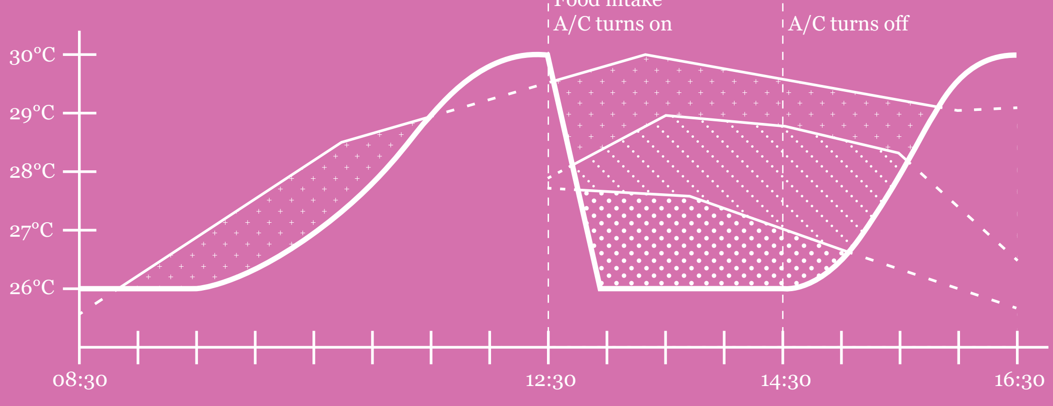
Technical University of Munich
Chair of Building Technology and Climate Responsive Design

Dynamic Cooling

Mitigating Climate Change through Temporal Discomfort

Sebastian Clark Koth



Technische Universität München
TUM School of Engineering and Design

Dynamic Cooling –
Mitigating Climate Change
through Temporal Discomfort

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Abstract

Air conditioning (A/C) is a significant environmental concern and the fastest-growing HVAC system, becoming ubiquitous in new buildings and renovations. The debate of decarbonizing building practice often centers around efficiency, even though sufficiency measures would offer more leverage. This thesis proposes a sufficiency approach to indoor cooling by defining necessary rather than comfortable thresholds. The objective is to understand the impact of broader thermal ranges and dynamic thermal environments on human thermoregulation and overall cooling energy demand, shifting the focus from subjective feedback to objective human thermoregulatory and adaptive capabilities.

The thesis suggests a significant potential for cooling energy savings within mechanically cooled office buildings by combining higher temperature thresholds with ceiling fans while still complying with standards, challenging the conventional reliance on mechanical cooling for thermal comfort. By addressing the gap in thermal comfort research, which lacks continuous data collection on thermoregulation and adaptive behavior in real-world environments, the thesis also presents a six-week measurement study observing nine participants in a naturally ventilated office without a cooling system. The findings indicate significant deviations in clothing insulation from standard assumptions, as well as significant sex differences in electrodermal activity, heart rate variability, and clothing insulation, highlighting the need for future research with larger, more diverse cohorts and enhanced environmental monitoring. Finally, this thesis explores how existing sealed office typologies can adapt to a warming world while minimizing the high energy demand for space cooling through *Dynamic Cooling*. This involves adjusting the cooling temperature profile to align with the human circadian rhythm to mitigate heat stress during times of heightened thermal sensitivity. The study compares the effect of dynamic cooling, constant cooling, and no cooling on the core body temperature (CBT) of 21 participants and conducts a comparative thermal dynamic simulation of 270 office configurations under these same cooling profiles. The results suggest no clear correlation between elevated indoor temperatures and CBT during morning hours, questioning the necessity and effectiveness of pre-lunch cooling. The simulation revealed a non-linear relationship between cooling energy savings and thermal comfort decline, with a 51.3% reduction in cooling energy demand and a 25.2%-36% increase in Over-Temperature-Kelvin-Hours (OTKH) from steady-state cooling to Dynamic Cooling profiles. Overall, the findings challenge traditional cooling standards, emphasizing the need to balance minimizing thermal discomfort and necessary cooling energy demand. Future research should refine thermal comfort standards to consider human thermoregulation dynamics, leveraging advancements in sensing technology for more accurate physiological metrics. This research can guide the building industry toward optimizing indoor environments for energy sufficiency and occupant wellbeing, promoting sustainable building practices.

Zusammenfassung

Klimaanlagen (A/C) sind das am schnellsten wachsende HLK-System, das mittlerweile in Neubauten und Renovierungen allgegenwärtig ist. Die Debatte über die Dekarbonisierung des Gebäudesektors meint oft Effizienz-, selten jedoch Suffizienz-Maßnahmen. Diese Arbeit präsentiert einen Suffizienz-orientierten Ansatz für die Innenraumkühlung, indem notwendige anstatt komfortable Schwellenwerte definiert werden. Ziel ist es, die Auswirkungen größerer Temperaturschwankungen und dynamischer thermischer Umgebungen auf die menschliche Physiologie und den gesamten Kühlenergiebedarf zu verstehen und dabei den Fokus von subjektiver Wahrnehmung auf objektive Thermoregulations- und Adaptionsmöglichkeiten zu verlagern.

Die Ergebnisse dieser Arbeit zeigen ein signifikantes Einsparpotenzial von Kühlenergie in Bürogebäuden durch die Kombination aus höheren Temperaturen und Luftbewegung, trotz Einhaltung geltender Normen, und stellt damit die herkömmliche Abhängigkeit von mechanischer Kühlung für thermischen Komfort in Frage. Die Arbeit präsentiert darüber hinaus eine sechswöchige Messstudie, die neun Teilnehmende in einem natürlich belüfteten Büro ohne Kühlsystem beobachtet. Die Ergebnisse zeigen eine signifikante Diskrepanz zwischen dem angenommenen und tatsächlichen Bekleidungsgrad sowie signifikante geschlechtsspezifische Unterschiede in der elektrodermalen Aktivität und der Herzfrequenz. Die Arbeit untersucht außerdem, wie bestehende Bürogebäude mit mechanischer Lüftung in einer sich wärmenden Welt angepasst werden können, bei gleichzeitiger Reduktion des Energiebedarfes für Raumkühlung. Dies beinhaltet die Anpassung des Kühltemperaturprofils an den menschlichen circadianen Rhythmus, um Hitzestress zu Zeiten erhöhter thermischer Empfindlichkeit zu mildern. Die Studie vergleicht die Auswirkung einer dynamischen Kühlung, konstanten Kühlung, und keiner Kühlung auf die Körperkerntemperatur (CBT) von 21 Teilnehmenden, sowie in einer thermodynamischen Simulation von 270 Bürokonfigurationen auf dessen Energiebedarf und thermischen Komfortempfindens. Die Ergebnisse deuten darauf hin, dass es keinen klaren Zusammenhang zwischen erhöhten Innentemperaturen und der CBT während der Morgenstunden gibt, was die Notwendigkeit und Wirksamkeit von Raumkühlung am Morgen in Frage stellt. Die Simulation zeigte eine nicht-lineare Beziehung zwischen den Einsparungen im Kühlenergiebedarf und dem Rückgang des thermischen Komforts, mit einer Reduktion des idealen Kühlenergiebedarfs um 51,3% und einem Anstieg der Übertemperatur-Kelvin-Stunden (OTKH) um 25,2%-36% vom statischen Kühlprofil zu den dynamischen Kühlprofilen. Insgesamt stellen die Ergebnisse traditionelle Kühlstandards in Frage und betonen die Notwendigkeit, das Minimieren von thermischem Unbehagen und den notwendigen Kühlenergiebedarf in Einklang zu bringen. Zukünftige Forschung sollte die Standards der thermischen Behaglichkeit verfeinern, um die Dynamik der menschlichen Thermoregulation zu berücksichtigen und Fortschritte in der Sensortechnologie für genauere physiologische Messungen zu nutzen. Diese Forschung kann die Bauindustrie dabei unterstützen, das Wohlbefinden der Nutzenden zu optimieren und nachhaltige Baupraktiken zu fördern.

