms is strong. The explained variance (R^2) is 42%, for the building comfort indices this is only 18% explained variance. Apparently, control opportunities are particularly important for physical health. A hypothetical explanation for this is proposed in Vroon et al. (1990): if there are stressful conditions, the person concerned can either choose external coping, in this case adapting the environment by means of control opportunities, or is forced to choose internal coping, accepting the circumstances, which in the long run can lead to an (over)load of the organism and thus to building-related health problems.

A study (Pigman, Brager & Zhang, 2018) in three mixed mode buildings examined the interrelationships between:

- Accessibility to an adaptive opportunity;
- Satisfaction with the opportunity to control the environment;
- Perception: how much confidence do people have that using the control option will have the desired effect.

The results show that accessibility is not a good predictor of satisfaction, but trust, based on observation, that the use of the control opportunities has the desired effect, is. The following example shows that the presence of control opportunities does not in itself guarantee satisfaction. In one of the three studied buildings, the users were generally too cold. Moreover, of the three buildings, they were the most dissatisfied with the option of controlling the temperature themselves. The temperature in this building had a year-round set point of 20°C to 22°C, which is considerably too cold in summer. The occupants had several means of control at their disposal: sun shading, light shading and ceiling fans. None of these are suitable for reducing the complaints about too low a temperature. Pigman, Brager and Zhang conclude: "*This begins to suggest that simply having some form of environmental control isn't necessarily helpful unless there is a clear match between the type of control and the likely source of thermal discomfort*." This is also a partial explanation why a standard composite index like the one in RP-884 does not work.

Discomfort and building-related health symptoms are not correlated with an index based on the *presence* of adaptive opportunities, but they are with an index based on the *effectiveness* or *usability* of adaptive opportunities as indicated by occupants themselves. This shows that there is still too little knowledge about the properties of adaptive opportunities that determine their effectiveness and usability. This concerns questions such as: which type of openable window is the most usable and does it depend on the type of building or room layout or on the type of HVAC system? Figure 7.1 shows reasons for satisfaction or dissatisfaction with openable windows, as reported by the occupants.



a. Reasons for satisfaction

b. Reasons for dissatisfaction

Figure 7.1: Reasons for satisfaction and dissatisfaction with openable windows.

Source: Pigman, Brager and Zhang (2018).

One might ask if a building classification based on adaptive opportunities is a good alternative to existing classifications? It is worth recalling the importance of adaptive opportunities for comfort and health, for the following reasons:

- The possibility to adapt the environment to one's own preferences;
- The ability to (partially) compensate for any malfunctioning of building systems;
- The possibility of positive alliesthesia;
- Promotion of health because one can choose external coping instead of internal coping.

These reasons, especially taken together, are so important to demand that a “normally good” building should have as many adaptive opportunities as possible, as judged by its occupants to be effective. This is confirmed by the results of Boerstra (2016). When a classification based on adaptive opportunities is developed, the danger of perverse incentives arises here as well. In such a classification, certain adaptive opportunities will be reserved for extra “good” buildings, or category I or A buildings. “Normally good” or “appropriate” buildings will have do with fewer adaptive options, even though they are particularly important for comfort and health. Here, as with the classification based on temperature limits, the aim should be to define requirements for an “good or appropriate building” and requirements for an “extra good building” are undesirable.

8 NEW PERSPECTIVES RESULTING FROM THERMAL COMFORT DATABASE II

8.1 INTRODUCTION

The results of field studies (Humphreys, 1975; de Dear et al., 1997; Nicol, & Humphreys, 2005) have led to a more realistic view of thermal comfort than the climate chamber models (Fanger, 1970) and to expanding standards to include opportunities for more adaptive approaches to indoor climate. Since the turn of the century, the amount of field research has increased enormously, not only in Europe and the United States, but also in Asia, South America and Africa. All this research of the last two decades has been collected in a global database: ASHRAE Global Thermal Comfort Database II (Földváry Ličina et al., 2018), which also includes data from RP-884 and SCATs (Chapter 3). Figure 8.1 shows the field surveys from database II classified by climate, continent and season.

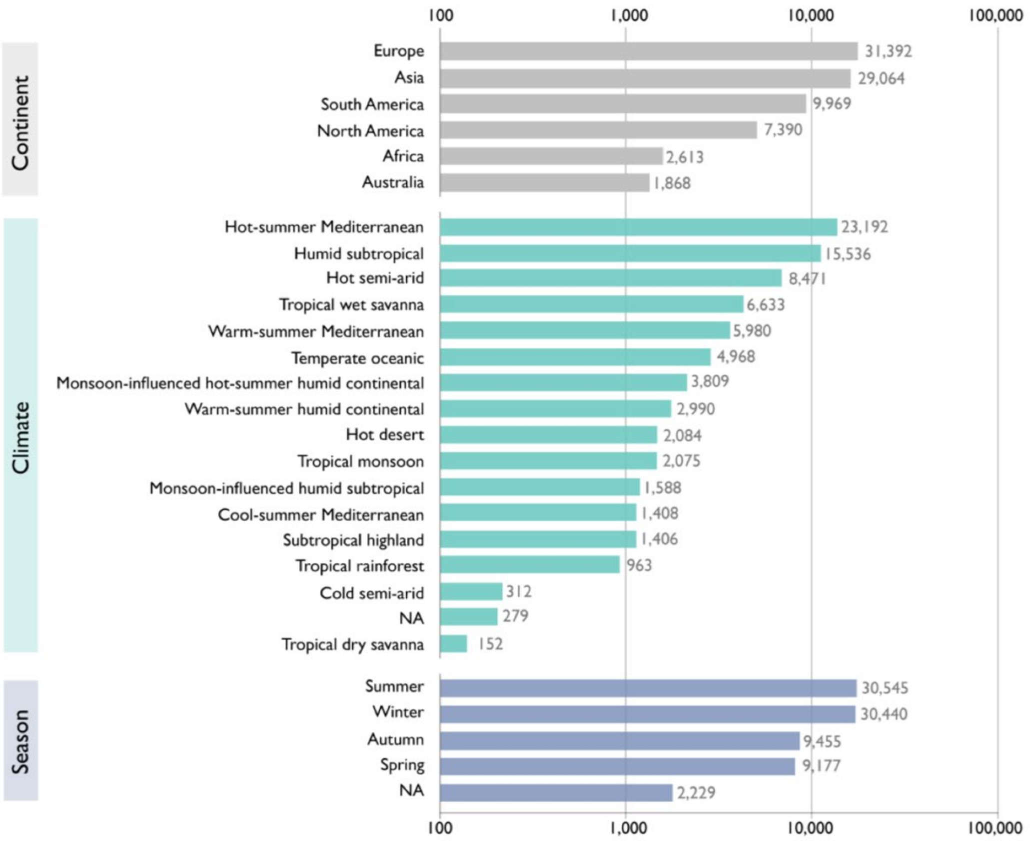


Figure 8.1: Distribution of field surveys by continent, climate and season. Climate is classified according to Köppen's classification system, the horizontal axis is a logarithmic scale. The numbers on the X axis are "records". Source: Földváry Ličina et al., 2018.

The first database from 1998, RP-884, on which the adaptive ASHRAE standards are based, consisted of over 20,000 data points distributed across 8 countries on 4 different continents and 11 climate zones, according to the Köppen classification. At the time of the new analyses

(2019), the current database consists of more than 107,000 records[15] distributed across 29 countries on 6 different continents and 16 climate zones. With this more extensive and geographically better distributed database, new analyses examine the following aspects of thermal comfort in buildings:

- The validity of the indoor climate categories;
- The validity of the PMV/PPD model;
- The validity of the original RP-884 based adaptive comfort model;
- The applicability of the adaptive model to building types other than naturally ventilated/non-air-conditioned/free-running buildings;
- The influence of humidity on thermal comfort;
- The differences in thermal comfort in different parts of the world;
- Possible improvement of the current practice of operating HVAC systems to enable energy savings.

The database is public and available online in order to carry out analyses: https://cbe-berkeley.shinyapps.io/comfortdatabase/.

8.2 THE VALIDITY OF THE INDOOR CLIMATE CATEGORIES

Chapter 7 outlined the objections to divide the indoor climate into quality or expectation categories. Using the ASHRAE Global Thermal Comfort Database II, it was possible to analyse the validity of the indoor climate categories, based on the PMV/PPD relationship, more precisely to better substantiate the empirical objections. Figure 8.2 shows that the differences in acceptability expressed by the PMV categories in the standards do not in reality give significant differences in the rates of acceptability or comfort (Li et al., 2019).

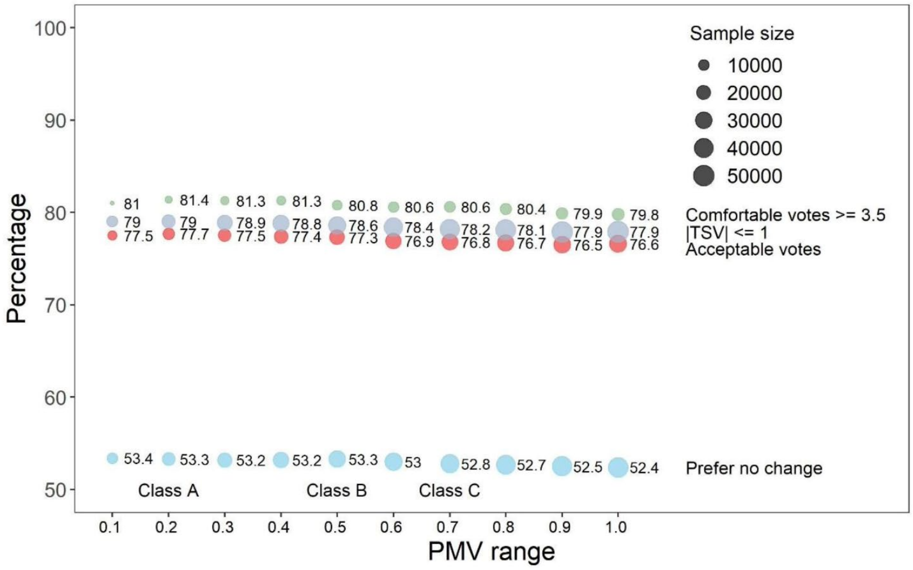


Figure 8.2: Actual percentages of comfort (green dots), thermal sensation (TSV) (grey dots), acceptability (red dots) and "prefer no change" (blue dots) compared to the PMV categories (Category A: +/- 0.2; Category B: +/- 0.5; Category C: +/- 0.7). Source: Li et al., 2019.

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[15] A record is a row in the database consisting of a building occupant's responses to questions such as thermal sensation and comfort and associated measurement values such as indoor air temperature, air velocity, humidity, outdoor climate data and estimates of clothing insulation and metabolism and calculated thermal indices.

It is clear that thermal comfort in buildings is achieved over a wide PMV bandwidth and that an indoor climate does not become more comfortable the closer PMV or temperature boundaries are controlled. This is a further confirmation of the results of Ahrens et al. (2010) in Table 7.1 and Table 7.2. The recently developped thermophysiological theories assume a thermoneutral zone within which comfort is achieved by physiological adaptation in combination with behavioural adaptive measures (Kingma, 2014; Parkinson, 2016).

8.3 THE VALIDITY OF THE PMV/PPD MODEL

One of the important findings of the analysis of the ASHRAE Global Thermal Comfort Database II is that the PMV/PPD model has low accuracy in predicting thermal comfort, both at the group and individual level. The explained variance (R^2) of the Observed Thermal Sensation by the PMV is low: 8%. The overall accuracy of the PMV model is found to be 34%. Even around "neutral", where the PMV is considered most accurate, the accuracy is below 60%. Figure 8.3 shows the main results of the analysis (Cheung, et al., 2019).

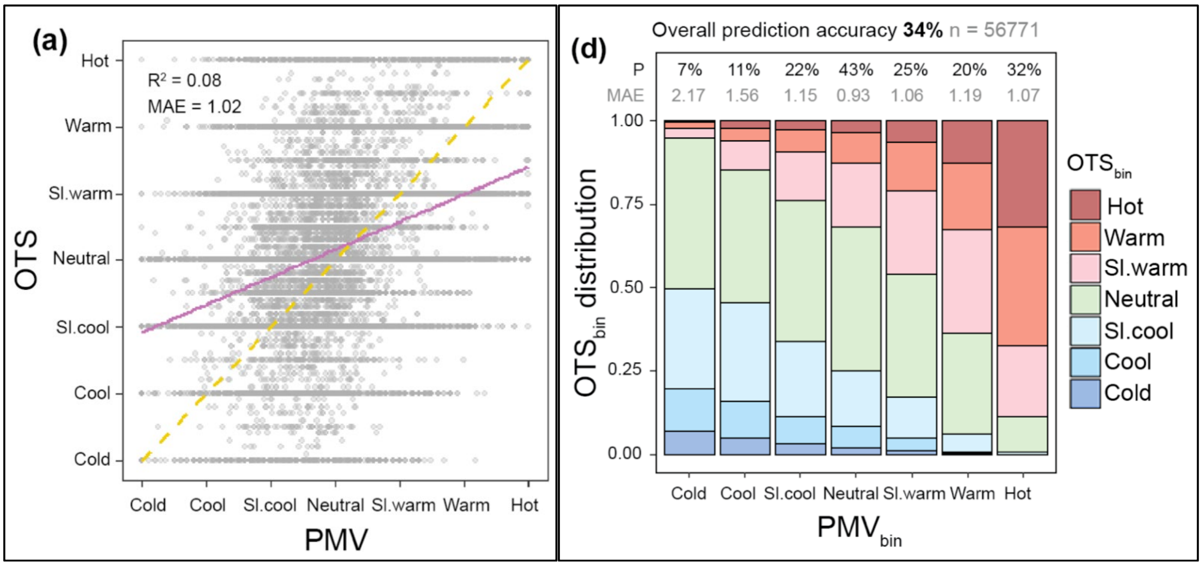

Figure 8.3: Analysis of the relationship between the Observed Thermal Sensation (OTS) and PMV. (a)= Raw data plot between OTS and PMV; (d)= Grouped OTS (OTS_{bin}) at each PMV_{bin} category with the overall prediction accuracy (P) and mean absolute error (MAE) at each PMV_{bin} category[16]. Source: Cheung et al., 2019.

The database is composed of data collected by many researchers who have followed different procedures and used different equipment and measuring method, for example, temperature, air velocity, metabolism and clothing insulation. These are potential sources of inaccuracies in the PMV/PPD model and raise the question of how reliable and robust the PMV model is when trained researchers cannot obtain correct results. Cheung, et al. (2019) concludes that, given its complexity, the PMV model has an unacceptably low prediction accuracy and that there is a need for simpler, non-deterministic models that better predict people's comfort in the built environment.

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[16] For the variable on the X axis of Figure 8.3(d), the PMV scores are divided into "bins", which are carefully chosen categories when making histograms. All bins have the same range and all data should be included.

To further investigate the validity of the PMV model, Figure 8.4 compares the actual observed percentage of dissatisfied with the classical PMV/PPD curve (Figure 2.2). The actual percentage of dissatisfied is not as sensitive to thermal sensation as the PMV/PPD predicts, which is evident from the flatter lines compared to the PPD. This confirms the previously mentioned observation that narrower comfort categories around PMV=0 do not give higher comfort in practice. Moreover, the lowest observed percentage of dissatisfied is around 20%, much higher than the 5% predicted by the PMV/PPD relation.

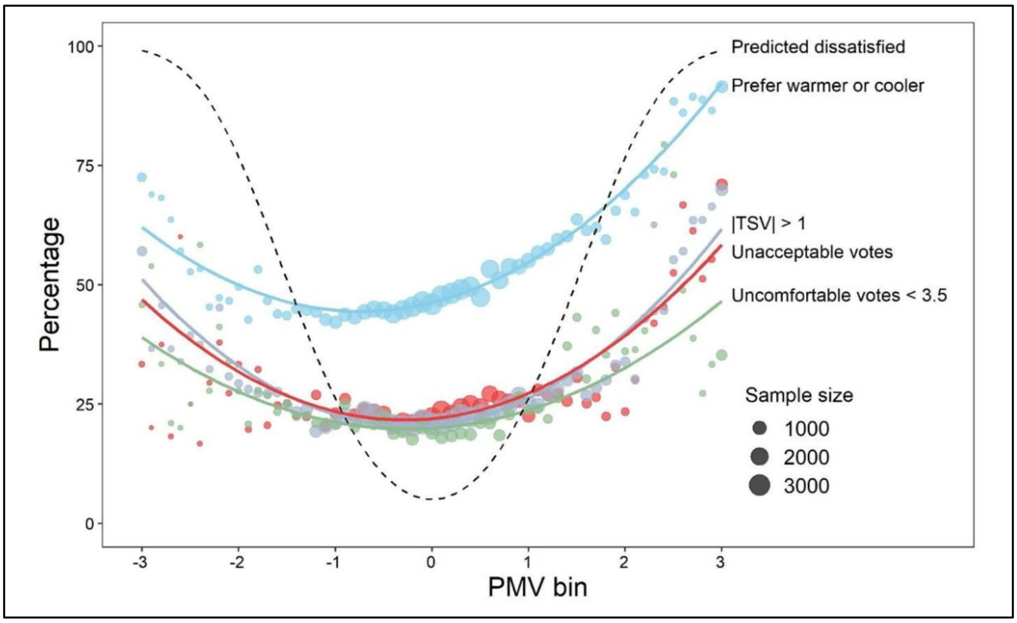

Figure 8.4: Observed percentage dissatisfied versus predicted percentage dissatisfied. Each dot represents the percentage dissatisfied and the lines are weighted by sample size. The X axis is the calculated PMV, divided into bins. The blue line indicates the preference for a warmer or cooler environment, the grey line is the absolute value for the TSV>1, the red line indicates that the thermal environment is rated as unacceptable and the green line are the "uncomfortable" votes, defined as <3.5 on the scale of 1 (uncomfortable) to 6 (comfortable).
Source: Li et al., 2019.

The reason for the poor validity of the PMV/PPD model lies more in the PMV index than in the PPD index. Figure 8.5 shows that the relationship found in the field between observed thermal sensation (OTS_{bin}) and observed percentage unacceptable (OPU) corresponds quite well to the PMV/PPD relationship developed in the climate chamber, but that the PMV, calculated from observed and measured variables, poorly predicts actual thermal acceptability (OPU). In particular, in the neutral and cold regions, there is no relationship between PMV_{bin} and observed percentage dissatisfied. (Cheung, et al., 2019; Li et al., 2019).