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List of Abbreviations

A_G	Surface Area of Component
µS	Mikrosiemens
ANS	Autonomic Nervous System
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASHVE	American Society of Heating and Ventilating Engineers
ASR	Occupational safety guidelines (Arbeitsschutzrichtlinien)
ATHB	Adaptive Thermal Heat Balance model
BMI	Body Mass Index
BPM	Beats per Minute
BSA	Body Surface Area
BTU	British Thermal Unit
BVP	Blood Volume Pulse
CBT	Core Body Temperature
CC	Constant Cooling
CET	Corrected Effective Temperature
CIBSE	Institute of Building Services Engineers
clo	Clothing Insulation
C_{wirk}	Specific Heat Capacity
DC	Dynamic Cooling
DGNB	German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen - DGNB e.V.)
DIN	German Institute for Standardization (Deutsche Institut für Normung e. V.)
DWD	German Weather Service (Deutscher Wetterdienst)
ECG	Electrocardiographic
EDA	Electrodermal Activity
EHT	Equivalent Homogenous Temperature
EN	European Sandard
ET	Effective Temperature
FR	Free Running

GAS	General Adaptation Syndrome
GCG	Gyrocardiography
GSR	Galvanic Skin Response
HF	High Frequency
HR	Heart rate
HRV	Heart Rate Variability
HTP	High Tolerance Phase
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IMU	Inertial Measurement Unit
IPCC	Intergovernmental Panel on Climate Change
IRT	Infrared Thermography
ISO	International Organization for Standardization
K	Kelvin
LEED	Leadership in Energy and Environmental Design
LF	Low Frequency
LMU	Ludwig-Maximilians-University in Munich, Germany
LSB	Lower Sideband
LTP	Low Tolerance Phase
MBT	Mean Body Temperature
MET	Metabolic Equivalent
MRT	Mean Radiant Temperature
NST	Non-Shivering Thermogenesis
OMV	Observed Mean Vote
OTKH	Over-Temperature-Kelvin-Hours
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPG	Photoplethysmography
ppm	Parts per Million
PPV	Predicted Percentage of Variance
PVC	Polyvinylchlorid

RCP	Representative Concentration Pathways
rH	Relative Humidity
RMSSD	Root Mean Square of Successive Differences
RQ	Research Question
SCC	Conventional (Constant) Cooling Simulation
SCG	Seismocardiography
SCL	Mean Skin Conductance Levels
SCR	Skin Conductance Responses
SD	Standard Deviation
SDC	Dynamic Cooling Simulation
SET	Standard Effective Temperature
SIA	Swiss Standard
SP	Passive Simulation
Ta / Tair	Air Temperature
Tamb	Outdoor Temperature
TC	Core Temperature
Tc	Core Temperature
Texp	Exposure Temperature
Tg	Globe Temperature
TNZ	Thermal Neutral Zone
Tr	Radiant Temperature
Trm	Running Mean Temperature
TRY	Test Reference Year
Tsk	Skin Temperature
TSV	Thermal Sensation Vote
TUM	Technical University Munich
v	Air Velocity
WWR	Wall to Window Ratio

“Comfort is a scheme for social control […] comfort doesn’t always come in the same way, but follows a dynamic that continually changes terms relating to supply and demand”

Tomas Maldonado, 1987

Chapter One

1. Thesis Framework

1.1 Introduction

The building sector significantly contributes to global CO_2 emissions, accounting for 34% of the final energy consumption and 37% of energy-related emissions worldwide [1]. Mechanical cooling, in particular, is the fastest-growing HVAC (Heating, Ventilation, and Air Conditioning) system [2]. This creates a vicious cycle: as global temperatures rise, the demand for air conditioning increases, leading to higher emissions and further warming. The global cooling demand is projected to increase globally by 790% between 2010 and 2050, and by 1,386% until 2100, despite efforts to improve energy efficiency and reduce emissions [3]. The IPCC Climate Change Mitigation Report, released in April 2022, outlines crucial strategies to address carbon emission reductions through sufficiency and prevent *Carbon lock-in* [4].
Carbon lock-in is defined as a set of techniques, protocols, and practices that resist low-carbon futures, thereby jeopardizing climate action by perpetuating, postponing, or preventing the shift to low-carbon alternatives in fossil fuel-intensive systems [5]. The IPCC report discourages the construction of new buildings in developed countries that continue to rely on carbon-intensive materials or mechanical HVAC systems and instead proposes that the building industry focus on retrofit methods [4]. Ignoring this principle locks in more carbon in absolute terms for decades to come, leading not only to more emissions but also perpetuating the socio-industrial impacts of carbon dependence, from ecological destruction and labor exploitation at extraction sites to continued reliance on fossil fuels more generally [6]. In many cases, buildings that are otherwise in good condition are demolished because there are no economic means to retrofit their mechanical or energy performance systems to meet contemporary regulations or market requirements. Such a tear-down approach creates additional problems – losing the embodied energy of an existing structure on top of the construction costs of the replacement, regardless of how efficient the new building might be [7]. According to the IPCC report, embracing adaptive reuse is one of the most effective means to resist these lock-in patterns and reduce carbon dependence in some of the worst-offending buildings [4].
For the past three decades, sustainability in the built environment has relied on efficiency improvements [8] – providing the same building type but doing so with more efficient measures, i.e. less energy-demanding HVAC systems [9] or increasing the building insulation through façade optimization [10, 11]. Efficiency represents short-term technological improvements and ignores the capacity for social and behavioral change. This approach has led to marginal reductions in carbon output in some buildings but has not reduced emissions overall. Efficiency has also served as a permission structure for building more, while the carbon emissions saved through efficiency have been overwhelmed by an increase in square meters per person in developed countries [4]. The International Energy Agency (IEA) notes that the carbon emissions resulting from increased air conditioning demand will negate the gains made through efficiency and other decarbonization efforts [12]. Failure to limit this demand for air conditioning will therefore have severe effects on

the overall emissions, but also on the stability and flexibility of the electrical grid [13], especially in cities at risk of significant warming. The IPCC encourages a shift towards sufficiency measures, emphasizing long-term actions driven by non-technological solutions that consume less energy in absolute terms [6]. Sufficiency interventions are driven by human needs and wellbeing within planetary boundaries; they rely on both adaptive reuse measures and changes to modes of occupation [4]. Developing frameworks to integrate change in behavior and comfort expectancy in the context of reuse technologies and retrofitting interventions is necessary, as well as methods to validate the impact of this change.

Decarbonizing existing building operations, especially buildings that are repurposed and renovated often throughout their lifecycle is a complex yet essential task. Office buildings are among the most challenging architectural typologies to decarbonize. Over the past 70 years, office buildings have been especially energy-intensive, relying heavily on HVAC systems within sealed facades, often lacking operable windows. Nonetheless, the building sector currently lacks a comprehensive approach to sufficiently decarbonizing the HVAC systems, particularly air conditioning, of this building typology. In office buildings, solutions mostly involve enhancing building control systems and improving the efficiency of air conditioning (A/C) technology [14]. Despite decades of development, these technologies are inadequate from the current perspective, as demonstrated by the ever-rising emissions [15].
The systemic transformation is sparked by a painful truth: most existing buildings have been built with little regard for their energy use, exhibiting an aesthetic and technological approach based on petroleum and its possibilities. Many office buildings constructed after the 1950s, both in Europe and elsewhere, were built when fossil energy was cheap and readily available, resulting in an intensive energy demand that is now locked in. Remarkably, even with the now general knowledge of the urgent need to reduce carbon emissions, buildings are still being constructed according to this outdated model – even a 'sustainable' office building relies on and perpetuates these unsustainable models. [6]
While concerted efforts are being made through policy mechanisms (i.e. Paris Agreement [16]) and industry metrics (i.e. DGNB [17] and LEED [18]) to more aggressively reduce carbon emissions in new construction, the ongoing carbon emissions from existing buildings present an even more complex problem with no easy solutions. Addressing this problem is moving past reliance on efficiency measures – past reliance on a 'technological fix' – and investing research into sufficiency measures, particularly in how the use and occupation of buildings, in combination with design interventions and technological refinement, can begin to more dramatically reduce emissions.

Office buildings typically have low levels of interior environmental quality [19] and a strong reliance on fossil fuel-intensive mechanical systems [20]. The facades of these buildings are predominantly glass, chosen both for aesthetic reasons and because a thin membrane allows for maximum rentable square meters on a given lot (a thick, thermally active façade would occupy more space) [7]. Further complicating matters, the limitations of current mechanical rooms, shafts, and ceiling heights often prevent an adaptation, or renovation of the existing mechanical system to changing directives or requirements. For these and many other reasons, business-as-usual updates to the mechanical systems and facades of mid-century buildings fail to meet even the basic performance requirements of more recently completed structures (which are still not sustainable enough). Additionally, while solar photovoltaic energy can support various air handling systems, the roof size of most office buildings is typically too small to accommodate enough solar panels to make a significant impact [21]. The all-glass façade also reduces the area available for solar panels. Consequently, the interior is overheated by the sun, relying heavily on mechanical HVAC systems to achieve thermal comfort. A comfort demand that is driven solely by our thermal comfort expectancy, as represented in the standardized methods of thermal comfort evaluation. As such, these buildings are over-reliant on fossil-heavy systems to cool interior environments that guarantee a nominal 'comfortable' environment, at the expense of global warming. Evaluating thermal comfort is therefore crucial for determining how we could condition such buildings in a manner that is more responsive to human comfort, without this energy impost.

Currently, two widely accepted and standardized methods are used to assess indoor environments: the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), and the Adaptive method. These methods, along with other (non-standardized) approaches, aim to minimize heat transfer and prevent physiological adaptation through thermoregulation (e.g., sweating) by keeping indoor conditions close to thermal neutrality [22]. Although these methods allow for variations in thermal factors such as clothing insulation, metabolic rate, and air velocity, heating and cooling systems in practice often respond only to fixed temperature set points. This results in narrow, rigid daily temperature ranges, especially in mechanically ventilated office buildings, leading to increasingly uniform indoor conditions worldwide [23]. This uniformity comes at the cost of higher heating and cooling demand and increased emissions [24]. All standardized thermal comfort models and methods focus on subjective perceptions of comfort and discomfort, often based on homogeneous samples, that may not apply globally. Many of them, like the PMV and adaptive comfort method, vary in their predictive accuracy across individual anthropomorphic characteristics [25], fitness level, group size, and non-steady-state environments [26]. Moreover, comfort perception does not always align with healthy conditions. Recent studies suggest that uniform and steady-state thermal environments might correlate with long-term health issues [27, 28]. In the discussion of sustainable and healthy architecture, the concept of comfort seems nothing more than a luxury, paid for by emissions and human health.

1.2 Research Aim and Objectives

New approaches are needed to validate healthy and sustainable indoor environments, focusing on sufficient indoor climates rather than merely conditioning towards ideal thermal comfort. This requires redefining thermal comfort standards based on the spatio-temporal dynamics of the human body, rather than a single optimum condition. Studies show that environments with larger temperature variations are acceptable if adaptive opportunities are provided [29]. Many scholars suggest exploiting this flexibility to reduce conditioning periods and spaces, potentially using higher cooling setpoint temperatures or temporal (dynamic) variations in setpoint temperature. Recent advancements in sensing technology and biomedical data acquisition offer reliable methods to measure thermoregulation, making physiological metrics a promising alternative to current subjective data collection methods. Understanding the impact of thermal environments on human thermoregulation and adaptation capabilities could inform our thermal indoor thresholds as well as offer a sufficiency approach to the rising energy demand of mechanical cooling.

The hypothesis of this thesis can be formulated as follows:

Cooling indoor spaces according to a temperature profile based on human physiology can function as a viable heat stress mitigation and sufficiency strategy to cut energy use in already existing office buildings.

To test this hypothesis the following research questions were proposed within this thesis work:

1) What are the potentials for energy-saving and health improvements when rethinking the current thermal comfort standards?
2) How do individual differences and adaptation behavior influence the potential of temporal thermal fluctuations and physiological adaptation possibilities?
3) How does a dynamic temperature profile affect human thermoregulation?
4) How does a dynamic temperature profile affect the overall cooling energy demand?

Each research question (RQ) was addressed within chapters 3-5 (as published peer-reviewed articles). The link between them and how they contribute to the overall methodology to answer the proposed hypothesis, is described in the following.

1.3 Methodology

Figure 1 illustrates the comprehensive methodological approach of this thesis. Initially, boundary conditions are established based on the specific research question (RQ) addressed in each chapter. Each RQ pertains to one of two study types: measurement, simulation, or both. The objective of these studies is to populate a data domain comprising five types, providing information on either the Thermal Environment, Thermoregulation, Adaptive Behavior in Measurement Studies, or Energy Demand and Thermal Comfort Evaluation in Simulation Studies. The data analysis and insights from each chapter are presented at the top of the respective data domain in Figure 1.

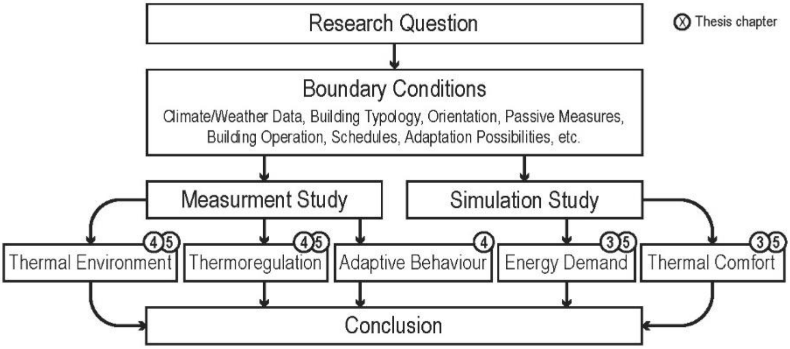

Figure 1 – Thesis Methodology.

This thesis focuses on pre-existing modernist office building typologies that rely on mechanically ventilated cooling to fulfill comfort as a scope of the framed problem statement. Consequently, the potential of behavioral adaptation, as understood in measurement studies of free-running/ naturally ventilated environments, as well as individual differences in physiology, may not be evident. The boundary conditions within simulation (Chapter 3) and measurement (Chapter 4) studies, therefore, expand this scope to offer diverse datasets and draw quantifiable comparisons. All simulation studies were performed using TRNSYS 18, with the parametric simulation tool TRNLizard, executed within the Grasshopper environment of Rhinoceros 7. TRNSYS 18 has been validated according to ANSI/ASHRAE Standard 140 Section 5.2 [30].

All measurement studies in this thesis were conducted in real office settings at the Technical University of Munich in Germany, some of which were modified to create specific climatic conditions. Additionally, some co-authored studies, referenced in this thesis and conducted concurrently, took place in the climate chamber (TUM SenseLab) at the Technical University of Munich. The climate control and data collection in these study environments adhered to the same methodological framework shown in Figure 2.

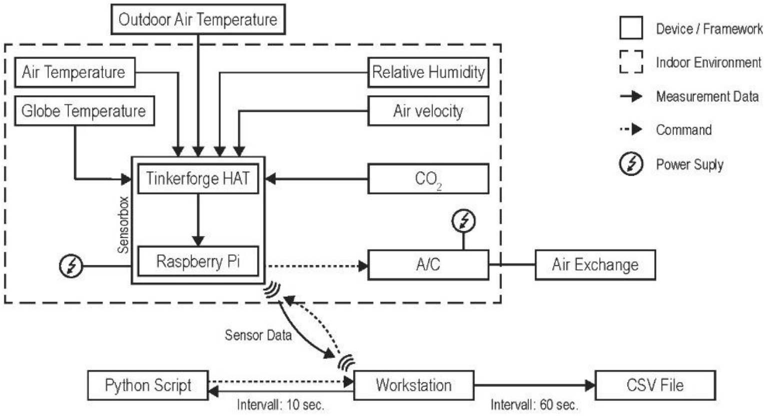

Figure 2 – Methodology scheme as designed for environmental control and data collection.

To regulate the indoor environment of office or laboratory spaces, a Sensorbox was designed and constructed. The Sensorbox connects to the necessary HVAC systems (in this thesis, only air conditioners were used to control the indoor climate) and environmental sensors. These sensors form a feedback loop with a workstation to monitor and adjust the indoor climate based on the preferred temperature setpoint which is continuously recorded in a CSV file.

1.4 Thesis Outline

Figure 3 visualizes the overall thesis outline as a continuous feedback loop of knowledge input to feedback knowledge for further research beyond this thesis work and scope.