As shown earlier in this book, it is difficult in practice to determine the PMV correctly, due to the large margins of uncertainty in the input variables of clothing insulation and, to a lesser extent, metabolism[17]. This confirms once again that a correlation found in climate chambers

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[17] The information in Figure 8.4 and Figure 8.5 partly overlap and partly differ. Figure 8.4 examines the relationship of PMV_{bin} with various occupant ratings, including the percentage of "unacceptable" votes. Figure 8.5 examines only the relationship of PMV_{bin} with the observed percentage of unacceptable votes (OPU). In both figures, this corresponds to the red curve. At first glance, it seems that the curves in the two figures are rather different, but that is not so. The U-shaped curve in Figure 8.5 is an artefact of the way in which the curve

between a calculated thermal sensation and the degree of satisfaction cannot be applied one-to-one in real-life conditions and that narrower PMV categories around a neutral point do not increase satisfaction.

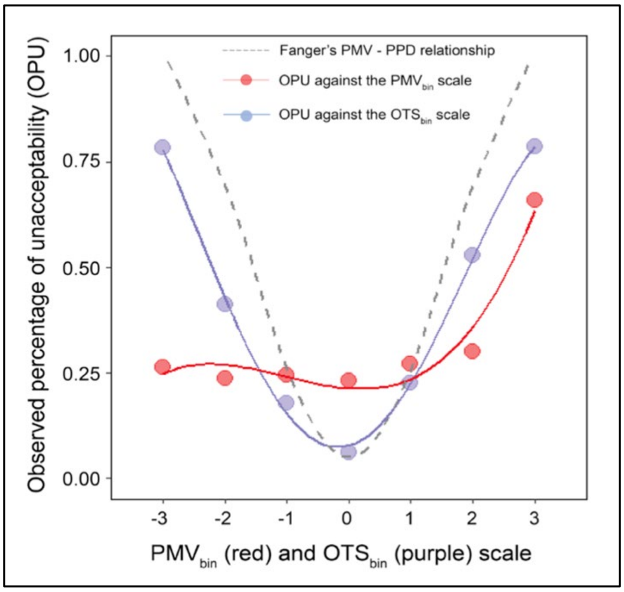

Figure 8.5: Relationship between the observed percentage of thermal acceptability (y-axis) and the observed and calculated PMV (x-axis): The red line shows the relationship between the Observed Percentage of Unacceptability (OPU) and the PMV (PMV_{bin}), the blue line shows the relationship between the Observed Percentage of Unacceptability (OPU) and the observed thermal sensation (OTS_{bin}). The dotted line is the theoretical relationship based on the PMV/PPD model. Source: Cheung et al., 2019.

8.4 ADAPTIVE THERMAL COMFORT IN DIFFERENT BUILDING TYPES

Figure 8.6 shows the neutral temperatures from the new database projected onto the original RP-884/ASHRAE analysis (de Dear & Brager, 1998), as shown in Figure 6.3. Looking at the neutral temperatures of the naturally air-conditioned buildings (blue line), the slope is similar to the original database, but about 2°C higher than the RP-884/AHSRAE line and 1°C higher than the value from SCATs/EN16798-1. To investigate the cause of this, analyses were made of buildings in “Asia” (Middle East, India, South, Southeast and East Asia) and “West” (Europe, North America and Australia). Figure 8.7 shows that both indoor and outdoor temperatures are higher in the Asian data compared to the Western data.

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was calculated, namely by means of a quadratic regression line. If we look at the red data points in Figure 8.4 in the cool area (PMV_{bin} between -3 and -1) a large proportion of the data points are below the curve, which means that in this figure too, in the cool and neutral area, there is little or no relationship between PMV_{bin} and the percentage of 'unacceptable votes'. The relationship in Figure 8.5 between percentage of unacceptable votes (OPU) and perceived thermal sensation OTS_{bin}, the blue-grey curve, is not shown in Figure 8.4.

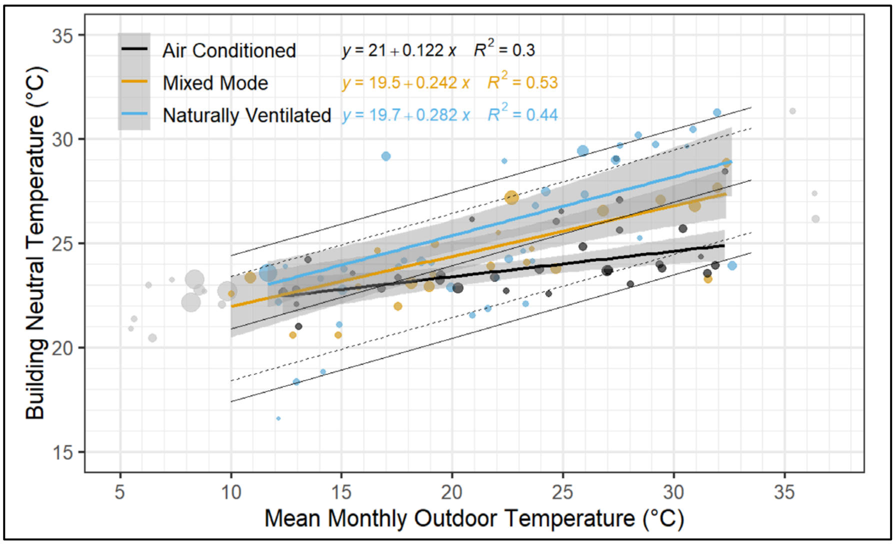


Figure 8.6: Neutral temperatures and mean monthly outdoor temperature during the survey in each building in the new database, projected onto the original RP-884 data (black solid and dotted lines), as shown in Figure 6.3. The air-conditioned buildings are shown in black, the mixed-mode buildings in yellow and the naturally ventilated buildings in blue. Each dot represents an individual building and the size of the dot indicates the weighting factor based on the sample size in that building. The grey areas indicate the 95% confidence intervals for each building type. *Source: Parkinson, de Dear & Brager, 2020.*

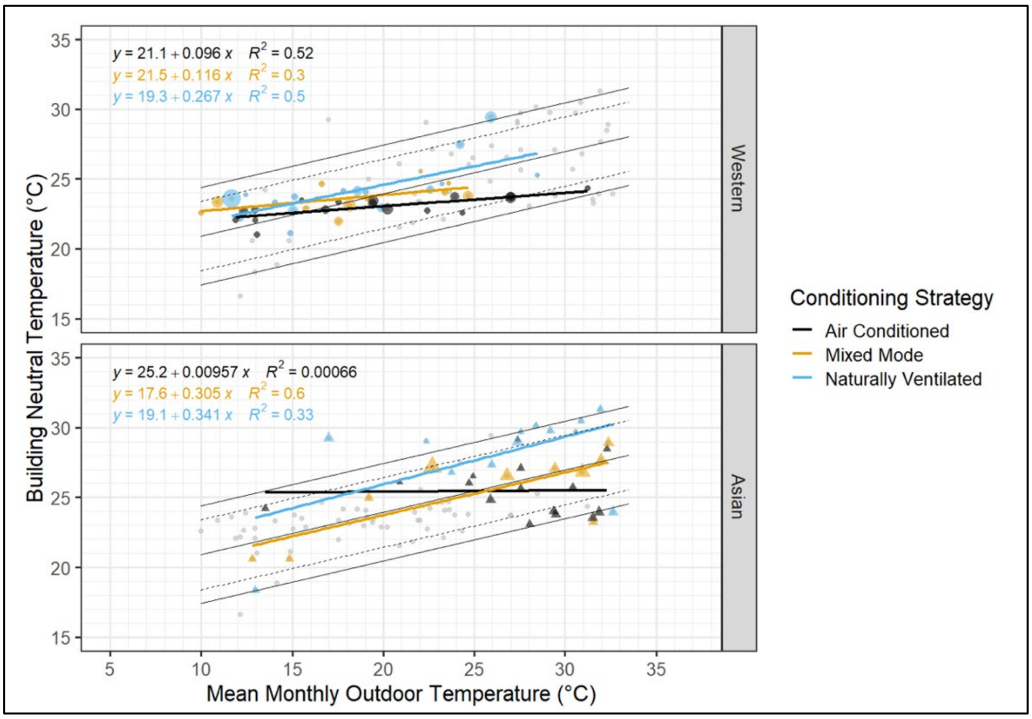


Figure 8.7: Neutral temperatures and mean monthly outdoor temperatures for Western and Asian countries. The air-conditioned buildings are shown in black, the mixed-mode buildings in yellow and the naturally ventilated buildings in blue. The grey dots are buildings from other regions for comparison. *Source: Parkinson, Dear & Brager, 2020.*

The neutral temperatures in both naturally ventilated and air-conditioned buildings in Asia are found to be slightly higher than in the Western data. The higher outdoor and indoor temperatures in Asian cities is the reason for the shift in neutral temperatures in Figure 8.7.

The original databases (RP-884 and SCATs) did not contain sufficient data from mixed-mode buildings to perform reliable analyses. The new database contains 25 mixed-mode buildings spread across different climate zones. Figure 8.6 shows that the neutral temperatures in the mixed-mode buildings (yellow lines) lie between those of natural and air-conditioned buildings, but are most similar to naturally ventilated buildings. In particular, the slope is equally steep. This supports the practical experience that well-designed and controlled mixed-mode buildings are perceived as naturally ventilated buildings at moderate temperatures and perceived as cooled buildings only at high temperatures. The low relationship between neutral temperatures and mean outdoor temperatures in air-conditioned buildings is present in all regions and cultures (black lines in Figure 8.6 and Figure 8.7).

The principles of adaptive comfort are usually associated with free-running, naturally ventilated buildings. The question arises to what extent adaptation also occurs in air-conditioned buildings. To this end, the neutral temperature for all building types is plotted against the mean indoor air temperature in Figure 8.8. The result is a much stronger relationship between the neutral temperature and the mean indoor air temperature than when the mean outdoor temperature is taken as the independent variable. The slope of the regression line is the same for all types of buildings and regions. The only difference is that both higher and lower air and neutral temperatures occur in mixed-mode and naturally ventilated buildings than in air-conditioned buildings, or in other words, that the indoor temperature in air-conditioned buildings falls within a narrower range than in other building types.

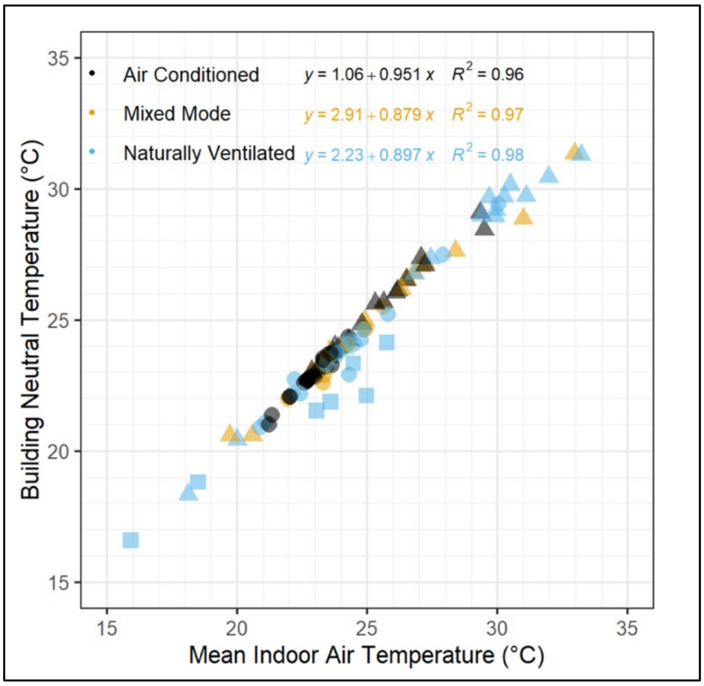


Figure 8.8: The neutral temperature for each building against the mean indoor air temperature for that building. The colours indicate the mode of climate control of the buildings. Sources: Parkinson, Dear & Brager, 2020.

Figure 8.8 shows that there is a strong relationship between what people experience as comfortable and the temperatures to which they are exposed indoors (see Section 2.4). This means that recent thermal exposure determines comfort temperatures, irrespective of the type of building and the method of conditioning. So, people in air-conditioned buildings also adapt, but to a temperature range that is significantly narrower, because it is controlled by the air-conditioning facilities. The reason why there is also a strong relationship between the comfort temperature and the outdoor temperature in naturally ventilated and mixed-mode buildings is because in those buildings there is a stronger relationship between the indoor and outdoor temperatures. Therefore, conventional adaptive models can predict comfort temperatures based on the outdoor temperature, but only sufficiently reliable when these are buildings where the indoor temperature varies with the outdoor temperature. This also means that air-conditioned buildings can be controlled over a wider temperature range than is currently the case, which can lead to greater comfort and lower energy consumption (Parkinson, de Dear & Brager, 2020). The main reason why this usually does not happen in practice, besides conservative design and air-conditioning practice, is the idea that a narrow temperature range would lead to higher productivity. That this is based on incorrect grounds is explained in Chapter 10.

8.5 INFLUENCE OF HUMIDITY AND OTHER PHYSICAL PARAMETERS ON THERMAL COMFORT

In order to investigate the influence of parameters other than air temperature on thermal comfort, the new database was analysed, taking the SET (Standard Effective Temperature) instead of air temperature (Parkinson, de Dear & Brager, 2020). The SET is an index in which air temperature, air humidity, mean radiant temperature, air velocity, clothing insulation and metabolism are included (see Section 2.4 for an explanation of the SET). Figure 8.9 shows the relationship between the neutral SET temperatures and the Mean monthly outdoor temperature for the 3 different climate control methods.

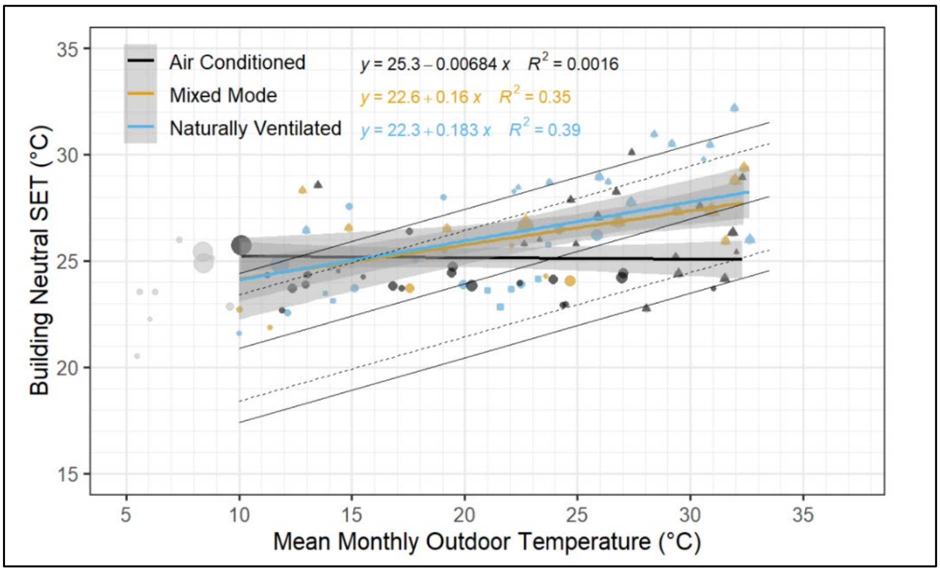


Figure 8.9: The same analysis as in Figure 8.6, but with the neutral SET temperature instead of the air temperature. Each point represents an individual building and the size of the point indicates the weighting factor, based on the sample size in that building. The grey areas indicate the 95% confidence interval. The grey dots are buildings that were outside the original comfort area and do not significantly affect the analysis.
Source: Parkinson, de Dear & Brager, 2020.

The above shows that the slope of the regression line becomes one-third smaller compared to the slope in Figure 8.6. This means that about one third of the adaptive comfort is accounted for by the heat balance parameters of the SET index, namely air velocity, humidity, clothing insulation and metabolism. This also means that two thirds of the adaptive comfort consists of factors that are not based on the physical heat balance. These are factors such as adaptive opportunities, experiences and expectations of the thermal environment (psychological adaptation) and on physiological adjustments of the body.

In the adaptive thermal comfort model, the influence of humidity is not explicitly visible. Some researchers and consultants indicated that humidity is an important parameter and that it is a shortcoming of the adaptive comfort model that the influence of humidity is not explicitly expressed (e.g., Bronsema, Bokel & van der Spoel, 2013). One reason may be that designers of air conditioning systems use the Mollier or psychrometric diagram, which was developed over a century ago for the design of air conditioning systems, and gradually became used for comfort assessments in other types of buildings buildings as well (Kumar et al., 2016). Also, there is our own anecdotical and subjective experience that when air temperatures are high and humidity is also high, it can feel “stuffy” and “hot” and we often sweat more. Figure 8.10 shows combinations of the dry bulb temperature and humidity ratios for each building in the new database in the psychrometric diagram (Földváry Ličina et al., 2018). Most of these points fall within the range up to 27°C (horizontal axis, left of the vertical dotted line) and up to 0.015 kg/kg (vertical axis, below the horizontal dotted line). The buildings that fall outside these boundaries are those in Thailand, India and Singapore that have neutral temperatures of 27°C to 34°C and relative humidity between 60% and 80%. Field studies in parts of India, for example, show that people begin to notice the impact of humidity only at temperatures of around 32°C and higher (Kumar et al., 2016). This is consistent with the strong relationship between mean air temperatures and neutral temperatures in buildings that is independent of (high) humidity levels (Parkinson, de Dear & Brager, 2020).