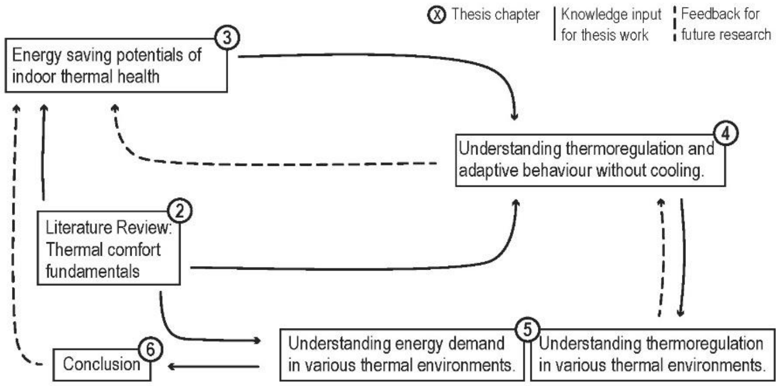

Figure 3 – Thesis outline as a continuous feedback loop.

Chapter One (not depicted in Figure 3) outlines the thesis by detailing its scope and aim, introducing the overall methodology and underlying framework. It concludes by discussing the thesis's impact and future relevance and summarizing its limitations.

Chapter Two summarizes the fundamentals and history of thermal comfort research and how it's currently quantified and evaluated before laying out the limitations and biases that more recent literature has concluded. The chapter then introduces new methodologies for quantifying thermoregulation, specifically in non-steady and non-uniform environments, and presents recent findings on the dependencies and independencies of the temporal and spatial nature of thermoregulation and human heat balance. This chapter is seen as a condensed overview and knowledge summary of the fundamentals underlying this thesis work.

Chapter Three emphasizes the urgent need to justify energy consumption, especially non-renewable sources, due to climate change and extreme weather conditions. In a simplified simulation, the chapter compares mechanically cooled office spaces with low-energy strategies, like fan ventilation, highlighting the significant energy savings, while still complying with standards (RQ1). The chapter concludes that embracing thermal fluctuations and adaptive comfort strategies in building design could potentially enhance thermal health and wellbeing while reducing energy use and mitigating the climate impact.

To understand the potential of reducing mechanical cooling, two experiments were conducted that evaluated the impact of various thermal environments and conditioning profiles on individual human thermoregulation and adaptation. These two experiments and their conclusion are presented in chapters Four and Five.

Chapter Four presents a field study exploring individual and temporal differences in thermoregulation and adaptive behavior in a naturally ventilated office (RQ2). Over six weeks, nine participants were observed, generating extensive data that revealed significant deviations from standard assumptions about clothing insulation and notable sex differences in physiological responses to temperature variations. The findings emphasize the complex relationship between air temperature and thermoregulatory responses, advocating for the development of more sustainable indoor climate regulations based on objective thermoregulatory boundaries.

Chapter Five introduces the concept of *Dynamic Cooling* through a measurement (RQ3) and simulation (RQ4) study, that adjusted cooling temperatures in office environments according to the average human circadian rhythm to reduce energy demand while minimizing heat stress. The study compared dynamic cooling, constant cooling, and no cooling, finding that dynamic cooling did not significantly impact core body temperature changes but increased temperature fluctuation throughout the day. Simulation results indicated that dynamic cooling could reduce energy demand while highlighting the complex trade-offs between thermal comfort and energy savings, suggesting a need for further research into hybrid cooling strategies and their real-world applications.

Chapter Six summarizes the main takeaways and discussions of the thesis, highlighting how these insights can inform and be applied in future research and practice and offers an adaptation to the current comfort standards.

1.5 Impacts

Developing new thermal comfort standards following the idea of thermoregulatory sufficiency does not rely on technological solutions but involves policies and daily practices that trigger behavioral change – in design culture, industry priorities, and how buildings are used and inhabited. As the IPCC report makes clear, significant upskilling is needed in the building industry this decade to create professional pathways for designers, engineers, policymakers, and industrial supply chains that can adapt to these changing demands. This thesis shifts the research focus of thermal comfort toward objective evaluations of thermoregulatory and behavioral adaptation and investigates the concept of a dynamic cooling pattern as a viable and low-cost sufficiency strategy for decarbonizing HVAC systems. The presented research methodology is broadly applicable and can impact architecture, engineering, and policy research cultures for existing buildings that are mechanically ventilated and grappling with a need to decarbonize operational energy without impacting comfort, well-being, and productivity.

1.6 Limitations

- Scope: This thesis does not aim to draw conclusions on how environmental conditions impact cardiovascular health, thermal comfort perception, and acceptance, or cognitive performance but rather use them as objective indicators for thermal comfort and thermal well-being.
- Dataset: The experiments conducted as part of the thesis consist of small and imbalanced datasets, particularly in the limited number of female participants, missing variation in age and BMI, and short observation periods confined to Munich's summer climate, which hinders generalizability.
- Environmental Variability: The measurement study protocol and analysis do not provide a comprehensive understanding of heat loss dynamics and overall thermal balance of the participant and need further validation through comprehensive studies using standardized protocols.
- Simulation: Simulations involved theoretical calculations that did not fully consider behavioral adaptation and human thermoregulatory processes.

Chapter Two

2. Fundamentals

As mammals, humans are homeotherms, meaning we must regulate our core body temperature around 37°C [31]. A deviation of just a few degrees can pose serious health risks or be life-threatening. We also regulate energy expenditure through physiological mechanisms and behavioral changes. This evolutionary adaptation allows humans to survive and work in environments with temperatures that differ significantly from what our bodies require. This necessity for minimal variation in body temperature also provides valuable insights into human comfort, health, stress, and productivity [32].
The limits of these self-regulating processes and our ability to adapt to different environments are primarily defined by the human body's ability to transfer heat. According to the second law of thermodynamics, the human body constantly exchanges heat with its surroundings, moving from a source of higher heat to a source of lower heat. There are two main ways this energy transfer occurs: sensible heat transfer and latent heat transfer. Sensible heat transfer is driven by the temperature difference between the body and its surroundings. It includes three processes: conduction, convection, and radiation. Latent heat transfer involves the energy required to change the phase of a substance, such as from liquid to gas (evaporation) or from gas to liquid (condensation) [33]. The exchange of heat between the human body and its environment involves a complex interplay of these mechanisms. These thermodynamic processes occur simultaneously, but the impact of each on our body is determined by environmental conditions. For example, latent heat transfer becomes particularly significant at surrounding temperatures close to or above core body temperature [34]. These interactions collectively determine whether there is a net gain or loss of heat, influencing the body's thermal balance. Ken Parsons conceptualizes this relationship through the concept of heat storage (S), where a positive value ($S > 0$) indicates a net heat gain and a negative value ($S < 0$) indicates a net heat loss [33].

2.1 Quantifying and Evaluating Thermal Comfort

The study of thermal comfort in indoor environments has evolved significantly over time, driven by the complex interactions between various environmental factors – meaning various physical attributes of the (indoor) environment – and human physiological responses. This section explores the historical context, key indices, and methodological foundations that have shaped our understanding of thermal comfort today.

The investigation into indoor environments and thermal comfort gained momentum during the Industrial Revolution, primarily due to health-related concerns in factories. Early pioneers such as Leslie (1804), Heberden (1826), and Aitken (1887) conducted foundational studies on parameters like air velocity, cooling rates of water, and the relationship between radiant temperature and air movement [33], laying the groundwork for subsequent research on thermal comfort. In 1848, in response to the cholera epidemic, the General Board of Health

Commissioners in Britain initially set guidelines for indoor environments based on subjective responses [35]. In parallel, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), formerly ASHVE, initiated laboratory studies to establish guidelines for comfortable indoor environments. The Effective Temperature (ET) index, developed in 1923 by Houghton and Yagloglou, was one of the earliest conceptual indices used to define comfort ranges based on variations in dry bulb temperature, radiant temperature, humidity, and air movement [36]. Subsequent studies by researchers like Rohles and Nevins led to refinements in the ET index [33]. Adaptations such as the Corrected Effective Temperature (CET) incorporated advancements in measurement techniques, particularly the use of black globe thermometers to account for radiation effects more accurately [33]. The Resultant Temperature was introduced by Missenard and adapted by the Institute of Building Services Engineers (CIBSE), focusing on the combined effect of air and radiant temperatures. Innovations such as the New Effective Temperature (ET*) and Standard Effective Temperature (SET*), proposed by Gagge et al., integrated physiological factors such as skin wettedness, mean skin temperature, and thermal heat loss [33]. These indices evolved into comprehensive models recognized by ASHRAE 55 [37] and ISO 7730 [38] standards. In the early 1930s, Thomas Bedford conducted a comprehensive field study assessing the thermal comfort of workers in industrial settings across various winter months in the UK [39]. His study involved measuring several environmental parameters and correlating them with subjective human feedback gathered through interviews. The parameters measured included air temperature (Ta) using a mercury glass thermometer, water vapor pressure (f), assessed with a sling hygrometer, mean radiant temperature (Tw) derived from air and wall temperatures, and air velocity (v) measured using a silvered kata thermometer. The culmination of Bedford's study was the development of the Bedford scale, which quantifies thermal comfort based on environmental parameters [40]. It assigns numerical values (from 1 to 7) to different levels of comfort and discomfort experienced by individuals: From much too cool (1) to much too warm (7), with comfortable (4) as the neutral midpoint. The scale suggests that deviations from a narrow range of thermal balance between the human body and its environment reflect varying degrees of discomfort [41].

Human responses to environmental stimuli often follow a coherent relationship. Increased exposure to light or noise typically results in a corresponding positive or negative reaction. For example, an increasingly louder environment generally leads to increasing discomfort, as well as lower light levels will also lead to more dissatisfaction. However, this direct stimulus-response relationship does not apply to temperature. Instead, temperature changes lead to an inverted U-curve in comfort levels as seen in the Bedford Scale. Moderate thermal environments are generally comfortable, but extreme cold or heat causes discomfort [42]. Bedford's longitudinal study highlighted individual differences in subjective comfort perception. Despite these variations, Bedford identified certain trends in environmental conditions as beneficial to comfort. Interestingly, his findings suggested that radiant temperature and globe temperature had minimal perceptible effects compared to simple air temperature. Similarly, changes in humidity showed little noticeable impact on comfort perception among study participants, as long as relative humidity was within normal limits [40]. It should be noted that the combination of excessively high humidity and heat, an increasing weather phenomenon, and climate shift due to global warming was most likely not experienced in Bedford's work. Bedford's scale was foundational in thermal comfort research, providing a framework for understanding the relationship between environmental factors and human comfort. It paved the way for subsequent studies and indices by Fanger aimed at quantifying and predicting thermal comfort. Povl Ole Fanger, a pioneering figure in thermal comfort research, outlined six fundamental parameters that define the thermal environment for humans. In his 1970 thesis "Thermal Comfort," Fanger identified air temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation as key factors that collectively regulate human comfort perception [43]. Early studies often overlooked the influence of radiation by using whirling thermometers to measure air temperature, which increased air movement and inadvertently equalized radiation with additional convection. Modern studies employ more sophisticated temperature measurement tools such as small thermocouples or thermistors in dataloggers. These instruments are less susceptible to radiation due to their size and shielding [39]. Radiant temperature is more challenging to measure accurately and varies significantly based on the location and direction of the sensor within the environment. Many studies approximate the Mean Radiant Temperature (MRT) as an indicator of radiant heat. However, there is no standardized definition of MRT, leading to varying interpretations [39]. Ole Fanger defined MRT as *'the radiant exchange experienced by a human-shaped body centred at the point of question'* [39]. Calculating MRT involves considering Ta, Tr, and the globe temperature (Tg), which introduces even more potential errors due to differing precision in these three measurements. An alternative approach involves infrared camera imaging to map radiant surfaces, providing insights into radiant asymmetry but requiring complex analysis and expensive equipment [39]. Globe Temperature (Tg), introduced by Vernon in 1930, measures the temperature at the core of a black-painted sphere, with a 150 mm diameter, mimicking the combined effects of air and radiant temperatures on the human body [33]. Despite debates over the best size for globe thermometers, Tg has gained popularity in comfort studies due to its standardized measurement approach [39]. There are more recent approaches that suggest calculations to adjust for non-standardized globe diameter sizes, like the pythermalcomfort library, i.e., by following the mixed convection developed by Teitelbaum E. et al., which lets you define the emissivity and diameter of the globe and also regards the measured air velocity [44].

Besides the environmental factors, Fanger included two human variables in his thermal comfort equation, metabolic rate and clothing insulation. The concept of metabolic rate measurement was first introduced by Gagge in 1941, defining 1 MET (Metabolic Equivalent) as the rate of heat production equivalent to a sitting person engaged in light work, equating to approximately 58.15 Watts per square meter of skin surface [45]. The use of a "standard person" in metabolic rate calculations can introduce significant errors when applied to diverse populations. Standards such as EN ISO 8996 [46] and EN ISO 7730 [38] acknowledge these limitations, allowing for error margins when estimating MET values or drawing conclusions about thermal comfort for individuals who do not fit the standard profile. The clothing factor influences human thermal comfort by impacting the insulation of our body against environmental conditions. Measuring its effect in real-time scenarios presents challenges like those encountered with estimating metabolic rate, often relying on assumptions or survey feedback. McCullough et al. (1985) pioneered the categorization of clothing types and their corresponding insulative values [39], establishing an extensive list that later became the basis for ISO Standard 9920 [47]. This standard quantifies combined insulation in clo units, where 1 clo equals 0.155 $m^2 \cdot K/W$ of thermal resistance [48]. Despite its utility, Goldman (2009) identified the use of clo in thermal comfort calculations faces several challenges [49]:

- Non-Uniformity and Cultural Influence: Clothing choice is influenced by climatic conditions and cultural norms. Factors like insulation, weight, and material composition interact to determine clothing comfort. Fashion trends and cultural importance of clothing therefore significantly impacts both clothing choice and thermal adaptation possibilities.
- Long-Term Adaptation: Changes in clothing are often constrained by social norms and logistical considerations. For instance, altering attire in workplace settings may not always be feasible due to social expectations or a lack of alternative garments. Consequently, adaptations in clothing often reflect longer-term (daily or weekly) adjustments rather than immediate responses to thermal fluctuations.
- Abstraction and Accuracy: The clo-value guideline, while standardized, may not fully account for diverse clothing types beyond traditional Western work attire. Efforts to include non-Western items have begun but are limited by the complexities of fashion trends and rapid changes in clothing styles. Loose clothing for warm weather, specialized textile properties, and heavy-duty outfits exceeding 1.5 clo pose additional challenges to accurate thermal comfort assessments.

Fanger's work aimed to establish a rational relationship between the thermal environment and human comfort perception. He defined comfort as the steady balance of thermal load (L), which represents the difference between internal heat production and heat loss to the environment. This balance is critical for maintaining comfort values of mean skin temperature and sweat secretion at the actual activity level [43]. To assess this thermal equilibrium through a predictive model, Fanger introduced the Predicted Mean Vote (PMV) index and Predicted Percentage of Dissatisfied (PPD). The Predicted Mean Vote (PMV) index quantifies thermal comfort on a numerical scale, analogous to the Bedford scale, assigning a numerical value to predicted thermal sensation based on the formula's output, ranging from +3 (hot) to -3 (cold), with 0 indicating thermal neutrality. This scale categorizes thermal sensation to correspond to subjective perceptions of comfort. In addition to the PMV, Fanger introduced the Predicted Percentage of Dissatisfied (PPD), which quantifies the proportion of occupants likely to feel dissatisfied with the thermal environment [45]. The PPD formula translates PMV scores into a percentage, indicating the likelihood of dissatisfaction among occupants. Fanger's PMV/PPD model has become a cornerstone in thermal comfort research and building standards worldwide. It provides a quantitative basis for evaluating and designing indoor environments that aim to maintain optimal comfort conditions.