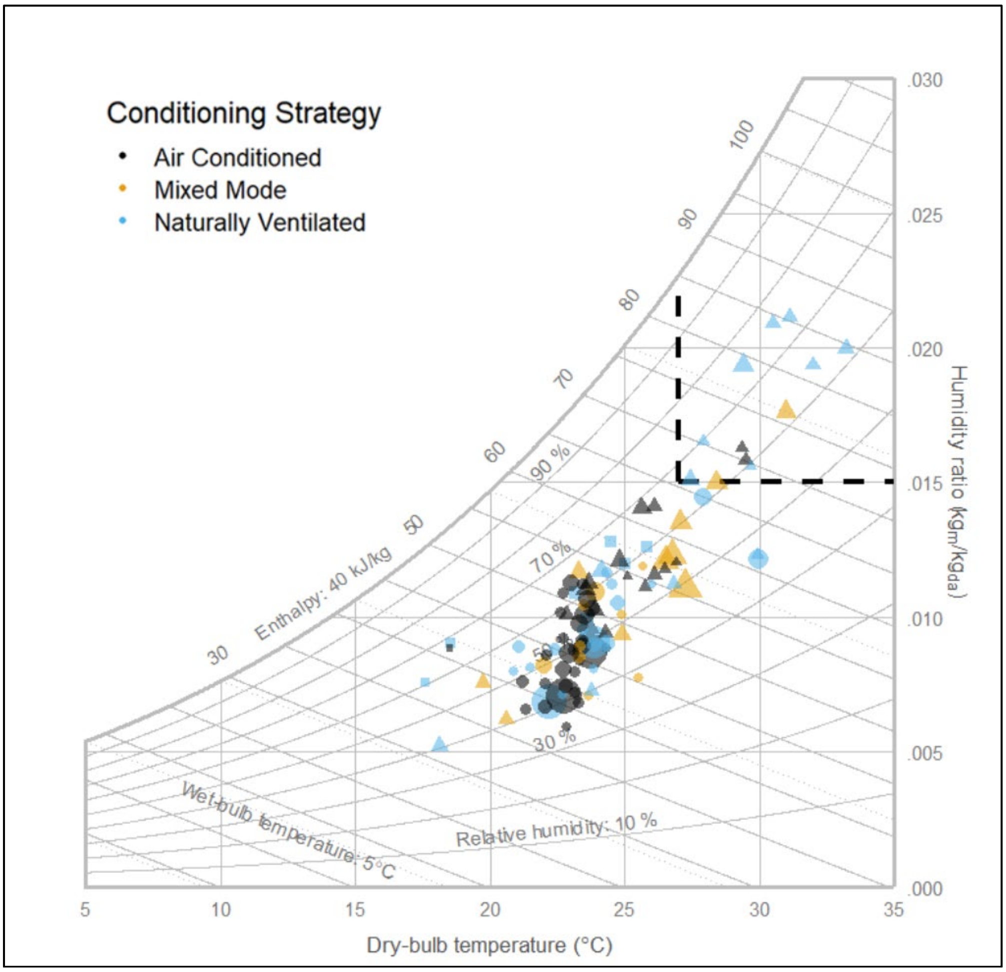


Figure 8.10: Psychrometric diagram showing the distribution of the combinations of mean indoor temperature and humidity for each building in the database. The majority of the (dry) air temperature and humidity ratios fall within the range of 20-27℃ and 0.005- 0.015 kg/kg, delimited by the black dotted line. The colour of the dots indicates the method of air conditioning and the size of the dots indicates the size of the data set per building. The shape indicates the region: circle=Western; triangle=Asian; square=other.
Source: Parkinson, de Dear & Brager, 2020.

To further investigate the influence of humidity in the adaptive comfort model, an advanced reanalysis of the ASHRAE RP-884 database was performed (Vellei et al., 2017). They also developed an alternative adaptive comfort model in which humidity was made explicit. To this end, humidity was classified into 3 categories: high: RH≥59%; medium: 37%<RV<59%; low: RV≤37%. The results show the following (Figure 8.11):

- The comfort temperatures are generally higher and the slopes between the outdoor temperature and the comfort temperature are steeper than in the adaptive ASHRAE model;
- Comfort temperatures are lower when humidity is high across the range of outdoor temperatures;
- The high humidity gives the narrowest range of acceptable temperatures, while the ASHRAE range corresponds to the range at average humidity.

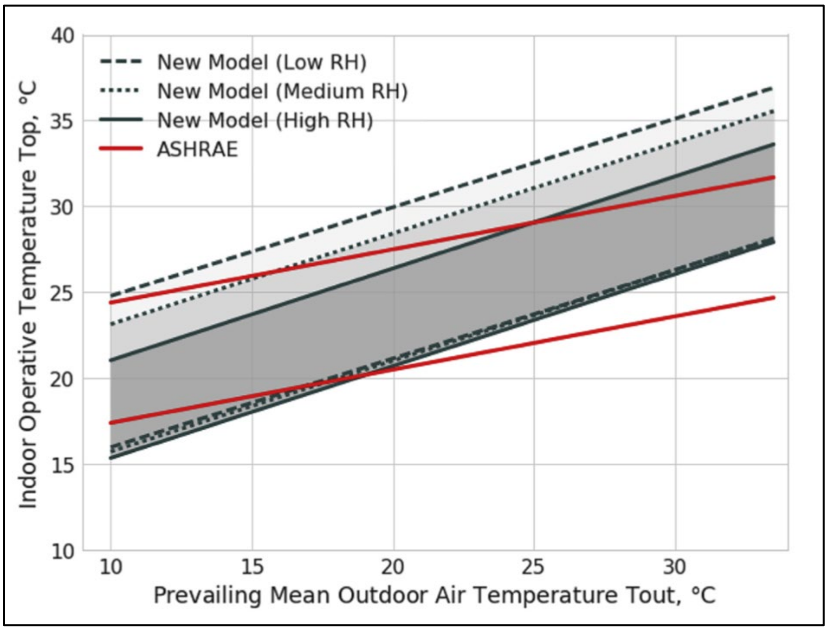


Figure 8.11: The adaptive bandwidth of the ASHRAE-55 standard (red lines) compared to the alternative adaptive model adjusted for different bandwidths of relative humidity.
Source: Vellei et al., 2017.

Then, with the new model, temperature exceedance simulations were carried out in naturally ventilated buildings, situated in different climates. The new model gives significantly fewer overheating events than the current ASHRAE model and the differences are greatest in climates with low humidity. The warmer the climate, the lower the predicted overheating. This means that the new model offers more possibilities for the design of naturally ventilated buildings in climates with medium or low humidity compared to the ASHRAE model. The main reason why humidity is not (yet) included in the adaptive comfort model is that occupants of buildings in humid climates are well adapted to high humidity. This involves various forms of adaptation: physiological adaptation, through which people readily release heat into the environment by sweating; behavioural adaptation, through the use of fans, windows to be opened and cross-ventilation and lighter clothing; and psychological adaptation, through the expectation that humidity will be high for large parts of the year. The relatively large proportion of buildings in hot/humid climates in the ASHRAE RP-884 database contributed to an overestimation of the influence of relative humidity in the ASHRAE adaptive model in temperate and dry climates.

8.6 PRACTICAL IMPLICATIONS OF DATABASE II

Through the analyses of the ASHRAE Global Thermal Comfort Database II, knowledge of adaptive thermal comfort has continued to increase. A key conclusion is that the principles of adaptive thermal comfort apply, to some degree, to all buildings, regardless of how they are climatized, because adaptive processes and expectations are shaped by exposure to indoor and outdoor temperatures (Parkinson, de Dear & Brager, 2020).

Conventional adaptive comfort models predict comfort temperatures reasonably well, but only in free-running buildings. Since most people spend most of their time indoors, indoor temperatures will most strongly drive our experiences and expectations of the indoor climate. The reason that the adaptive comfort models show a limited relationship between outdoor temperatures and neutral temperatures in air-conditioned buildings is because of the small bandwidth in indoor temperatures in this type of building (Figure 8.8); there are too few data points in the cool and warm temperature regions due to the air-conditioning system controlling the temperature within narrow limits and because there are few temperature control opportunities available (Parkinson, de Dear & Brager, 2020; Schweiker & Wagner, 2016). The strong dependence of the neutral temperature on the mean indoor temperature is due to recent thermal exposure, independent of the climate system. This seems to contradict previous findings (de Dear, Brager & Cooper, 1997), but it is explainable, because all types of indoor climate (naturally ventilated, air-conditioned, mixed-mode) offer adaptive possibilities to a greater or lesser extent. The more adaptive opportunities, the greater the adaptation effect. It is a continuum of various adaptive opportunities and not a binary classification of two extreme conditions (Van der Linden et al., 2006). The new, more extensive database provides more knowledge to adjust and improve the first generation of adaptive guidelines.

In the future, a better distinction will have to be made between the various functional characteristics of the built environment, e.g. offices, schools and homes, because the adaptive potential here in particular can be (very) different. The analysis of the ASHRAE Global Thermal Comfort Database II by Li et al. (2019) shows, among other things, that the upper and lower limits of the ISO-7730 and EN 16798-1 standards for office buildings can be extended by around 2°C (Figure 8.12).

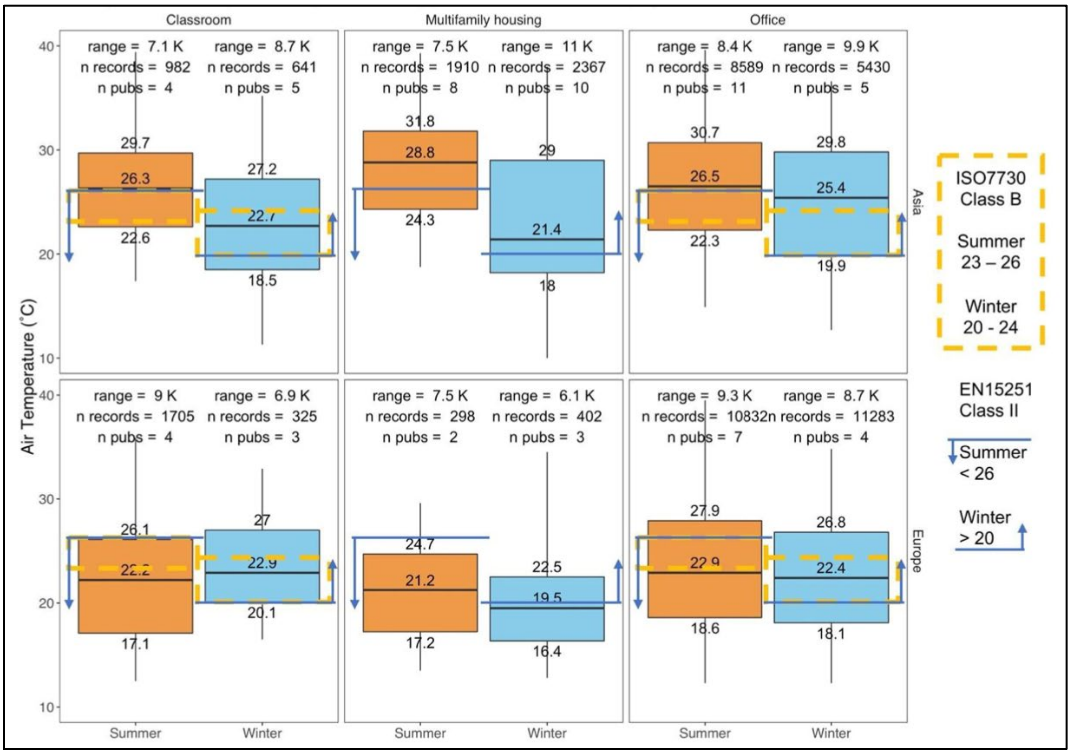


Figure 8.12: The boxes represent ranges of acceptable temperatures in database II for classrooms (left), homes (centre) and offices (right), for summer (red) and winter (blue). A differentiation is made for Asian (top) and European (bottom) data. The coloured bandwidths are compared with ISO7730 (yellow dotted line) and EN15251/EN16798 (blue arrows).
Source: Li et al., 2019.

The ASHRAE Global Thermal Comfort Database II provides new insights for different building types:

NATURALLY CONDITIONED BUILDINGS

The results of the new database show similar results compared to the original analysis. In the relationship between the outdoor temperature and the comfort temperature, the gradient of the regression line is similar to that in the existing standards. The comfort temperature thus increases by about one third of a degree for each degree of outdoor temperature. However, the Y-intercept in the new database is 1 degree higher in the Western countries and 2 degrees higher in Asia. This means that future standards will have to take into account the slightly changed values as a result of the expanded database. This will most likely be done in some regional classifications based on climate-specific and cultural data and not on country level (Parkinson, de Dear & Brager, 2020).

MIXED-MODE BUILDINGS

Because the indoor climate in mixed-mode buildings can be controlled by both passive properties and natural ventilation as well as by mechanical cooling, it was unclear until now whether the adaptive guideline or the PMV model-based guidelines apply. The first ASHRAE database did not contain sufficient data to make statements about this. Therefore, in the ASHRAE-55 and EN15251/EN16798 the adaptive guidelines only apply to buildings without cooling. However, the ASHRAE database II contains considerably more data from mixed-mode buildings and shows that the comfort responses of the occupants of mixed-mode buildings are closer to those of naturally ventilated buildings than of air-conditioned buildings (Figure 8.6). When the SET index is used (Figure 8.9) instead of the air temperature, the mixed-mode buildings are even more similar to naturally ventilated buildings and it appears that the occupants of mixed-mode buildings have similar experiences and expectations as in naturally ventilated buildings. Cooling is then only used in very hot conditions (Deuble & de Dear, 2012; Rupp et al. 2018a; Parkinson, de Dear & Brager, 2020).

If mixed-mode buildings were assessed in the standards as "naturally ventilated" rather than "air-conditioned" it would have a substantially beneficial effect on both comfort and energy use. The indoor climate in mixed-mode buildings is characterised by three different control schemes:

- The period that only natural conditioning/ventilation takes place;
- The period that is exclusively mechanically cooled;
- The transition period between the two.

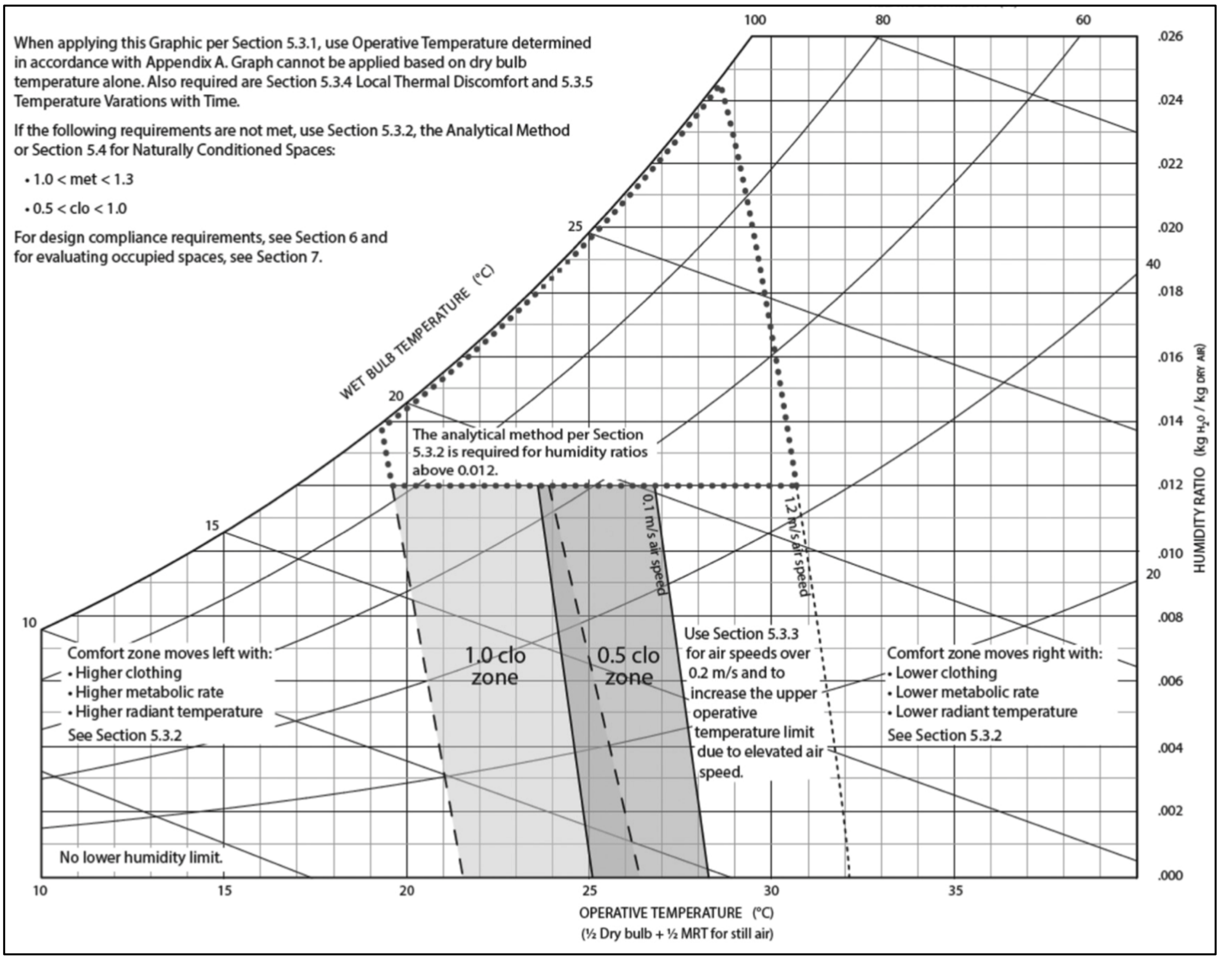
This means that basically two approaches can be used to assess the indoor climate in mixed-mode buildings (Parkinson, 2020):

1. The adaptive model applies during the period when natural ventilation is in operation. When mechanical conditioning comes into effect and windows are (or must be) kept closed and cooling is provided to the top of the conventional PMV-based comfort zone for conditioned environments (27°C, 50% RH, 0.5clo), the PMV model will apply;
2. The adaptive model applies both in the period when natural ventilation is in use and when mechanical cooling is in operation. Mechanical cooling then ensures that the upper limit of the adaptive model is not exceeded. The recent analyses of ASHRAE database II, as discussed in this chapter, show that this approach provides a more pleasant and healthier indoor climate and consumes less energy and is therefore recommended (Parkinson, de Dear & Brager, 2020).