In the 1990s, the adaptive theory of thermal comfort, pioneered by Michael Humphreys and Fergus Nicol, represents a paradigm shift from static comfort models like the PMV and Bedford scale to understanding comfort as a dynamic process influenced by environmental conditions and human adaptation. Michael Humphreys and Fergus Nicol's field studies challenged the notion of a single optimal thermal environment for human thermal comfort. Their research, which began in the early 1970s, revealed several key findings that reshaped the understanding of thermal comfort. They observed that people's preferred indoor comfort temperatures varied significantly across different geographic locations worldwide. This variability suggested that comfort is not universally defined but rather influenced by local climate and cultural factors. Humphreys and Nicol hypothesized and later demonstrated a strong correlation between outdoor and indoor comfort temperatures. They found that people preferred indoor temperatures that adapted to the prevailing outdoor climate conditions. [40]

This adaptiveness in neutral temperature according to the outdoor temperature has also been confirmed by 6330 thermal comfort study responses in India, analyzed by Manu et al. [50], in which the authors conclude differences in the adaptive model according to the mode of operation differentiating naturally ventilated, mixed mode, and mechanically ventilated office buildings.

To better quantify the relationship between indoor and outdoor temperatures, Nicol and Raja (1997) and Nicol and McCartney (2002) introduced the concept of an exponentially weighted running mean temperature (Trm) [50]. This method provided a more accurate representation of the outdoor climate's influence on indoor comfort, by weighing the temperature by time discrepancy to the present. ASHRAE 55 recommends a calculated timeframe between 7 - 30 days [50]. Both ASHRAE 55-2004 and EN 16798-1 [51] specifically address adaptive comfort in naturally ventilated or free-running buildings, with no mechanical cooling, though it should be noted that the underlying studies and datasets are not the same and the standards therefore show slight differences in their classification and thresholds. The ASHRAE database contains about 21,000 questionnaires conducted and analyzed by Brager and de Dear [52] primarily in office buildings in Thailand, Indonesia, Singapore, Pakistan, Greece, the UK, USA, Canada, and Australia [53]. The adaptive model used in DIN 16798-1, which replaced EN 15251, is based on a yearlong data collection by Nicol and Humphreys [54] which involved 26 buildings in Europe, specifically France, Greece, Portugal, Sweden, and the UK [55]. Furthermore, DIN 16798-1 extends adaptive comfort considerations to mixed-mode ventilated buildings, reflecting broader applications of the adaptive model, as long as natural ventilation is given.

The adaptive comfort principle in both cases suggests that individuals in discomforting environments will adapt over time. This human adaptation plays a crucial role in thermal comfort perception. Richard de Dear and Gail S. Brager categorize human adaptation into three key pillars: behavioral, physiological, and psychological adjustments to thermal environments [52].

Behavioral adaptation encompasses conscious or unconscious adjustments at personal, technological, and cultural levels to achieve thermal comfort. Behavioral adaptation is considered highly effective in achieving thermal comfort as it allows individuals to actively respond to environmental changes. Nicol, Humphreys, and Roaf [40] identified four primary actions individuals can take to regulate thermal comfort:

1. Modifying Internal Heat Generation (Metabolic Rate): Adjusting activity levels to increase or decrease metabolic heat production.
2. Regulating Heat Loss (Clothing): Altering clothing insulation to retain or release heat.
3. Manipulating the Thermal Environment: Using technological devices like air conditioners (A/C) or heaters to modify indoor climate conditions.
4. Changing Environment (Location): Moving to different spaces or zones with varying thermal conditions.

Research indicates that occupants with control over their environment, such as the ability to open windows, tend to report higher thermal comfort satisfaction compared to those without such control [56]. Conversely, environments with automated systems (e.g., HVAC systems) may restrict adaptation opportunities, leading to lower tolerance for thermal variations [52].
Baker and Standeven (1996) [52] introduced the concept of adaptive opportunity, defining it as the range of possible adaptations within a given environment. This concept compared controlled conditions of climate chambers, where adaptations are limited, with field studies in environments offering extensive adaptational possibilities. For instance, while individuals may desire to adjust their environment behaviorally, such as by opening windows, the structure of a climate chamber may not allow for such actions. Conversely, in a field study setting with flexible controls over A/C, fan ventilation, or windows, adaptation behaviors may become habitual rather than solely responsive to thermal cues [57]. This approach could be integral to contemporary building standards and guidelines, that have so far mostly relied on climate chamber studies, to emphasize the importance of understanding user-controlled environmental management in optimizing thermal comfort.

Psychological adaptation, as defined by Richard de Dear and Gail Brager in 1998 [52], refers to alterations in perceived sensory experiences due to past experiences and expectations. While it is acknowledged that psychological factors influence thermal perception, comprehensive studies in this area are sparse, leaving the exact significance of thermal sensation somewhat ambiguous. McIntyre (1980) was among the first to explore how expectations and personality traits impact an individual's thermal response [52]. Paciuk delved deeper into the perception of expectation and control, distinguishing between available control (adaptive opportunity), describing the range of possible adaptations an individual can make in a given environment, exercised control (behavioral adjustment), which refers to actual behavioral adaptations undertaken by individuals, and perceived control (expectation), the expectation of control over one's thermal environment [52]. Research has shown that perceived control significantly affects thermal comfort in various contexts, such as comparing laboratory tests to field studies and contrasting naturally ventilated buildings with air-conditioned ones. Environments where individuals have less personal control tend to foster higher expectations for thermal homogeneity, thereby increasing sensitivity to temperature variations [52]. A study by Candido et al. [58] was able to show that activity-based working spaces – meaning offices that offer the ability to get up and move – correlate with ratings for thermal comfort even when the environmental conditions remain the same. Humphreys summarized some key principles in his adaptive theory to enhance human comfort [56]:

1. Predictability: Occupants should have a clear understanding of what to expect from their environment.
2. Normalcy: The environment should align with socially and climatically acceptable ranges.
3. Variety: Providing a range of usable options allows individuals to select preferred thermal conditions when possible.
4. Control: In fixed locations, ensuring adequate control over the thermal environment minimizes discomfort.
5. Avoidance of Sudden Changes: Gradual temperature changes are preferable to sudden shifts.

To address discrepancies between predicted and actual thermal comfort ratings, Fanger and Toftum (2002) [59] introduced the PMVe by incorporating an expectancy factor. This constant adjusts the PMV based on the level of expectancy individuals have regarding their thermal environment, ranging from low expectancy ($e = 0.5$) in buildings without air conditioning in warm climates to high expectancy ($e = 1$) in air-conditioned buildings in moderate climates [59]. This adjustment helps align predicted thermal comfort models with actual perceptions in diverse environmental settings. Schweiker and Wagner's Adaptive Thermal Heat Balance model (ATHB), informed by ASHRAE RP884, integrates behavioral, physiological, and psychological adaptations into a combined thermal comfort equation. This holistic approach acknowledges the multifaceted nature of human responses to thermal environments, enhancing the accuracy of comfort predictions across different building types and climates [60].

Besides behavioral and psychological adaptation, physiological adaptation has become an interest in thermal comfort research over the last decades. Physiological adaptation describes the gradual reduction of strain induced by environmental stressors like temperature through physiological responses over time [61]. So far literature recognizes two main forms of adaptation: genetic adaptation (intergenerational) which describes evolutionary changes over generations and

acclimatization (within a lifetime) which describes short-term adjustments within an individual's lifetime. Early comprehensive data on acclimatization were collected by Humphreys and Nicol in the 1970s, highlighting its importance in understanding human responses to thermal stressors. [52]
Acclimatization primarily occurs through physiological changes in systems like cardiovascular and endocrine responses [62]. The human body dynamically maintains thermal equilibrium through complex mechanisms: metabolic heat production where cells produce heat via metabolism, heat exchange facilitated by conduction, convection, and evaporation between the body and its environment [33], vascular response with vasoconstriction and vasodilation adjusting blood flow to regulate heat exchange, and sweating and shivering where sweat production increases evaporative heat loss while shivering generates internal heat through muscle movement [62]. Quantifying these responses can give us a better understanding of the body's thermal strains and its capability of mitigating such in any given environment and over time.

As research into thermal comfort advances and our understanding of the myriad parameters influencing human perception grows, quantifying comfort in its dynamic nature has become increasingly complex. Dean Hawkes argues that comfort should be viewed as a multifaceted phenomenon rather than reduced to a single numeric value derived from environmental parameters [63]. Historically, comfort assessment has heavily relied on methodologies that solicit subjective feedback. Standards like ASHRAE 55 define thermal comfort as “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluations” [37]. This approach utilizes occupant voting systems that directly correlate subjective feedback with comfort perception. However, these numerical values derived from subjective feedback are subject to biases and often lack the temporal precision and data resolution required to establish correlations between individual parameters [61], as discussed in the following.