AIRCONDITIONED BUILDINGS

Although it is becoming increasingly clear that mixed-mode buildings should also be assessed using the adaptive model, air-conditioned buildings still appear to be designed and assessed using the PMV model. However, designers of fully air-conditioned buildings are better off using the principles of adaptive thermal comfort (Parkinson, de Dear & Brager, 2020). People adapt to the temperatures to which they are exposed and it is better for comfort and energy use to consider seasonal influences in control strategies and setpoint temperatures rather than designing a sort of climate chamber in a building. And as Chapter 10 shows, the arguments for promoting workers' performance by controlling temperatures within a narrow temperature range are refuted. For air-conditioned buildings, the most appropriate neutral temperature could be derived from the graphical comfort zone for summertime (clothing insulation 0.5clo) on the psychrometric diagram of ASHRAE-55 (Figure 8.13). This corresponds to setpoints of 24°C-27°C at a relative humidity of 50% and an air velocity of up to 0.2m/s (Parkinson, de Dear & Brager, 2020).

However, occupants who have long been accustomed to a fixed temperature of around 22°C will have to get used to the fact that during summer time the indoor temperature is higher, sometimes by as much as 5°C. This can be achieved by gradually increasing the temperature over a period of several weeks in summertime, so that occupants can gradually adapt to the higher temperatures both behaviourally and psychologically.


When applying this Graphic per Section 5.3.1, use Operative Temperature determined in accordance with Appendix A. Graph cannot be applied based on dry bulb temperature alone. Also required are Section 5.3.4 Local Thermal Discomfort and 5.3.5 Temperature Varations with Time.

If the following requirements are not met, use Section 5.3.2, the Analytical Method or Section 5.4 for Naturally Conditioned Spaces:

- 1.0 < met < 1.3
- 0.5 < clo < 1.0

For design compliance requirements, see Section 6 and for evaluating occupied spaces, see Section 7.

The analytical method per Section 5.3.2 is required for humidity ratios above 0.012.

Comfort zone moves left with:
- Higher clothing
- Higher metabolic rate
- Higher radiant temperature

See Section 5.3.2

Use Section 5.3.3 for air speeds over 0.2 m/s and to increase the upper operative temperature limit due to elevated air speed.

Comfort zone moves right with:
- Lower clothing
- Lower metabolic rate
- Lower radiant temperature

See Section 5.3.2

No lower humidity limit.

Figure 8.13: Graphical method for determining the thermal comfort zone for air-conditioned environments. Acceptable operative temperatures (to) and humidity for a metabolism of 1.0 to 1.3 with, clothing insulation of 0.5 to 1.0 clo and air velocities up to 0.2m/s.
Source: ASHRAE-55, 2017.

9 THERMAL COMFORT IN DWELLINGS, SCHOOLS AND HOUSING FOR THE ELDERLY

9.1 INTRODUCTION

Most of the research on thermal comfort has been conducted in offices, but in recent years there has been an increased focus on research in homes, schools or residential and care centers for the elderly. Because the adaptive opportunities in such environments are different from those in offices and age and health can vary greatly, acceptable, comfortable and healthy temperature ranges can therefore also be different.

9.2 THERMAL COMFORT IN DWELLINGS

More than in other types of buildings, occupants of dwellings have the most flexible adaptive opportunities available to feel comfortable in a wide range of conditions[18]. Figure 9.1 shows the results of a comparative analysis of thermal comfort in about 100 dwellings and about 700 different types of free-running buildings. The mean neutral temperature of the dwellings (the dashed line) and all but one of the neutral temperature per dwelling (the squares) fall within the 95% zone of the entire database. This means that thermal comfort in (free running) homes is related to the outdoor temperature in the same way as in other free running buildings (Nicol, 2016).

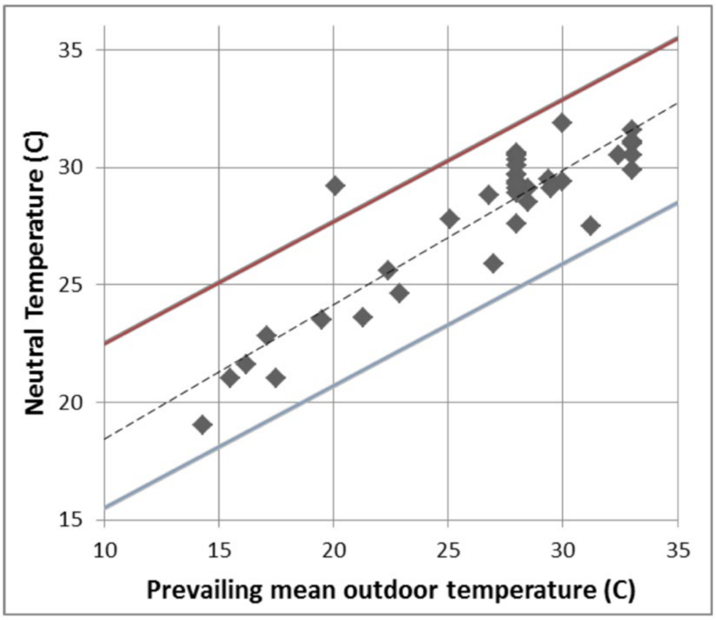


Figure 9.1: Neutral temperatures in free-running dwellings (the squares) and the corresponding regression line (dotted line). The neutral temperatures fall largely within the 95% confidence interval of the entire thermal comfort database. This is the interval between the red and blue line. *Source: Nicol, 2016.*

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[18] Of course, the quality of the home is crucial here. Poor insulation, limited access to windows, poor outdoor air quality, little personal space and a poor heating system are examples of aspects that make it difficult to adapt, which can result in comfort and health issues.

The differences in neutral temperatures between homes are greater than for other building types because people in homes form a more heterogeneous group than people in office buildings and their behaviour at home is different from that in the office. At home, the adaptive opportunities are greater because of the greater freedom to adjust and vary clothing, to change the temperature setting, to use sun blinds, to open or close windows and doors, to go to another room with a different temperature or to sit on a balcony, terrace or in the garden.

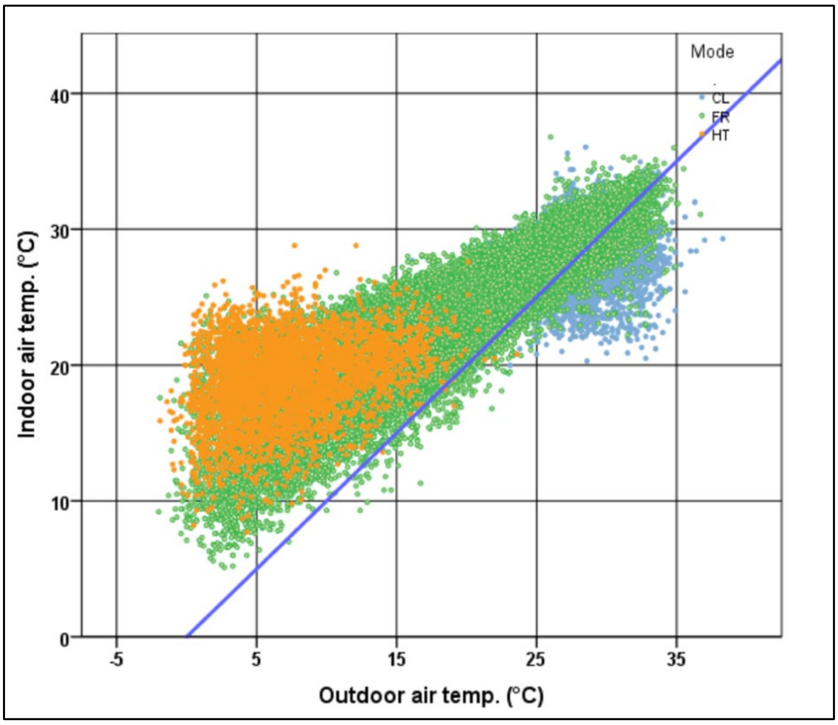

Figure 9.2: Temperature clouds for Japanese homes. HT, orange=heated; CL, blue=cooled; FR, green=free running, not heated and not cooled. The blue line indicates where the indoor temperature equals the outdoor temperature. *Source: Rijal, Humphreys & Nicol, 2015.*

Figure 9.2 shows the observed temperatures in homes where heating (HT, orange), cooling (CL, blue) and no heating and no cooling, i.e. free running (FR, green), are taking place. Below an outdoor temperature of around 17°C, heating takes place and the internal temperatures then vary between around 10°C and 25°C, a bandwidth of 15°C. Here, a more or less horizontal boundary can be observed at an indoor temperature of about 25°C. In dwellings with air-conditioning, cooling takes place at outdoor temperatures above about 17°C, leading to indoor temperatures of between 20°C and 30°C. Here, also horizontal boundary exists at an indoor temperature of about 20°C. In dwellings where no cooling and/or heating is provided, the indoor temperature range is more diverse, from around 5°C to 35°C, at outdoor temperatures between 0°C to 35°C because here the temperature is controlled exclusively by passive means and is therefore more related to the outdoor temperature (Rijal, Humphreys & Nicol, 2015).

Analysis of surveys in homes in England, Saudi Arabia and Japan show 3 temperature “areas” of homes that are heated (Japan and England), cooled (Japan and Saudi Arabia) and free running (England and Japan) (Figure 9.3). The heated and cooled areas have a larger indoor temperature bandwidth (15K) than that of the free-running areas (8-10K). This contradicts the expected shape in standards and guidelines which assume that conditioned buildings have a narrower bandwidth.

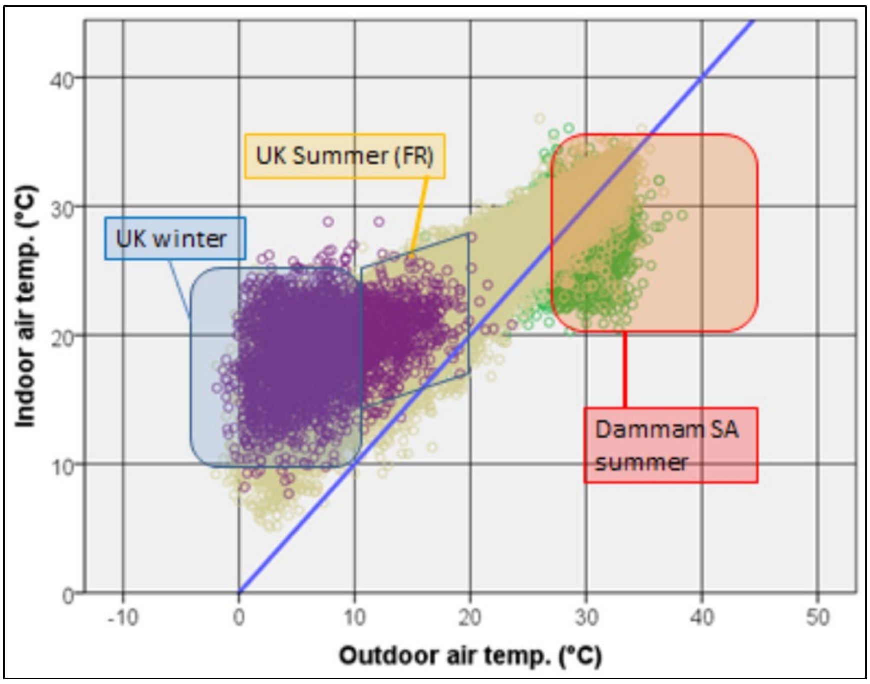

Figure 9.3: Merged results of English and Japanese heated homes (purple), English and Japanese free-running homes (yellow) and residential cooled homes from Japan and Saudi Arabia. The blue line indicates where the indoor temperature equals the outdoor temperature. Source: Nicol, 2016.

The reason for these temperature differences in homes with the temperature ranges in the current standards is that residents themselves have full control over their indoor climate and installations and also have to pay the necessary energy costs for this themselves. As a result, residents are also more motivated to adapt their clothing to the weather conditions and temporarily accept a lower level of comfort (and thus save energy) (Nicol, 2016).

A study in over 2300 homes in England examined the behaviour of residents during hot weather (Raw, 2018). When asked what residents do in summertime conditions (not a heat wave) to keep from getting too hot, 29% answered that they use blinds, 79% open the window during the day and 53% at night, while 40% open the exterior doors and 35% open the interior doors. In addition to these adaptive measures on the dwelling, the occupants made various personal adjustments: 53% adjusted their clothing, 48% slept under thinner bedding, 29% used a ventilator, 39% used cold drinks, 18% took a bath or shower and 6% went somewhere else to sit indoors and 29% went outdoors (Table 9.1).

Table 9.1: Strategies people take to avoid getting too hot in 2,300 homes in the UK.
Source: Raw, 2018.

Would not get too warm					9
Do something to avoid getting too warm	Environment-focused	Control heat gain	Turn heating down or off		60
			Shading	Internal	25
				External	4
		Remove heat	Natural ventilation	Windows (day)	79
				Windows (night)	53
				External doors	40
			Mechanical ventilation	Extract only	4
				Supply & extract	1
				Supply & extract + heat recovery	
			Air circulation within building	Internal doors	35
				Doors to shared parts	13
			Air conditioning	Hired	<1
				Present in the home	2
				Heat pump	<1
	Self-focused	Insulation	Clothing		53
			Bedding		48
		Cooling	Fan		29
			Drink		39
			Bath/shower		18
			Rest		8
		Change location	Indoors		6
			Outdoors		29
			Away from home		5

What is striking is the great diversity of measures that people take to avoid getting too hot. In the event of a heat wave, more residents took various additional adaptive measures to avoid getting too hot (Figure 9.4).

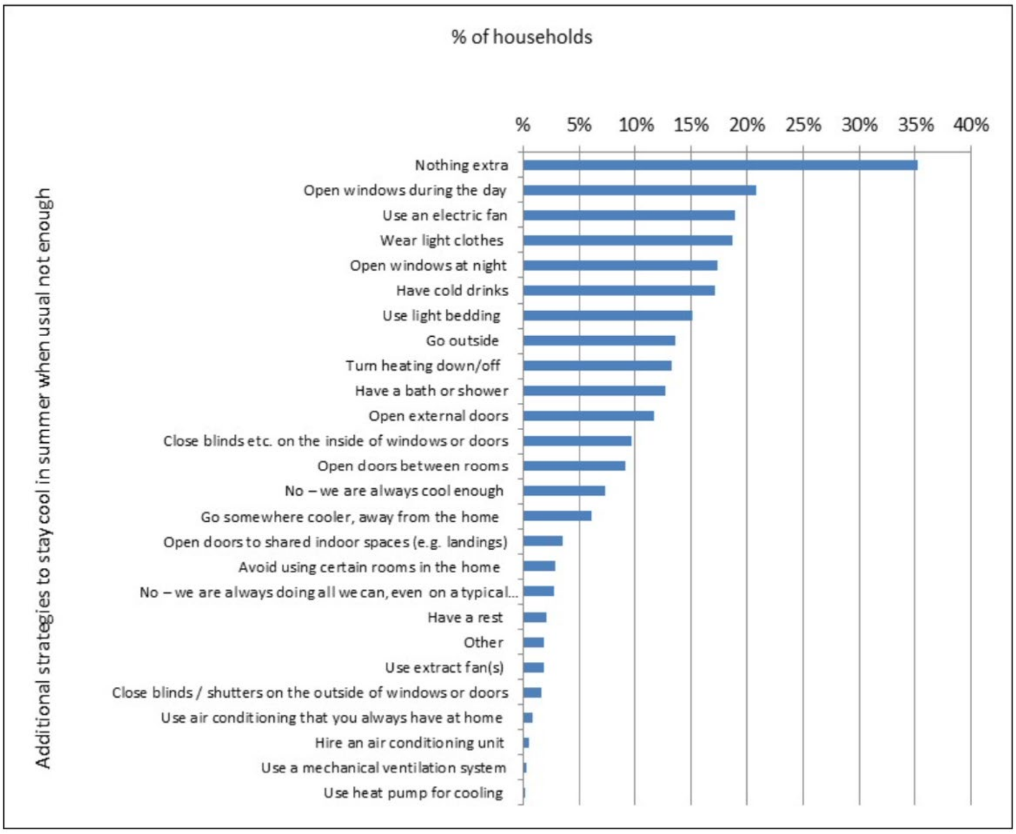

Figure 9.4: Percentage of households taking additional measures in the event of a heat wave.
Source: Raw, 2018.

The temperature in bedrooms deserves special attention. People sleep on average about one-third of the time and the quality of sleep affects the recovery from physical and mental fatigue that has occurred during the day (Li & Lan, 2016). Insufficient quality of sleep is associated with reduced cognitive performance in the elderly and learning performance in children. Poor sleep also increases the risk of obesity, type 2 diabetes and cardiovascular disease (Nigai et al., 2010; Kingma et al., 2012) and adversely affects the immune system (Opp, 2009). In addition to too much light, too much noise and poor air quality, temperature also affects the quality of sleep. The temperature directly around the human body should be lower than approximately 30°C to enable comfortable sleep. The combination of bed clothing, sheets and duvet determines this temperature together with room temperature and air velocity and are the available adaptive options to enable a comfortable sleep (Nicol, 2019). Adequate thermal insulation therefore makes it possible to sleep comfortably at very low temperatures, but in a very warm environment there is a limit to the exclusion of thermal insulation.

9.3 THERMAL COMFORT IN SCHOOLS

The quality of the indoor environment (thermal comfort, air quality, acoustics, light) in classrooms influences learning performance (Bluyssen, 2009, 2013). This means, among other things, that, partly in view of the future higher temperatures in summer, the more frequent and more intense heat waves (Montazami & Nicol, 2013) and the current poor quality of the indoor air quality and climate in existing schools (Bluyssen, et al., 2018), guidelines on ventilation and (adaptive) comfort are needed specifically for school buildings (Teli et al., 2017). Children have a lower metabolism than adults for the same activities (Havenith, 2007). This seems to be due to a smaller body volume/surface area ratio of younger children, which makes their heat loss relatively higher. Also, children produce less sweat than adults but have a higher skin temperature, so children can lose less heat through sweat evaporation and rely more on heat loss through convection and radiation (Almeida et al., 2016; te Kulve et al., 2020). However, under everyday conditions, children are more active (playing outside during school breaks and after school) than adults for a significant part of the day. In children, an mean metabolism of 1.5 Met has been observed (de Dear et al., 2015), while adults have a metabolism of 1.2 Met on average when doing office work. In terms of thermal insulation, clothing worn by younger children is more flexible than that worn by adults, which means that clothing insulation is better suited to the prevailing temperatures (de Dear, 2015). However, on the other hand, especially younger children are partly dependent on their caregivers when it comes to clothing choice (Folkerts, 2019) and therefore children may be limited in their adaptive capabilities (Teli, 2012).

Research on children's thermal comfort and thermal preference has examined the association of subjective temperature perceptions with physical measurements of the environment. The question is to what extent children are able to express their thermal feelings in the same subtle way as adults[19]. There is evidence that young children tend to vote more on the extreme categories of a 7-point scale (e.g. Table 2.1), while students who have some knowledge of the indoor environment give a more nuanced rating (Hellwig, 2017). Other research concluded that children aged 7 to 11 were able to understand child adapted scales (pictures instead of text) for thermal sensation and preference because few

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[19] For example, the differences between “neutral”, “slightly warm”, “warm”, and “hot”.

conflicting and missing values for the subjective ratings of the thermal environment were found (Teli et al., 2013).

Looking at individual studies of thermal comfort in children, for example, a study in a naturally ventilated kindergarten found that children preferred lower temperatures than the PMV model indicates (Yun et al., 2014). A study in Australian primary and secondary schools found that the neutral and preferred temperature was around 22.5°C on average, lower than the PMV and adaptive model predict (de Dear et al., 2015). The bandwidth of acceptable temperatures around the mean is greater, indicating a broad adaptive capacity in children (Teli et al., 2013; Humphreys et al., 2007). In a study in naturally ventilated classrooms with children between 7 and 11 years old, the subjective ratings were compared with the adaptive comfort model. In summer, children preferred lower temperatures compared to the adaptive EN15251 standard (Teli et al., 2012). In another study in English schools where measurements were assessed using the adaptive model of EN-15251, the schools were found to meet the standard, but when the results were assessed using an adaptive model adapted for children, there were significantly more exceedances of the acceptable temperature range. This adaptive thermal comfort model for children was developed because of the physiological differences between children and adults (Teli et al., 2017). Although children on average find it warmer than adults, it appears that children are less sensitive to temperature variations when exposed to changing temperatures in naturally ventilated, not air-conditioned, classrooms than children in air-conditioned classrooms (de Dear et al., 2015). This corresponds to the effect found in adults in naturally ventilated and air-conditioned environments (see Section 4.3).

A study in 32 naturally ventilated classrooms in England found that compared to adults, children's comfort temperature was 1.9°C lower during summer and 2.8°C lower during the heating season (Korsavi & Montazami, 2020). During the heating season, children exhibit less personal adaptive behavior than outside the heating season. Teachers are primarily responsible for regulating classroom temperature based on their perception of the thermal environment and not on the perception of the children. The researchers recommend that new schools or renovations consider opportunities for adaptive behavior as part of the design process, targeting both teachers and children. Teachers should be aware that children have lower comfort temperatures than adults and should motivate children to communicate about this and use adaptive options.

Analyses of the ASHRAE Global Thermal Comfort Database II (Figure 8.12, bottom left) show that for children in schools in winter, the lower limit of both the PMV model (ISO-7730, Category B) and the adaptive model (EN15251, Category II) correspond reasonably well to the measured actual acceptability, but that temperatures of about 3°C above the PMV upper limit for winter still appeared acceptable. In summer, the acceptable temperature range for children matches both the PMV model (ISO-7730) and the adaptive model (EN1525), but the mean comfort temperature is well below the mean of the prescribed ranges (Li et al., 2019).

9.4 THE ELDERLY AND THERMAL COMFORT

During heat waves, more people are admitted to hospital and more people die than in an average year. Inevitable physiological and mental changes occur as people age. Metabolism slows down and the skin, where the thermoreceptors are located, becomes less sensitive, which can alter thermal perception (Blatteis, 2012). Physical ageing in general leads to less efficient defence mechanisms against (extreme) temperatures, which can lead to an impaired thermal balance of the body and to health problems. This is reinforced when people also become mentally less resilient. In addition, there are differences in the quality of homes and, in combination with large income differences, it can be difficult and expensive for some of the elderly to feel (thermally) comfortable in their homes (Day, 2015; Van Hoof et al, 2010). In addition, the energy transition will result in many residential buildings being equipped with innovative climate systems. For example, a system with a heat pump and low temperature heating can provide a more stable and uniform indoor climate, but it is not known whether this will lead to a different comfort experience for (older) residents (Rudge, 2012). With such systems, it may take longer for the temperature to reach a set point and it is often not possible to overcompensate quickly and briefly when, for example, someone is too cold (and Allieshesia is not possible, see Section 4.6). Sitting together by the heater on a cold winter's day or hanging something to dry on the radiator is no longer possible. This is somewhat similar to the 1960s and 1970s when coal and gas fireplaces had to make way for central heating (Fernandez-Galiano, 2000). Heavily insulated façades, without opening windows, can create a risk that elderly, less mobile residents are deprived of contact with outdoor conditions and, for example, can no longer feel and hear a breeze from outside, smell the plants and flowers in the garden or hear the sound of birds singing or children playing. Being deprived of such sensory stimuli can have a negative effect on the health and wellbeing of elderly people who, for various reasons, are no longer able to walk and cannot spend time outside.

Simulations with an elderly adjusted thermoregulation model show that perceived thermal conditions influence the body's thermal state. Elderly people who, from a neutral situation, are subjected to prolonged exposure to cold conditions cool down so much that this cannot be corrected with warm clothing, and when they move to warmer conditions it takes much longer for the body to return to its original thermal state (Henshaw & Guy, 2015). Furthermore, a study in 57 homes with 71 residents over 65 years of age showed, for example, that women had a lower neutral temperature (23.6°C) than men (25.1°C) and that older people over 85 years of age more often found it warmer or colder than neutral than the younger group (65-69 years). The group that had more fragile health reported being too cold more often (Martins et al., 2020). A study in 6 care homes in south-eastern Australia with a total of 322 residents found that, on average, residents preferred a 0.9°C lower temperature and wore more clothing compared to the average adult population (Tartarini et.al., 2018). However, most residents were able to optimise their thermal comfort through adaptive measures, such as varying clothing and using fans and opening and closing windows. Furthermore, it appeared that the residents preferred lower temperatures than the upper limit of the adaptive thermal comfort model and the researchers argue that a linearly increasing upper limit without an absolute limit may not be applicable to the group of elderly people in care homes.

There is therefore increasing evidence that special attention should be paid to the thermal needs and preferences of different groups of older people in the design and operation of housing for the elderly (Shibasaki et al., 2013).

10 PRODUCTIVITY, TEMPERATURE AND THERMAL COMFORT

10.1 INTRODUCTION

Since the thermal environment affects physiological, psychological and behavioural processes (Chapter 4), it can be assumed that it therefore also affects workers' performance or productivity. In recent years, much research has been published on the empirical relationship between temperature, thermal sensation and work performance. However, the results are not always clear. This is mainly because performance is difficult to quantify due to the different types of work and test methods. Performance can be studied with (simulated) office work, psychological tests, or self-reported performance. In addition, the environment can be quantified by air temperature, by an index such as the PMV or by subjective thermal comfort. Most of these publications are based on research in air-conditioned buildings or climate chambers with active cooling. Moreover, it appears that the relationships between temperature and performance in air-conditioned environments are not representative of passive climate-controlled buildings and that the arguments for cooling workplaces for higher performance do not apply to passive buildings where people can adapt to conditions.

10.2 PERFORMANCE AND TEMPERATURE

In an often-cited meta-analysis of research on the influence of indoor temperature on objectively measured performance, office work performance is highest when the indoor temperature is around 22°C (Wargocki et al, 2006, 2007). At higher or lower temperatures, performance decreases (Figure 10.1). According to this analysis, the relationship is only statistically significant below 20°C and above 24°C. Thus, there is a plateau between 20°C and 24°C where performance is at its maximum. This interpretation is supported by Zhang, de Dear & Hancock (2019) who argue on both empirical and theoretical grounds that in a relationship between an environmental variable and performance, an inverted U-shaped curve with a plateau is more likely than an inverted U curve without a plateau.

These results are widely accepted and it is often concluded that when the temperature in buildings rises above 22°C or 24°C, the productivity of staff will decrease, even if they feel comfortable at that temperature. The question is whether this relationship is also valid for passively conditioned/non-cooled buildings. To this end, the descriptions of the studies on which the meta-analysis is based (Seppänen et al., 2003; Wargocki et al., 2006) and the original studies themselves were examined in more detail. This shows that 15 of the 24 studies are based on experiments in climate chambers, 5 were conducted in air-conditioned buildings with a closed façade and 2 in air-conditioned buildings with limited usable windows.

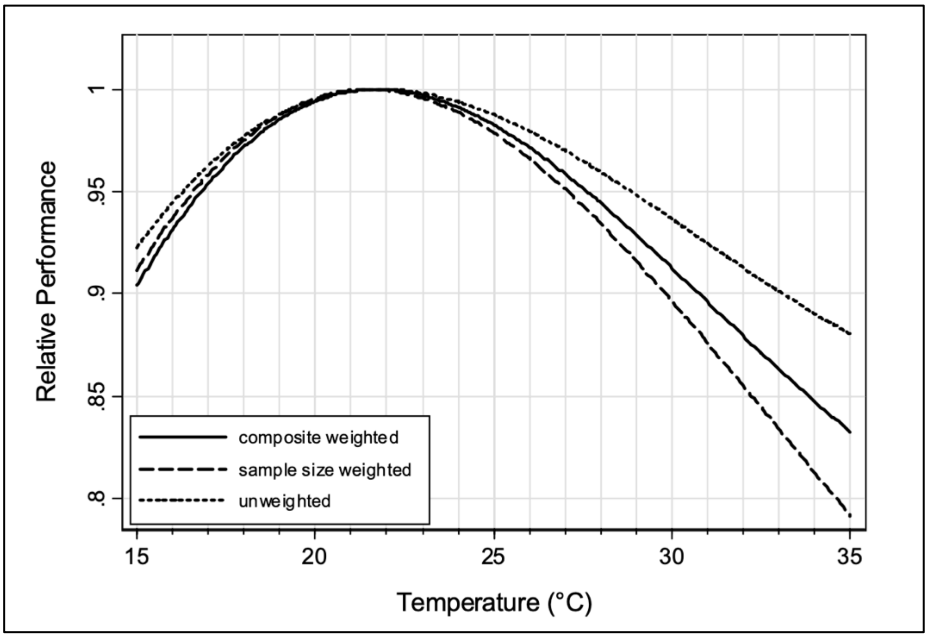

Figure 10.1: Relative performance versus indoor temperature. The maximum performance is set to 1. "Unweighted" means that the data of the different studies are not weighted, "sample size weighted" means that the data of the different studies are weighted with the number of subjects per study, "composite weighted" means that the data of the different studies are weighted with the number of subjects per study and the relevance of the performance scores for office work. This publication assumes that the composite weighted curve is the best indicator of performance in office work. Source: Wargocki et al., 2006.

One study was conducted in a mechanically ventilated office building without active cooling but without openable windows, and one study was performed in an industrial building without cooling. Thus, of the 24 underlying studies, 22 were conducted in conditioned environments. It is also stated that the relationship found relates to office work in general. The results are based not only on typical office work (in the experiments mostly work in call centres), various mental work and learning tasks, but also on driving skills, simulated factory work and working in a sewing workshop. In the meta-analysis, the results of these different types of work have been combined into a single equation, even though it is conceivable that they are related to temperature to different proportions. The question therefore remains whether the distribution found relates to the pure relationship between office work and temperature, or to the various underlying relationships. This is only partly solved by giving the tasks that are less similar to office work a lower, arbitrary weighting factor in the composite weighted analysis.

Another problem is that five of the six field studies on objectively measured work performance are based on data from call centres. The advantage of this approach is that the individual performance of call centre employees can easily be derived from the call records and that other data, such as the time of day, can also be included. In general, this approach appears to work well: in four of the five call centre studies, call duration, processing time or a combination of the two increases when temperatures are less comfortable. This is cross-validated by Wargocki et al. (2004), who showed that with lower air quality, mean call duration increased. Whether the quantitative effect of temperature on call centre work is also representative of other types of office work remains to be seen, although there is no reason to expect major differences.

All in all, it can be concluded that in actively air-conditioned environments productivity is highest at temperatures between 20°C and 24°C. This area corresponds well to the comfort zone in air-conditioned buildings according to the PMV model, assuming a metabolism of 70W/m^2 and a clo-value of 1.0 clo, which is sufficiently representative based on the descriptions of the underlying studies. Productivity decreases as the temperature falls below 20°C or rises above 24°C. This is a less definite relationship than shown in Figure 10.1, and does justice to the conclusion of Wargocki et al. (2006, 2007), that the relationship has a high degree of uncertainty.

The question then arises as to whether the correlation found is also valid to some extent for free-running buildings. In that case, for example, productivity would be 6% lower at 28°C than in an actively air-conditioned office at 22°C. As mentioned, none of the 24 underlying studies took place in naturally ventilated office buildings. Occupants of free-running buildings have a different thermal experience, preferring a higher indoor temperature in summer and showing much more adaptive behaviour than in air-conditioned buildings, in particular adjusting their clothing insulation and the air velocity by opening the windows.

Next, the extent to which adaptation plays a role in the studies underlying Wargocki, et al. (2006, 2007) is examined. First, 21 of the 24 underlying studies relate to buildings without openable windows, 2 to buildings with limited useable openable windows and one to buildings with openable windows. So, there were hardly any subjects who could adjust air speed and air temperature by opening windows.

Secondly, in 14 of the 15 laboratory studies, the clothing insulation was either prescribed by the researcher or the subjects were asked not to change their clothing during the study. One experimental study did ask subjects to adjust their clothing in order to maintain a thermally neutral experience and found no significant effect of temperature on performance. One might expect that in the field studies, where subjects were free to adjust their clothing, they would do so to the same extent as in free running buildings. However, Chapter 3.2 showed that occupants of air-conditioned buildings adjusted their clothing insulation to a much lesser extent than occupants of naturally ventilated buildings.

Finally, in all 15 climatic chamber studies, there was no relationship between the indoor and outdoor temperature. In at most 3 of the 9 field studies, this relationship could be expected to some extent based on the description of these buildings.

In summary, in almost all of the studies underlying the meta-analysis (Wargocki, et al., 2006, 2007), the major forms of adaptation that enable users of naturally ventilated buildings to accept and prefer higher indoor temperatures in summer than users of air-conditioned buildings were severely limited or did not function. If air-conditioned and naturally ventilated buildings differ so much in terms of thermal comfort and occupant behaviour, it cannot be excluded that there is also a (significant) difference in the influence of temperature on performance. Therefore, the meta-analysis cannot be considered representative of free-running environments.

A recent meta-analysis is based on 35 studies on the effect of indoor temperature on performance in office work (Porras-Salazar et al., 2021). The methodology in this study is similar to that of the meta-analysis in Wargocki et al. (2006, 2007), but is based only on studies of cognitive skills essential for office work or actual office work in office-like environments. Also excluded were studies with only self-reported performance or physiological measurements. Some of the 24 studies on which Wargocki et al. (2006, 2007) is based were therefore dropped, but on the other hand studies not included in Wargocki et al. (2006, 2007) were included. In total, the meta-analysis is based on 35 studies, some of which were also used in Wargocki et al. (2006, 2007). Of these, 33 were conducted in controlled environments, i.e. not in real-life situations. This means that the result, like the correlation in Wargocki et al. (2006, 2007), is not representative for free running environments.

The results are given in *Figure 10.2*. No relationship is found between indoor temperature and performance. The explained variance (R^2) is very low: 2%, and the relationship is not statistically significant. This applies to both the 20°C to 30°C temperature bandwidth representative of offices and the broader range between 18°C and 34°C.

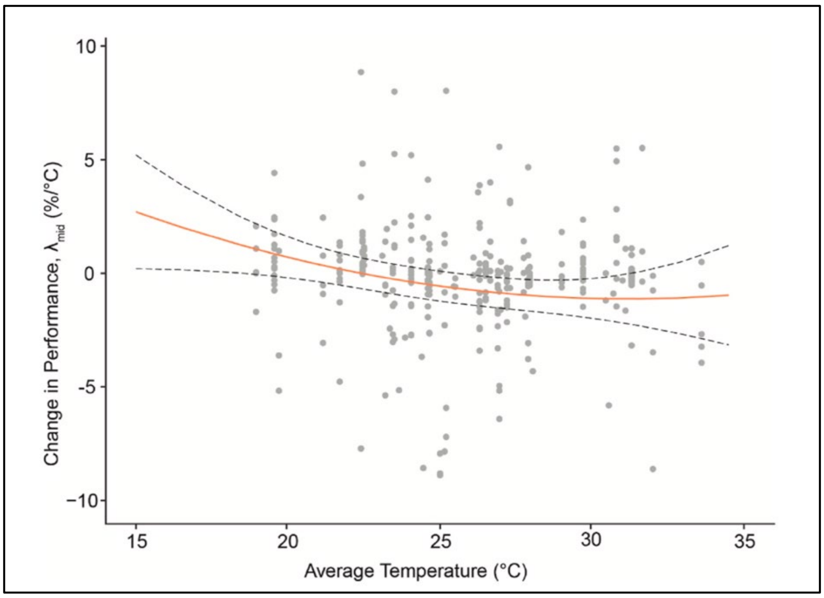

Figure 10.2: The relationship of change in performance with mean temperature. The red line shows the correlation, the dashed lines the 95% confidence interval. The grey dots are the original data points. λ_{mid} is the change in work performance in % per 1℃ increment in temperature, whereby positive λ_{mid} indicates an increase in performance with increasing temperature; while negative λ_{mid} indicates a decrease in performance with increasing temperature. Source: Porras-Salazar et al., 2021.

The article identifies several limitations of this meta-analysis. The main ones are the differences in methods of determining performance, multiple confounders that were not corrected for, and the fact that temperature alone may not fully describe how the thermal environment affects performance. The paper argues that these limitations may be the cause of the failure to find a link between performance and temperature and that, if these limitations were removed, a link might be found. Therefore, the article concludes that the lack of a link does not necessarily disprove that temperature has an effect on office performance. In fact, the idea that temperatures between about 18°C and 34°C have an effect on office performance has been disproved by the results as long as there are no new research results to the contrary. Of course, the limitations mentioned should be avoided in future research, but it is not possible to know in advance what the results will be.