2.2 Limitations in Quantifying Thermal Comfort

Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), introduced in 1984 and later standardized (ISO 7730), have become widely adopted despite criticisms of their accuracy [40]. Humphreys et al. [40] reference Doherty and Arens' study in 1988, which highlighted a temperature bias and sensitivity towards activity levels. The PMV performs most accurately for a resting, naked person at 28°C, but overestimates responses in hotter or colder temperatures, as well as showing poor performance at higher metabolic activity (MET) rates [40]. These findings were also verified by Parsons and Webb's empirical data collection. The findings of Humphreys et al. [40] further revealed significant discrepancies between the PMV with the Standard Effective Temperature (SET) index. Cheung et al. [64] analyzed the accuracy of PMV and PPD using the ASHRAE Global Thermal Comfort Database II and found that the PMV accurately predicted thermal sensation only 34% of the time compared to observed mean vote (OMV) data [26]. PPD consistently overestimated dissatisfaction, with errors ranging from 15% to

25% even when assuming PMV accuracy. Variations in accuracy across different ventilation strategies, building types, and climate zones were also notable [64].
Griffiths (1990) introduced a preference question into the ASHRAE scale, allowing individuals to indicate their preferred thermal sensation alongside their perceived one [39]. Nicol et al. [39] noted that in Humphreys and Hancock's 2007 study, people often reported their perceived and preferred sensations aligned, even if outside the neutral comfort zone. Due to the inherent inaccuracies and biases associated with subjective feedback, recent studies have raised concerns about its reliability in comfort studies [61].
One major bias lies in the language barrier. Questionnaire design and interpretation can introduce biases due to language differences. Subjective feedback in thermal comfort studies can be significantly influenced by linguistic barriers, leading to errors in interpretation and confusion of meanings across different languages. Humphreys et al. [40] highlight a bimodal response pattern observed in the ASHRAE scale: while the term "warm" might imply comfort in everyday language, on the scale (+2), it denotes discomfort due to positive heat storage (thermal sensation). This discrepancy arises because respondents often judge based on their perception of the space's quality (value judgment) rather than the physical heat storage. Tochihara et al. (2012), as cited by Parsons [33], conducted a study using translated questionnaires in different languages, revealing significant variations in how thermal conditions were described. For instance, Indonesian respondents described thermal neutrality using the translation for "cool," while Japanese respondents ranged between "warm" and "cool," and English speakers tended towards "slightly warm" [33].

Another major uncertainty lies in scale asymmetry, as biases can arise from the distance and symmetry of voting scales used in comfort assessments. Schweiker et al. [65] argue that common feedback questionnaires are inherently biased due to asymmetrical scaling assumptions. They critique the assumption that equal intervals exist between consecutive scale values, implying equal perceptual distances between each pair. However, research by Fuchs et al. (2018) and Al-Kathri and Ghadi (2019), cited by Schweiker et al. [65], demonstrated through latent class regression that thermal perception categories exhibit irregular widths and central category shifts along the thermal continuum. This challenges the linear regression analysis often used to assume equidistant scale values. The belief in symmetry is also questioned in the context of PMV and PPD equations, which suggest that "neutral" on the scale corresponds to absolute comfort with the lowest dissatisfaction rate (~5%). Schweiker et al. refute this, citing Meyer (1998), who presented a PMV-PPD curve showing the lowest possible PPD of 15% between neutral and slightly warm. This finding was further supported by studies of different climate zones showing similar shifts in perception along the scale. [65]

That individuals may not always be fully aware of their thermal preferences or able to communicate them accurately (psychological consciousness bias) is also seen as another significant measurement error in comfort studies, particularly in laboratory settings. This bias occurs when participants alter their responses to align with the study's goals, often subconsciously, if they perceive it as socially desirable or preferable [66]. Jung & Jazizadeh [67] further illustrated a psychological bias with data showing the same individual experiencing differing thermal sensations under identical conditions across two consecutive months. They attribute this inconsistency to several factors: 1. Existing scales may not adequately capture nuanced thermal perceptions, 2. Occupants' understanding of thermal comfort can vary widely. 3. Failure to account for contextual factors, such as variations in clothing insulation or other physiological and psychological factors, and 4. Inaccurate quantification of indoor conditions, i.e. spatial variations in temperature distribution within a space [67].

These biases and challenges underscore the complexities and limitations of relying solely on subjective verbal feedback in comfort studies, necessitating alternative approaches for more accurate assessments.

2.3 Quantifying and Evaluating Thermoregulation

More recent advancements in technology, as well as newer medical insights, have shifted its view to quantify more objective biological signals [61]. Biological signals can serve as effective tools for measuring dynamic biological activities within the human body. They can be broadly categorized into two types: physical signals and physiological signals [68]. Physical signals involve observable physical changes in the body due to muscle movements, such as eye movement, pupil size, respiration, vocalizations, and facial expressions. However, data from physical signals can be prone to errors due to partially conscious control or intentional acting, making them more difficult to interpret objectively [68]. Physiological signals represent vital bodily functions that occur subconsciously, including cardiac activity, exocrine activity, brain function, and muscle excitability. These signals are crucial for indicating changes in the body's state and are used extensively to detect stress responses [67]. The quantifying of thermoregulation offers an alternative to the quantifying of thermal comfort by addressing the boundaries of acceptable discomfort or, more precisely, stress. This challenges the current approach of achieving thermal neutrality to understanding the limits of human adaptation through thermoregulation in environments of discomfort.

Stress is a multifaceted phenomenon without a universally accepted scientific definition, as it varies across professions and perspectives [68]. From an evolutionary standpoint, Cannon describes stress as the organism's response to a threatening situation, triggering a fight-or-flight response. This physiological perspective was expanded by Selye, who conceptualized stress as a General Adaptation Syndrome (GAS), involving stages of alarm, resistance, and exhaustion in response to environmental stressors [68]. Stressors can be external (exogenous) or internal (endogenous) stimuli that provoke a stress response. However, there is considerable inter- and intra-individual variability in the response to stressors, indicating the influence of cognitive evaluations [68]. Lazarus [69] introduced the concept of primary and secondary appraisals: primary appraisal assesses the personal significance of a situation, distinguishing between irrelevant and stressful conditions, while secondary appraisal evaluates coping options and available resources. This cognitive evaluation shapes individual perceptions of stress as either positive (eustress) or negative (distress), significantly impacting productivity and well-being [70]. Neurologically, stress triggers increased sympathetic nervous system activity, resulting in the release of stress hormones, elevated heart rate, and heightened cardiac contractions. Eustress reflects the body's successful adaptation to stress, returning to a reduced level of activity afterward, whereas distress occurs when the body cannot recover from prolonged sympathetic dominance [70].

While quantifying thermal comfort remains challenging due to its abstract nature involving multiple parameters, measuring and comparing autonomic nervous system (ANS) responses to environmental stressors through multimodal physiological data analysis offers a tangible approach. This methodological shift from subjective comfort assessment to objective biosignal measurement underscores the potential for advancing comfort research with more reliable and detailed insights. The most common physiological stressors used in current thermal comfort research and within this thesis work are identified in the following.

The electrocardiographic (ECG) signal has been a foundational biosignal in well-being studies due to its robustness and amplitude close to 1 millivolt (mV) [71]. An ECG records the cardiac cycles, illustrating the ionic potential changes in the heart through electrodes typically placed on the chest, hands, or legs. Each cardiac cycle consists of three main signal waves: the P-wave, QRS complex, and T-wave, which reflect the depolarization and repolarization activities of the heart's atrial and ventricular cells. These signals provide insights into the heart's rhythmic activity and can be used to derive both heart rate (HR) and heart rate variability (HRV) [61].