10.3 PERFORMANCE, THERMAL SENSATION AND THERMAL SATISFACTIONS

In addition to the relationship of performance with objectively measured temperature, other researchers have also investigated the relationship with subjective thermal sensation vote (TSV). Figure 10.3 shows a relationship between the TSV and the objectively measured performance (Jensen, 2008). The equation found is:

$$\text{Relative performance} = -\,0.0029\,\text{TSV}^2 - 0.0034\,\text{TSV} + 0.999 \qquad (1)$$

This relationship is based on four experimental studies in climate chambers and in air-conditioned office rooms where the temperature was set by the researchers. The subjects performed simulated office work (calculation and/or word processing) at different temperatures. They were asked to indicate their thermal perception on the 7-point ASHRAE scale.

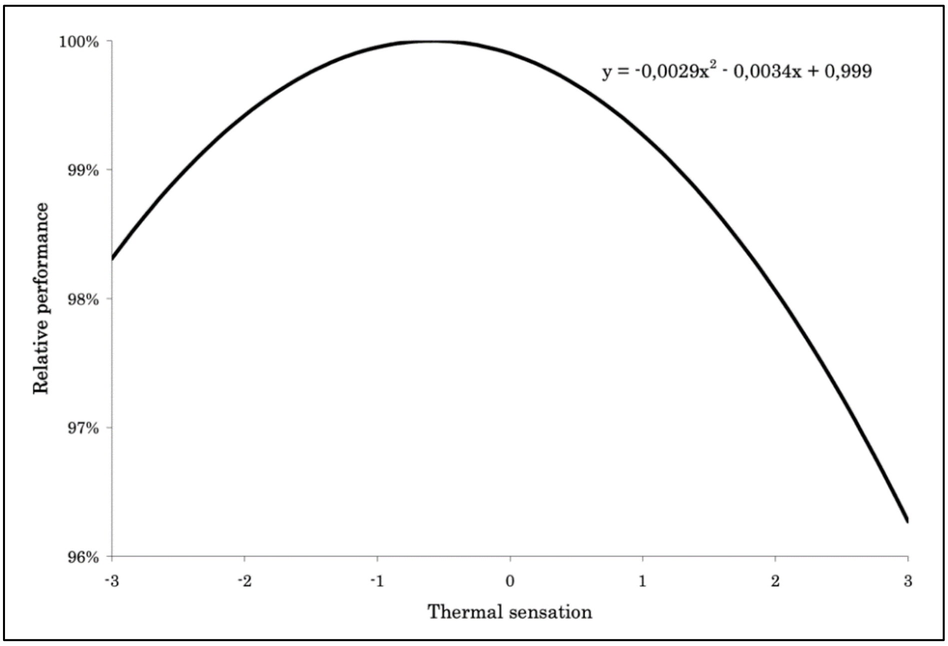

Figure 10.3: Relative performance as a function of thermal sensation. *Source: Jensen, 2008.*

Lan et al. (2011) also present a correlation between TSV and objectively measured performance, see equation (2). The comparison is based on the results of three climate chamber studies in which temperature and clothing insulation were influenced by the researcher. The subjects did mental tasks and in one study simulated office work at different temperatures. They were also asked for their thermal perception on the 7-point ASHRAE scale (Table 2.1). The relationship is close to that of Jensen (2008):

$$\text{Relative performance} = -\,0.035\,\text{TSV}^3 - 0.215\,\text{TSV}^2 + 99.865 \qquad (2)$$

According to both Jensen (2008) and Lan et al. (2011), maximum performance is found at a point slightly below TSV = 0. Therefore, according to Lan et al. (2011), it is better to set the optimal PMV values between -0.5 and 0 rather than between -0.5 and +0.5, as is common in current guidelines. However, this is neither necessary nor desirable for several reasons.

Firstly, this will be impossible in practice. Although the temperature can be controlled in such a way that the PMV is -0.5 to 0 for a given assumed mean clo value, occupants will still adjust their clothing to optimise their personal comfort. Moreover, this can lead to overcooling as described in Chapter 1, resulting in an increase in the likelihood of physical symptoms. Also, further narrowing of the temperature boundaries increases the likelihood of more thermal discomfort due to the "narrow temperature boundary paradox" (Section 4.7). It is also less desirable because routine work has been shown to be performed best under slightly cool conditions, but tasks requiring creativity and logical thinking are performed faster under conditions that are perceived as slightly warm (Jensen et al., 2009). Office work today, apart from routine tasks, increasingly requires creativity and logical thinking on the part of employees at all levels. This is also evident from the results of Lipczynska et al. (2018) presented below, where productivity was found to be highest at a TSV that is just slightly higher than neutral. Moreover, equations (1) and (2) above show that at TSV = 0, relative performance is 0.999, i.e. only 0.1% below the assumed optimum.

In summary, performance in varied office work is generally highest with a plateau around TSV=0. How wide this plateau is in general or in particular cases cannot be deduced from Zhang, de Dear & Hancock (2019). If the width is at least as large as for conditioned environments in Figure 10.1, namely 4°C, then a plateau of at least between TSV=-0.5 and TSV=+0.5 can be expected.

There are also studies that show that the relationship of performance with TSV or with the acceptability of thermal sensation is stronger than the relationship of performance with temperature. Research in hot conditions in Singapore (Lipczynska et al., 2018) shows that increasing the cooling setpoint from 23°C to 26°C, supplemented by adjustable ceiling fans (per 1 to 3 occupants) increased the acceptability of thermal sensation from 58% to 91%. At the same time, a significant energy saving was achieved. The change of setpoint had no effect on self-reported productivity. TSV and thermal sensation acceptability did have an effect, not only on self-reported productivity, but also on sleepiness and concentration (Figure 10.4). Self-reported productivity was found to be highest when thermal comfort was slightly warmer than neutral. Also, self-reported productivity was highest when acceptability of the thermal sensation was maximal.

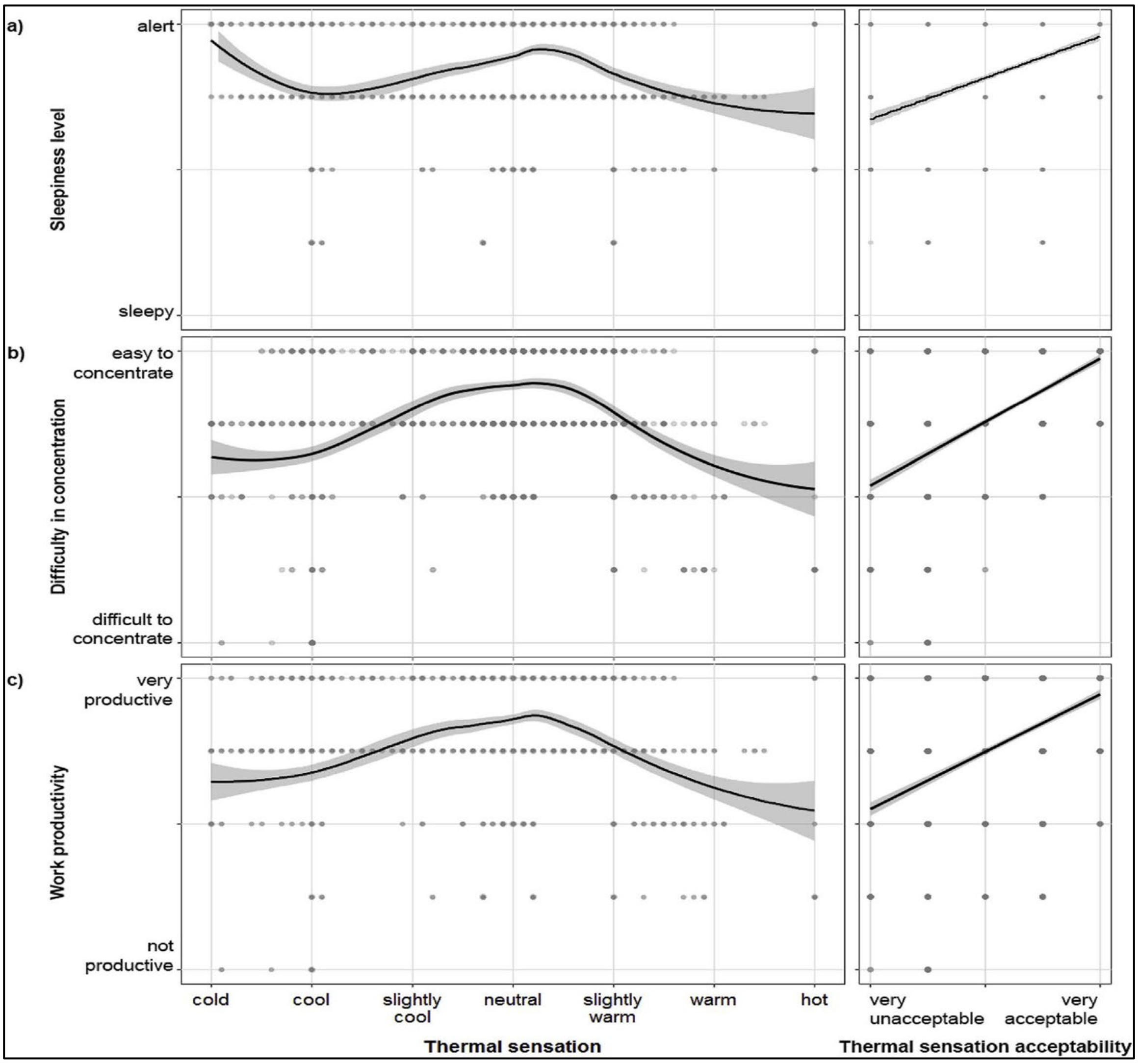

Figure 10.4: The effect of thermal sensation on sleepiness (a), concentration (b) and productivity (c). Source: Lipczynska et al., 2018.

Research in Japan on the effects of COOL BIZ[20] in a real work space (Tanabe et al., 2015) showed that self-reported productivity did not correlate with temperature (Figure 10.5), but correlated very strongly with satisfaction with the thermal environment when this was achieved through adaptive features such as fans and lighter clothing (Figure 10.6) The correlation is very similar to that shown in Figure 10.4, the bottom right image.

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[20] The COOL BIZ campaign was initiated by Japan's Ministry of Environment as a means to help reduce Japan's electricity consumption by limiting the use of air conditioning. The Japanese Prime Minister set the example by not wearing a business suit but light, summer clothes. This allowed the office temperature to be set a few degrees higher while maintaining thermal comfort and performance levels.

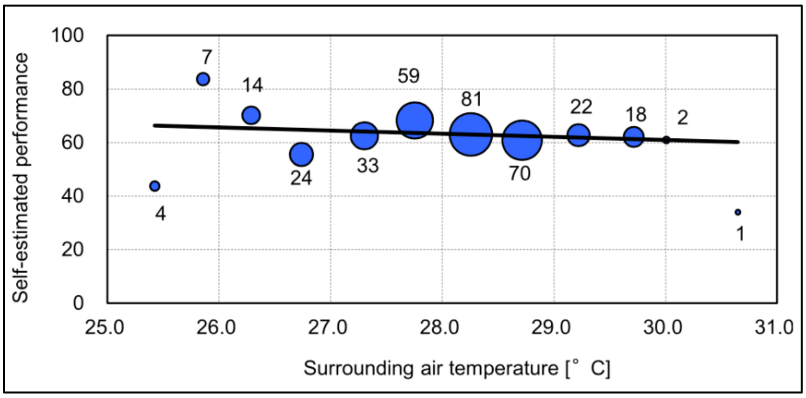

Figure 10.5: The relationship between ambient air temperature and self-reported performance ($y = -1.19x + 96.5$, $R^2 = 0.045$, $p < 0.001$, $n = 335$). Source: Tanabe et al., 2015.

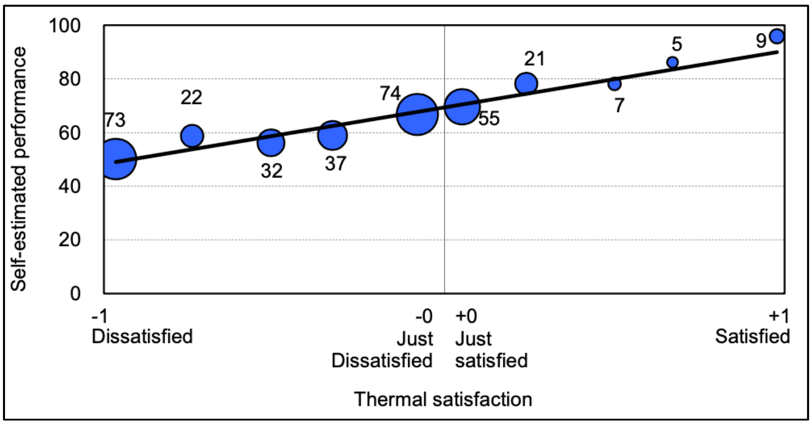

Figure 10.6: The relationship between thermal satisfaction and self-reported performance ($y = 21.1x + 69.3$, $R^2 = 0.944$, $p < 0.001$, $n = 335$). Source: Tanabe et al., 2015.

Also, in a laboratory situation with a relatively high temperature of 28.5°C, subjects were offered different conditions to still feel relatively comfortable, namely, clothing with a lower clo value, a tabletop fan, an air-conditioned shirt, an office chair with a perforated metal seat and back, and combinations thereof. Also, performance was measured objectively through simulated office work. There was no difference in performance with the different conditions. However, objectively measured performance was higher when *satisfaction* with thermal sensation was higher.

10.4 PERFORMANCE AND OPEN-PLAN OFFICES

The detrimental effects of open-plan offices on comfort were discussed in Section 5.5, so it is useful here to also examine the influence of open-plan offices on performance. In addition to the influence of temperature, much research has been done into the effects of other aspects of the indoor environment in offices on performance and absence due to illness, such as air quality and noise, in most cases based on objective measurements. Larger office spaces lead to a loss of performance of around 3 to 15% and the as yet unquantified effects of visual problems, lack of view and physical symptoms (Leyten, Raue & Kurvers, 2014). In addition, many of these effects have been investigated in laboratory situations, which may underestimate the effect in practice, as Seppänen et al. (2006) show. In practice, a performance loss of 10 to 20% is possible in larger office spaces. As far as short-term sick leave is concerned, this can be up to 30% higher in larger office spaces than in room offices, partly due to the greater chance of mutual contamination, partly due to weakening of the body through physical symptoms and partly because dissatisfaction with the indoor environment lowers the threshold for calling in sick (Leyten et al., 2014).

10.5 CONCLUSIONS ON PRODUCTIVITY, TEMPERATURE AND THERMAL COMFORT

Based on the available research results, it can be concluded that under certain thermal conditions, work performance is highest when users perceive their environment as maximally comfortable or maximally acceptable and that performance decreases as they perceive the environment as less comfortable or less acceptable. This is true for both self-reported and objectively measured productivity. Incidentally, this also applies to other aspects of the indoor environment (Leyten et al., 2014).

In all likelihood, this involves an inverted U-curve with a plateau. Assuming this also applies to naturally ventilated buildings, then performance will be highest at a plateau around the neutral or comfort temperature, which may correspond to higher temperatures than what is neutral or comfortable according to the PMV model. Performance will decrease as the temperature is further below or above the plateau.

As for the width of this plateau, in air-conditioned environments it is about 4C wide. It is likely that in naturally ventilated, free running buildings the plateau will be at least as wide. Sections 7.1, 8.2 and 8.3 showed that in existing buildings there are no differences between the indoor climate categories (A, B, C) in perceived comfort and acceptability of temperature. Since perceived comfort and acceptability of temperature are determinants of employee performance, it is likely that there is also little difference in performance between the three categories. This implies that the plateau extends to category B or even category C. It is argued in Chapter 6 that category B (PPD=20%) is the most realistic bandwidth for newly constructed buildings. Therefore, it is very likely that the plateau extends at least to category B at the top and that in naturally ventilated, free-running buildings that meet category B, no perceptible performance loss due to excess temperature is to be expected.

It is also interesting to know in which environment the performance is higher: in a fully air-conditioned environment without openable windows where the temperature is within the plateau of 20°C to 24°C, or in a naturally ventilated environment at a category B adaptive comfort temperature, all other conditions being equal. In air-conditioned environments there are generally more building-related symptoms such as headaches and fatigue and concentration difficulties than in naturally ventilated/free running environments. The same applies to dissatisfaction with the thermal indoor climate and air quality. Headaches, fatigue and concentration problems lead to a loss of performance, as does dissatisfaction with the indoor thermal environment and air quality (Leyten & Kurvers, 2007). If the generalisation is correct that the highest performance is achieved in an environment that is perceived as the most comfortable, then we might expect that working performance will be higher in well-designed naturally ventilated, free running or hybrid buildings than in fully air-conditioned buildings with the corresponding comfort temperature.

11 DESIGN RECOMMENDATIONS FOR OPTIMAL THERMAL COMFORT

11.1 INTRODUCTION

People perceive changes in the thermal environment in different ways and have different strategies to respond to them. The first response is autonomous, through vasoconstriction and vasodilation of the blood vessels. The second response is behavioural thermoregulation, for example by opening or closing windows, lowering or raising blinds, putting on warmer or cooler clothing or sitting in a different place in the room or building. The degree of discomfort controls these forms of behavioural adaptation to prevent as much as possible the next autonomous thermophysiological reaction, namely sweating or shivering. This means that the building design must allow for behavioural thermoregulation as much as possible. A building design that interferes with this adaptive process, such as a completely closed façade, an indoor climate that is decoupled from the outdoor climate, open plan office layout, will eventually lead to discomfort and eventually to complaints about the indoor climate and even the office environment as a whole. Like the autonomous forms of thermoregulation, behavioural adaptation is a natural biological response and it is the responsibility of building professionals to facilitate this natural and basic need for occupants to adequately influence the (thermal) environment. Building design that takes account of thermal adaptation is also, in general, energy efficient and is based on quantifiable and qualitative factors that address both the human-building interaction and the building-climate interaction.

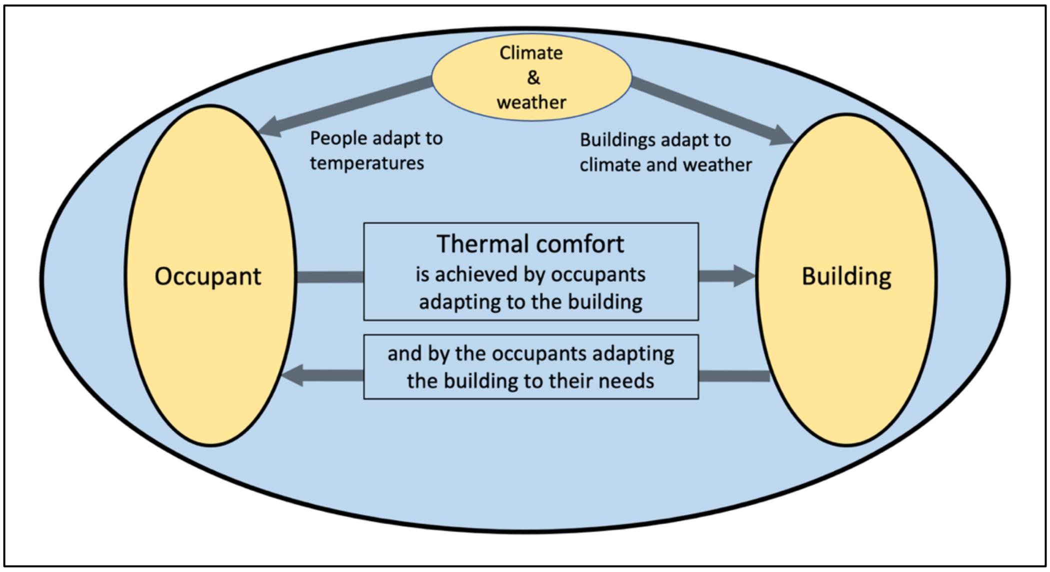

Figure 11.1: The principle of thermal adaptation in buildings.
Source: based on Humphreys & Nicol, 2015.

In buildings where robust design principles are optimised, the indoor climate to some extent varies with the outdoor climate and adaptation by the occupants is possible because the indoor temperatures are logical and predictable. However, the indoor climate should not heat up or cool down too quickly because adaptation takes time. Effective shading, thermal mass and simple, robust natural, mechanical or hybrid ventilation are crucial elements in allowing the indoor temperature to vary with the outdoor temperature in such a way that people can adapt.

In order to provide the vast majority of the occupants with a thermally comfortable indoor climate most of the time, the following requirements and design principles have been formulated:

- Performance requirements for comfortable indoor temperatures;
- Opportunities for behavioural, physiological and psychological adaptation in buildings;
- Controlling indoor temperatures through building physics and passive design solutions;
- HVAC systems focusing on comfort and health.

These principles are explained in more detail in the following sections.

11.2 PERFORMANCE REQUIREMENTS FOR COMFORTABLE INDOOR TEMPERATURES

1. In naturally ventilated and hybrid buildings the operative temperature largely remains (see 2, below) within the adaptive bandwidth of category II of EN 16798-1 (Figure 6.2). This corresponds to a maximum of 20% dissatisfied. Narrower limits do not give extra comfort or higher performance (Sections 4.7, 7, 8.2 and 10.5).
2. Exceedances of this bandwidth (simulated or measured) meet all criteria as mentioned in Section 6.5.
3. In air-conditioned buildings the setpoint in summer is between 24°C and 27°C at a relative humidity of 50% and air velocities up to 0.2m/s (Figure 8.13).
4. During the heating season, each room has the option of controlling the temperature over a range of -2°C to +2°C.

11.3 INCORPORATE ADAPTIVE OPPORTUNITIES IN BUILDINGS

BEHAVIOURAL ADAPTATION

1. Openable windows. This is one of the most effective and therefore one of the most important possibilities to influence the temperature and air quality in a room. Plan preferably one openable window per one or two persons. In order to be able to exchange air with the outdoors without draughts in different weather conditions, a continuous variable window setting or a window with small gap settings is essential. See Figure 11.2 for examples. If adequate ventilation is not possible due to pressure differences between facades, consider an outward-opening window (Spilka or H-window). This is an example of a window that can be opened easily and where the openings at both the top and the bottom allow for an adjustable air flow (Figure 11.3).

Figure 11.2: Examples of window levers allowing small gaps or continuous variable window settings. Source: SecuProducts BV.

Figure 11.3: Example of a continuous variable window setting. Source: Spilka Norway.

2. Provide rooms and/or desks with ceiling and/or desk fans (Figure 11.4). These can be used at temperatures from about 26°C. Choose fans with brushless, low-noise DC motors that can be controlled individually[21].

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[21] See *Ceiling Fan Design Guide* (Raftery & Douglass-Jaimes, 2020).

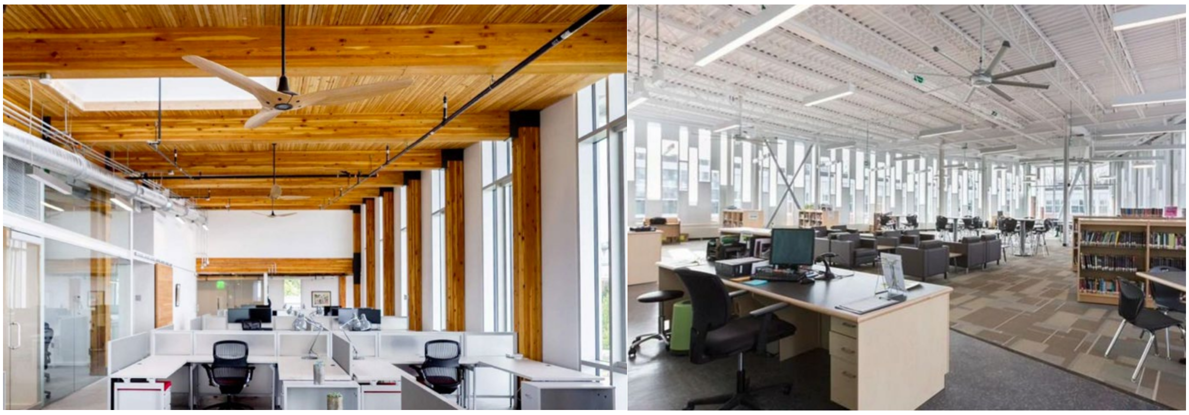

Figure 11.4: Examples of advanced ceiling fans. *Source: Big Ass Fans.*

3. Provide options for choosing a warmer or cooler place within the building. In a naturally ventilated building, temperature differences will usually occur naturally. Flexible workplaces increase the options for choosing warmer or cooler places in the building. Circulation areas and areas where people do standing or more strenuous work can be somewhat cooler within the range in winter.
4. Flexible working hours make it easier for occupants to choose working conditions that are comfortable for them.
5. A strict dress code obstructs behavioural adaptation.
6. Consider the use of office furniture with possibilities to adjust the immediate thermal environment. The facilities should have a high degree of robustness (Section 5.4), the following is important here:
   - The devices are individually adjustable and have a fast perceptible effect on the immediate thermal environment;
   - The operation of the devices is transparent;
   - The devices requires no or simple periodic maintenance.
7. It is essential that building users are instructed how the building and all the facilities affecting the indoor environment function in order to achieve the comfort and energy-saving goals.

PHYSIOLOGICAL ADAPTATION

The ability for physiological adaptation is enhanced by exposing occupants to varying temperatures such as those found in a well-designed naturally ventilated or mixed-mode building. Exposure to narrow temperature ranges, such as those typically found in air-conditioned buildings, reduces the adaptive capability (Section 4.3).

PSYCHOLOGICAL ADAPTATION

Psychological adaptation is promoted when temperature changes are understandable for the occupants on the basis of the type of building and the outside temperature. In Section 4.5 it was explained that in non-air-conditioned buildings, thermal comfort is a bonus factor: if the indoor climate is okay, the building as a whole is rated higher, if it is not okay, the building is not rated lower. In air-conditioned buildings, on the other hand, thermal comfort is a basic factor: if it is adequate, the building is not rated higher, and if it is not adequate, the building is rated lower. A free-running building thus promotes psychological adaptation. If cooling is unavoidable, for example due to the local climate, a mixed-mode building is preferable, because then the building is free running part of the time, which promotes the possibilities for adaptation and because thermal comfort is a proportional factor here and not a basic factor.

11.4 EXAMPLES OF CONTROLLING INDOOR CLIMATE THROUGH PASSIVE DESIGN SOLUTIONS

People generally feel more thermally comfortable and the various forms of adaptation are better achieved if the indoor climate behaves naturally. The indoor climate behaves more naturally if building physics/passive solutions are chosen instead of purely HVAC solutions. These include, for example, a form of exterior sun blinds and thermally effective building masses combined with night ventilation. Night ventilation can also be achieved in a partially active manner, for example by automatically controlled (upper) windows in combination with central mechanical exhaust ventilation.

Building physics solutions combine a number of advantages: they make mechanical cooling redundant in many cases, they provide a comprehensible and predictable relationship between indoor and outdoor temperatures for occupants, and they encourage occupants to make use of adaptive opportunities as much as possible. Apply fully active solutions only when this is unavoidable in order to control the indoor climate. Examples of passive and architectural solutions are explained below.

LOCATION, SHAPE, SPATIAL ARRANGEMENT AND SOLAR RADIATION

1. Consider a layout in which the use of the space can be tuned as much as possible to the sunlight. This makes adaptation easier. Rooms with a higher heat demand are best oriented towards the south, west or east. Sun shading and opening windows are then adaptive options to achieve comfort. For example, bedrooms can be oriented to the north or north-east, a kitchen to the east and a living room to the south/west. As an example, see Figure 11.5.
2. An orientation with the longitudinal axis in an east-west direction makes it possible to optimally harvest and reject solar heat.
3. A long rectangular building shape and a limited construction depth enable optimum use of daylight, cross-ventilation and a division into a mix of smaller rooms.
4. Variations in facade orientation allow most windows to have a north/south orientation and the fewest windows an east/west orientation.
5. Consider locating areas that benefit from the winter sun on the south side (e.g. living rooms).
6. Consider locating areas that benefit from cold on the north side (e.g. kitchens, bedrooms).

Figure 11.5: Example of optimisation of the spatial layout of a dwelling that provides opportunities to adapt by coordinating use of space and position of the sun.
Source: Alders, 2016.

WINDOWS AND DAYLIGHT

1. A glass percentage in the façade of approximately 20% to 40% provides for an optimal balance between sufficient daylight to limit the energy consumption of artificial light and limiting the heat load from the sun in summer to prevent overheating. For north-facing facades, 20% is often mentioned and about 50% for south-facing facades, provided that an efficient adjustable sunshade is used[22].
2. Adjustable light blinds on the inside of windows prevent large differences in brightness and glare. Note: Internal light blinds are not effective in preventing solar heat gain.

SHADOWING

1. Adjustable external blinds with a g-value below 0.20 are superior to tinted glass or internal blinds because their solar control properties are insufficient on sunny days and they block out too much heat at times when solar heat is desired in the building.
2. Consider that windows on south-facing facades can be fully exposed to the sun during the heating season by means of adjustable external blinds. Therefore, fixed forms of shading are less desirable in those places.
3. Consider exterior blinds in the form of horizontal exterior blinds or screens in addition to or instead of cantilevers or overhangs to keep out the low east and west sun.
4. Seasonally adjusted shading is also possible through vegetation. For example, place deciduous trees in front of the south façade of a building. In summer, these will act as shading. In the heating season, when the trees are bare, it allows solar heat to reach the façade.

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[22] This applies to a temperate maritime climate in the northern hemisphere.

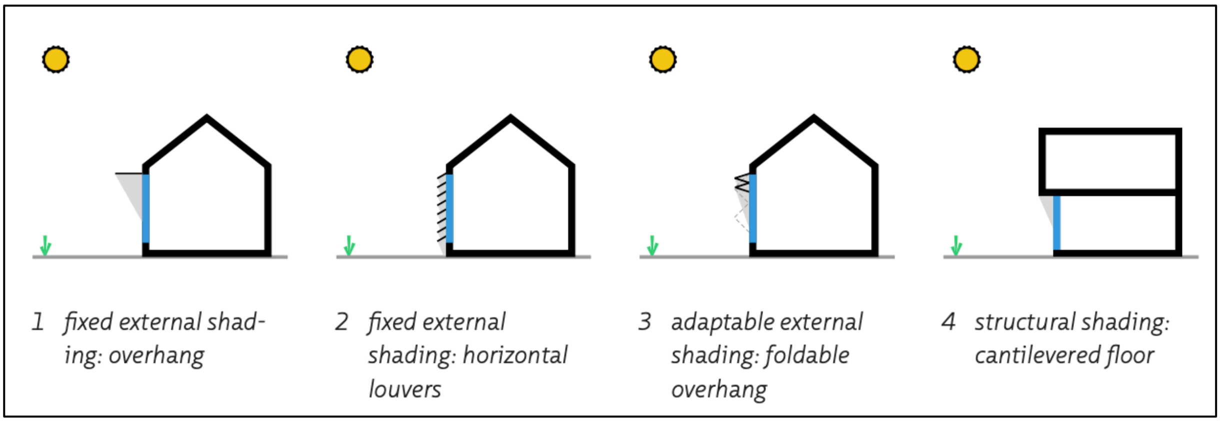

Figure 11.6: Different forms of outdoor sun protection. *Source: Looman, 2017.*

THERMAL MASS

Building mass in combination with night ventilation. During the day, heat is stored in the building mass and by ventilating with cooler external air during the night, the heat is removed from the building, so that the next morning starts with a lower indoor temperature (Figure 11.7).

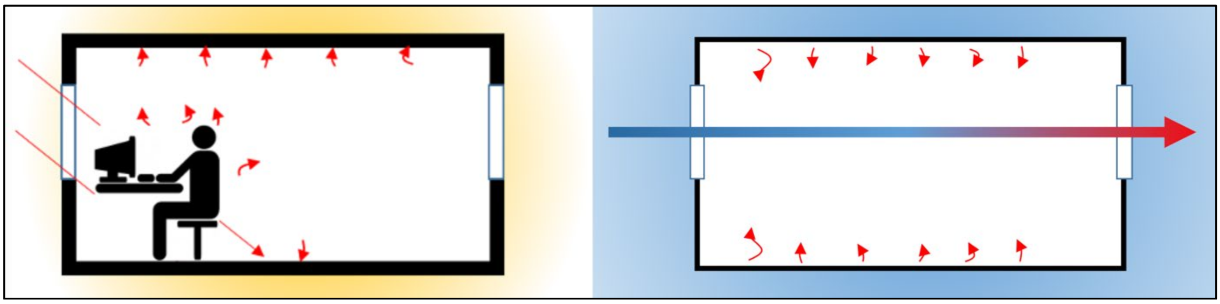

Figure 11.7: The principle of night ventilation. The heat stored by the building mass during daytime (left) is extracted by the ventilation air during the cooler night (right).
Source: TVVL, 2016.

Thermal mass affects both the level of the temperature peak (which gets lower) and the time of the temperature peak (which gets later), allowing either the occupants to adapt more easily to the higher temperature in the afternoon, or, in the case of an office building, the temperature peak falls in late afternoon or after working hours. See Figure 11.8.

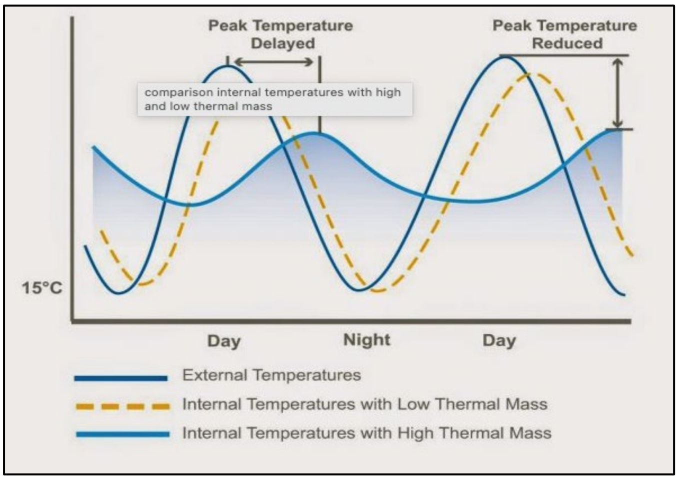

Figure 11.8: Thermal mass affects both the time and the level of the maximum indoor temperature.

In homes, thermal mass absorbs heat during the day, but it takes a while for the structure to cool down. During a heat wave, people can therefore slowly adapt to the higher indoor temperature. It takes one to two weeks for the entire mass to warm up, but when the heat wave is over, it takes several days for the mass to cool down again.
This can be a disadvantage for bedrooms, because they can remain warm for several days at night. During a heat wave, you'd rather sleep in a room with little mass than in one with a high thermal mass. Rooms can be cooled during the night by ventilating with the cooler outside air, which cools down the thermal mass and reduces the interior temperature the next morning (Figure 11.9).

Figure 11.9: Examples of burglar-proof ventilation windows and shutters.
Source left: Knipping; right: Beltman Architects.

NATURAL VENTILATION DUCTS

1. Consider natural ventilation ducts based on the chimney effect or solar heat (temperature differences). See Figure 11.10. The effect of the stack effect can be enhanced by applying a solar chimney. See Figure 11.11.

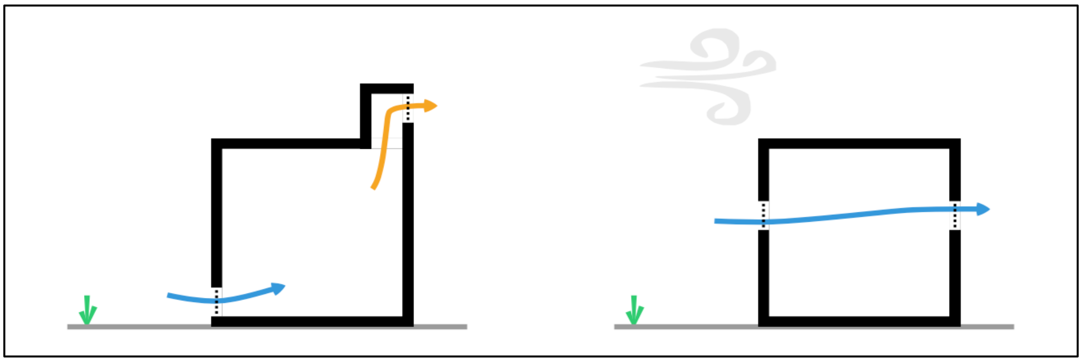

Figure 11.10: Natural ventilation due to temperature differences (left) and pressure differences (right). *Source: Looman, 2017.*

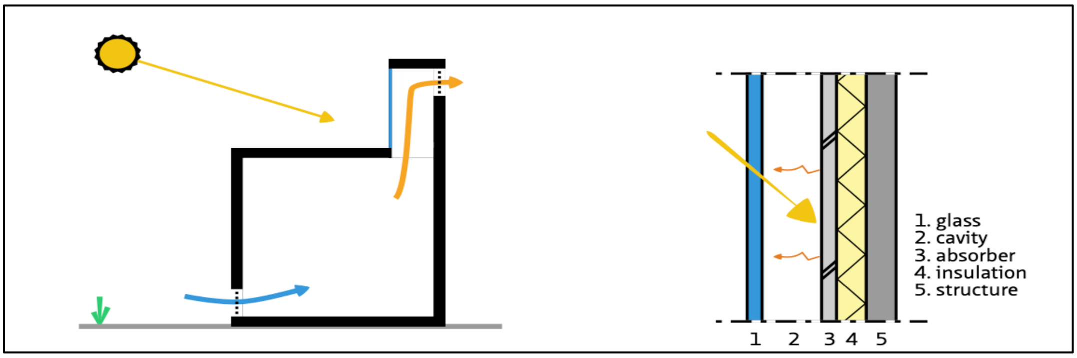

Figure 11.11: The principle of a solar chimney and a cross-section of the part exposed to solar radiation. *Source: Looman, 2017.*

2. Consider using some form of wind catcher to promote natural ventilation. See Figure 11.12.

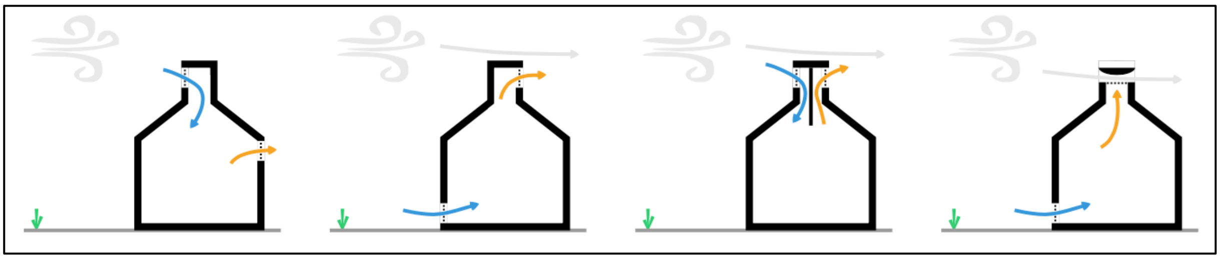

Figure 11.12: Different forms of wind catches, from left to right: -Opening on the windward side creates overpressure in the room; -Opening on the leeward side creates underpressure; -A combination of both; -The wind speed is increased by the venturi[23] *effect and creates pressure differences.* *Source: Looman, 2017.*

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[23] A venturi is a narrowing in a flow duct, which, in this case, causes the air to increase in velocity and a pressure drop at that point; the venturi effect.

COLLECTING SOLAR HEAT

Consider using a conservatory (sunspace or winter garden). Due to the large glass surface, the temperature in a conservatory follows the outside temperature faster than the rest of the building (workspace or house) with less glass and more mass. To prevent overheating in the summer, the sunspace must be well ventilated to the outdoors. Doors, windows or ventilation openings in the common wall allow daytime winter heat to flow from the sunspace into the main building. In addition to being used to capture solar heat, a conservatory can also be used as an adaptive option to achieve a different temperature and thermal environment than in other spaces in the house.

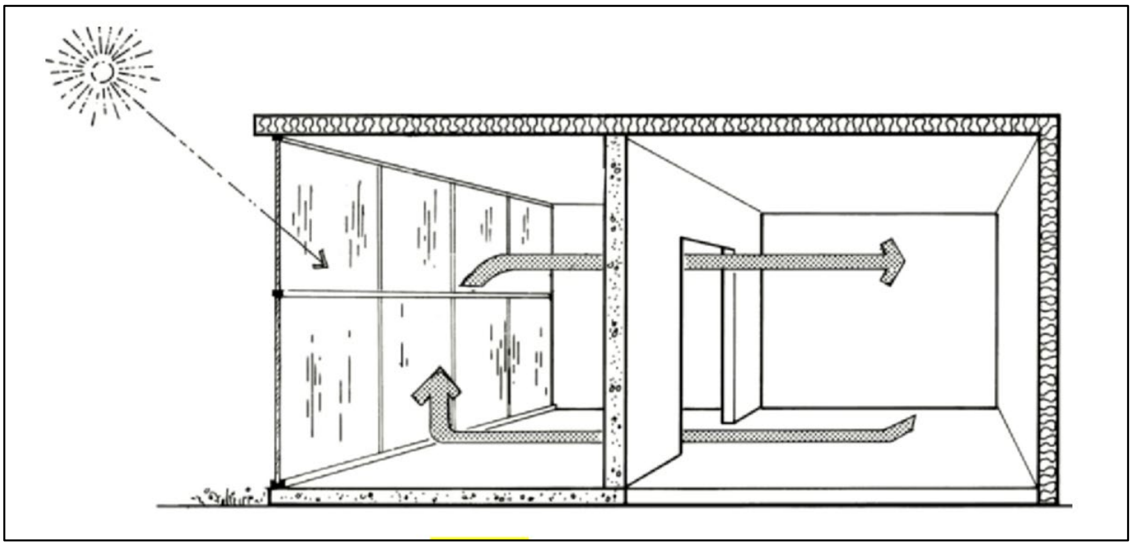

Figure 11.13: During the day, the sunspace collects solar heat and distributes the heat to the rest of the building. Thermal mass stores the heat for nighttime use. Source: Lechner, 2014.

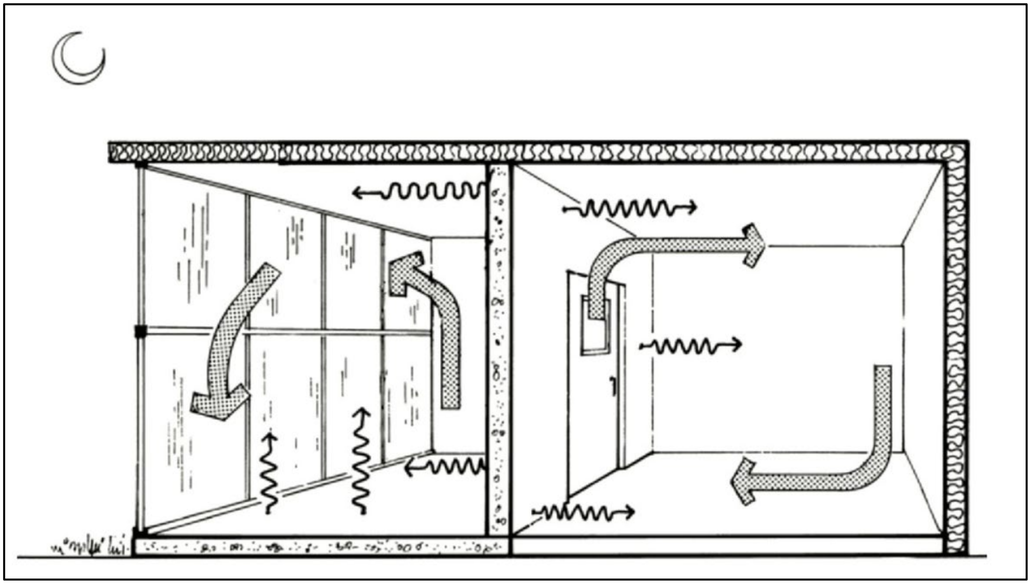

Figure 11.14: At night, the sunspace must be sealed from the main building to keep it from becoming an energy drain on the main building. Source: Lechner, 2014.

11.5 CLIMATE SYSTEMS AIMED AT COMFORT AND HEALTH

1. Consider using a form of *natural ventilation or hybrid ventilation with mechanical extract ventilation* as much as possible by applying the building physics measures mentioned under 11.4. See Section 1.1 for definitions of installation types;
2. If the performance requirements for thermal comfort and ventilation are not met when applying the building physics measures mentioned under 11.4 and the choice under Section 11.5: 1, consider a form of *hybrid ventilation without mechanical cooling*;
3. If the performance requirements for thermal comfort and ventilation are not met by applying the building physics measures mentioned under 11.4 and the choices mentioned under 11.5: 1 and 2, consider a form of *mixed mode ventilation*[24], in which the free running mode is active for as much as the day as possible[25].
4. Only consider a climate system with *full mechanical cooling* if it appears that the performance requirements for thermal comfort and ventilation will not be met by applying the building physics measures[26] mentioned under 11.4 and the choices mentioned under 11.5: 1, 2 and 3;
5. Apply as much as possible the principles of robust climate design as mentioned in Chapter 5 under “Technical functioning and interface between occupant and building”.

The above showed examples of design solutions are focused on adaptive opportunities and passive principles, complemented by healthy climate systems to achieve a comfortable and energy-efficient indoor climate have been presented. These examples relate to a Western European maritime climate. In other climate zones, like a hot-dry climate, hot-humid climate or a Mediterranean climate, different combinations of solutions will be needed to obtain thermal comfort. A very effective tool for this is *Climate Consultant*. This is a free and easy-to-use, graphical computer program (Windows and MacOs) that helps architects, builders, contractors, homeowners and students understand their local climate. It uses climate data from thousands of weather stations around the world and translates this raw climate data into various graphical representations of the effect on sustainable design solutions on thermal comfort (https://www.sbse.org/resources/climate-consultant).

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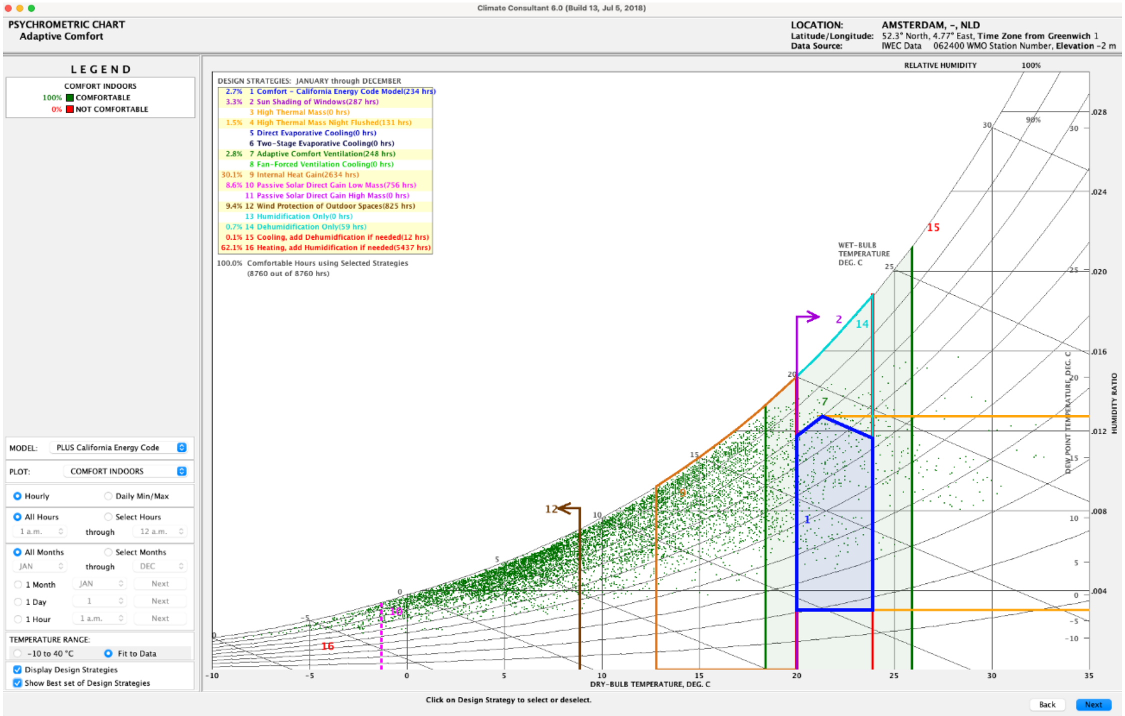
[24] In this type of building the indoor climate is free-running for much of the time up to a certain temperature, and above that, mechanical cooling is used to some extent.

[25] This choice is influenced by the local climate, the chosen location, the particular purpose of the building and limitations in the application of building physics measures.

[26] Systems that make use of cool surfaces, such as radiant ceilings, wall cooling and passive cooling convectors (chilled beams), prove to be preferable to active air cooling. Furthermore, this avoids the risk of microbiological contamination of filters, ducts and cooling and humidification units.



Climate Consultant 6.0 (Build 13, Jul 5, 2018)

PSYCHROMETRIC CHART
Adaptive Comfort

LOCATION: **AMSTERDAM, –, NLD**
Latitude/Longitude: 52.3° North, 4.77° East, **Time Zone from Greenwich** 1
Data Source: IWEC Data 062400 WMO Station Number, **Elevation** -2 m

LEGEND

COMFORT INDOORS
100% 🟩 COMFORTABLE
0% 🟥 NOT COMFORTABLE

DESIGN STRATEGIES: JANUARY through DECEMBER

2.7%	1 Comfort – California Energy Code Model(234 hrs)
3.3%	2 Sun Shading of Windows(287 hrs)
	3 High Thermal Mass(0 hrs)
1.5%	4 High Thermal Mass Night Flushed(131 hrs)
	5 Direct Evaporative Cooling(0 hrs)
	6 Two-Stage Evaporative Cooling(0 hrs)
2.8%	7 Adaptive Comfort Ventilation(248 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
30.1%	9 Internal Heat Gain(2634 hrs)
8.6%	10 Passive Solar Direct Gain Low Mass(756 hrs)
	11 Passive Solar Direct Gain High Mass(0 hrs)
9.4%	12 Wind Protection of Outdoor Spaces(825 hrs)
	13 Humidification Only(0 hrs)
0.7%	14 Dehumidification Only(59 hrs)
0.1%	15 Cooling, add Dehumidfication if needed(12 hrs)
62.1%	16 Heating, add Humidification if needed(5437 hrs)

100.0% Comfortable Hours using Selected Strategies
(8760 out of 8760 hrs)

MODEL: PLUS California Energy Code
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Select Hours
1 a.m. through 12 a.m.
● All Months ○ Select Months
JAN through DEC
○ 1 Month JAN Next
○ 1 Day 1 Next
○ 1 Hour 1 a.m. Next
TEMPERATURE RANGE:
○ -10 to 40 °C ● Fit to Data
☑ Display Design Strategies
☑ Show Best set of Design Strategies

Click on Design Strategy to select or deselect.

Figure 11.15: Example of an output of the effects of design solutions on thermal comfort.
Source: Climate Consultant.

It is recommended that the analyses in Climate Consultant are initially tested against the adaptive thermal comfort model. Only when insufficient thermal comfort can be achieved, the traditional (PMV-based) comfort model can be chosen. Climate Consultant uses design solutions from 2030 Palette (http://2030palette.org), a free online platform that succinctly presents principles and tools for carbon-neutral and resilient built environments for designers, planners, builders and policy makers worldwide.

11.6 CLIMATE CHANGE, DESIGN CHOICES AND ADAPTATION

Climate change is causing summer temperatures to rise, making good building physics choices even more important. Although users often prefer naturally ventilated buildings with open windows to air-conditioned buildings, these can temporarily become too hot, especially during heat waves, depending on the design and building choices. Building designs that are sub-optimal in terms of building physics then often opt for full air conditioning, which can avoid high summer temperatures. However, because the indoor climate is then largely decoupled from the outdoor climate, thermal adaptation of the users in such buildings is more difficult because the temperatures are not logical and predictable and the natural clothing behaviour of users conflicts with the indoor climate. In countries where it is very hot for much of the year, people are adapted to high temperatures by physiological, behavioural and psychological adaptation. In temperate regions, such as the Netherlands, very warm periods are usually short, so that adaptation cannot always take place in full. The average duration of a heat wave in the Netherlands, measured from the year 2000, is 9 days. Both full air conditioning and only natural ventilation can present different problems for people to adapt to during different weather periods. As argued earlier, full air conditioning is best avoided in most cases. Problems with overheating in naturally ventilated buildings are best avoided by applying as many building physics measures and adaptive options as possible. In the case of a design with balanced mechanical ventilation without cooling, a possible future warmer climate can be taken into account by reserving space in the ventilation system for a cooling section. The non-cooled building can then be turned into a mixed-mode building in which the indoor climate varies with the outdoor climate for a large part of the year and a sustainable form of cooling is only used during very hot weather conditions to enable optimal adaptation of people to the building.

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SYMBOLS

A_{du}	Body surface	[m^2]
P_c	Heat transfer by convection from the outer surface of the dressed body	[W/m^2]
P_{av}	Sensible heat emission through respiration	[W/m^2]
P_d	Warmteafgifte door diffusie van waterdamp door de huid (latente warmte)	[W/m^2]
P_l	Heat emission through diffusion of water vapour through the skin (latent heat)	
P_{zv}	Heat dissipation through evaporation of sweat from the surface of the skin	[W/m^2]
H	Internal body heat production	[W/m^2]
I_{cl}	Heat resistance of the clothing	[m^2·K/W]
M	Metabolism	[W/m^2]
p_a	Partial water vapour pressure	[Pa]
PD	Percentage of people dissatisfied with draught	[%]
PPD	Predicted Percentage of Dissatisfied	[-]
PMV	Predicted Mean Vote	[-]
T_u	Relative turbulence intensity	[%]
v_a	Air velocity	[m/s]
σ	Standard deviation of mean air velocity	[-]
wf	Weighing factor	[-]
W	External Work	[W/m^2]
ΔT	Difference between maximum and minimum (air) temperature	[K]
η	Mechanical efficiency external labour	[K]
ΔT_{diff}	Difference between air and comfort temperature	[K]
ε	Emission coefficient	[-]
T_a	Air temperature	[˚C]
T_{mrt}	Mean radiant temperature	[˚C]
T_o	Operative temperature	[°C]
T_{out}	External temperature	[°C]
T_{rm}	Running mean outdoor temperature	[°C]
t_{od-1}	mean of maximum and minimum outdoor temperature yesterday	[°C]
t_{od-2}	mean of maximum and minimum outdoor temperature day before yesterday	[°C]
t_{od-3}	mean of maximum and minimum outdoor temperature day before yesterday	[˚C]
T_s	Mean skin temperature	[°C]

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