Heart rate (HR) is the simplest measurement obtained from ECG recordings, calculated as the number of QRS complexes per minute (BPM). The heart rate's intrinsic rhythm is governed by the sinus node but can vary due to influences from the sympathetic and parasympathetic nervous systems, as well as hormonal and reflexive factors. A typical resting heart rate ranges between 60 to 80 BPM, although variations are significant among individuals [70]. **Heart rate variability (HRV)** provides a more detailed assessment by measuring the variation in consecutive heartbeat intervals, specifically the R-R intervals on the ECG. These variations in interval length are influenced by the autonomic nervous system (ANS), which regulates cardiovascular functions through baroreceptors and chemoreceptors to maintain homeostasis. Short intervals indicate periods of stress, while longer intervals suggest calmness [70].

A more sophisticated approach involves analyzing the frequency components of the ECG signal, distinguishing between **high-frequency (HF)** and **low-frequency (LF)** domains [67]. The LF domain primarily reflects sympathetic nerve activity responsible for thermoregulation, while the HF domain corresponds to parasympathetic control of heart rate, particularly influenced by respiratory rhythms. The ratio of LF to HF frequencies serves as an indicator of stress intensity, offering a nuanced perspective on autonomic nervous system dynamics [67]. Technological advancements have also introduced alternatives to traditional ECG measurements for stress detection, such as Seismocardiography (SCG) and Gyrocardiography (GCG). These methods offer more precise measurements in laboratory settings but have not yet supplanted ECG in field studies due to their practical applicability [72].

Electrodermal activity (EDA), also known as galvanic skin response (GSR), monitors changes in electrical conductivity due to sweat gland activity on the skin's surface. Sweat glands, primarily eccrine glands across most skin areas and apocrine glands in specific regions like the armpits and pubic areas, respond to stimuli including emotional arousal triggered by environmental influences [33]. Advancements in wearable technology have significantly increased the popularity of EDA measurements, which capture both tonic and phasic changes in sympathetic nervous system activity. Tonic changes, reflected in mean skin conductance levels (SCL), indicate overall arousal during resting periods and are measured in microsiemens (μS) [73]. Phasic changes, represented by skin conductance responses (SCRs), capture rapid fluctuations in response to stimuli, providing insights into momentary emotional and physiological responses [70]. EDA data can be analyzed through both time and frequency domains. The time domain method offers detailed temporal insights, while the frequency domain method, robust against confounding factors, correlates well with cognitive, physical, and orthostatic stress levels [73].
It should be noted, that long-term adaptation involves both physiological and behavioral regulatory mechanisms, which is why consequences of heat stress occur particularly where people are not adapted to heat [74]. During heat acclimatization, the thermoregulatory mechanisms are adapted, and physiological responses change. The load error for the onset of sweat activity as well as the salt content are reduced to make evaporation more efficient while avoiding excessive salt loss. This adjustment can take place within a few days and is therefore to be considered in the evaluation of studies on thermal perception and measurements of physiological values of sweat activity over several days. [75]

Core Temperature (Tc) of the human body is well-perfused and relatively uniform, maintaining a core temperature (Tc) around 37 ± 0.5 °C at rest [76]. Daily temperature variations can reach up to 0.5 °C among healthy individuals, influenced by factors like the menstrual cycle, food intake, and daily rhythms, with the lowest temperature typically at 4 a.m. and the highest at 6 p.m. Peripheral body parts are cooler than the core, affected by environmental conditions and vasoconstriction. The Tc reflects a balance between heat production and loss, with the body adjusting its metabolic rate to maintain this balance. The hypothalamus regulates Tc through mechanisms like metabolism, muscle tone, thyroid, and adrenal activity [76]. Accurate Tc measurements necessitate invasive methods for monitoring, involving the insertion of probes or implants. Despite its precision, this method can induce discomfort and stress in participants, affecting the reliability of comfort assessments [77]. Accurate temperature monitoring also depends on the measurement site, with the tympanic membrane, nasopharynx, esophagus, and pulmonary artery being preferred clinical sites [76].

Skin Temperature (Tsk) plays a crucial role in assessing thermal comfort as it reflects the body's thermal state and responses to environmental stimuli. Healthy individuals typically maintain Tc within a range of 1 K, while Tsk fluctuates more widely, ranging between 15°C to 42°C across various studies [61]. The skin, as the largest organ of the human body, is thereby responsible for roughly 90% of heat losses [76]. Non-invasive measurement techniques include Infrared Thermography (IRT), which captures body radiation, and thermocouples placed directly on the skin. These methods are preferred due to their comfort and suitability for long-term and continuous monitoring [78]. Calculating the exact mean skin temperature across the entire body surface is impractical. Instead representative points are selected, that best reflect the mean temperature of specific body areas [79]. Studies exploring local differences have observed temperature variations of up to 1.1 K between different facial regions, such as the forehead, chin, and cheeks [60]. The sympathetic activity of the autonomic nervous system (ANS) regulates Tsk in response to stressors. This includes vasoconstriction leading to decreased Tsk and thermogenesis for core temperature maintenance [78]. Research by Parkinson et al. [80] indicates a negative correlation between changes in Tsk and perceived thermal comfort in warm environments and a positive correlation in cold environments. This dynamic interaction highlights the role of skin temperature in regulating thermal pleasure, influenced by the rate of change in Tsk [80].
Newer literature suggests mean body temperature (MBT), the combined temperature feedback of the skin and core, to be a more accurate indicator of overall thermal status and comfort perception. The MBT is a calculated value following the formula of $\text{MBT} = a \cdot \text{Tc} + (1 - a) \cdot \text{Tsk}$, with a anywhere between 0.64 and 0.7 in neutral and 0.79-0.8 in hot environments [81]. Though this method seems valuable to the overall insight into the human body heat balance, the calculation of such is not yet standardized in ISO 9886 [82].

2.4 Thermal Health

Given that we currently spend over 90% of our time indoors [83], understanding indoor climates' impact on health is crucial. Early studies, like Griffiths' 1975 laboratory experiment, highlighted declines in social interaction linked to non-standard indoor temperatures, laying foundational insights into the impact of indoor climates on human behavior and comfort [33]. Recent advancements in thermal comfort studies leverage objective data collection through biosignals to not only assess immediate stress responses but also quantify the long-term health impacts of indoor environments. Studies now connect indoor temperature profiles to energy expenditure, brown fat activity, obesity, skeletal muscle metabolism, insulin sensitivity, blood pressure, cardiac output, and immune system function. Metabolic syndrome, encompassing obesity, type 2 diabetes, cardiovascular disease, and certain cancers, is particularly linked to prolonged exposure to thermal-neutral environments. [23]
Research indicates that both cold and mild warmth can positively impact metabolic health. Non-shivering thermogenesis (NST) increases energy expenditure without shivering, benefiting

metabolic rate. Studies by Yoneshiro, cited by Van Marken Lichtenbelt [23], show that exposure to temperatures between 14–16°C for lean adults increases energy metabolism, improves insulin sensitivity, and enhances cardiovascular stability. Such exposure can also boost NST capacity across various age and health groups. Despite these benefits, there's a global trend towards maintaining homogenous indoor temperatures year-round, potentially limiting the natural metabolic benefits associated with temperature variations [23]. Understanding individual thermal exposure profiles and history becomes essential for informed decisions regarding comfort, productivity, and health implications.

While this thesis does not propose insight into health benefits based on indoor thermal conditions or comfort, the developed methodology and outcomes could aid in linking the impact of thermal environments to human cardiovascular function and developing a more objective framework toward sufficient building operation standards.

2.5 Dynamic Thermoregulation

As exemplified, most comfort metrics and methods rely on steady-state conditions when assessing the influence of indoor environments on the predicted thermal comfort. Most thermal comfort research assumes that if the parameters used to calculate and predict thermal comfort are constant, the same thermal parameters will ignite the same comfort intensity and significance at any given moment throughout the day. Standards like DIN 16798-1, ASHRAE-55, ISO 7730, etc. therefore recommend limiting daily temperature ranges to 4°C [51] or 5°C [38], dependent on the running mean outdoor temperature according to the adaptive method. This global trend towards more uniform indoor environments and tighter control of the indoor environment has led to air conditioning becoming one of the fastest-growing HVAC systems worldwide, with a growing energy consumption rate of 4% yearly since 2000 [15]. One way of substantially minimizing this energy use is to allow for more thermal variation and adaptive behavior. As mechanical systems and their size are dictated by the thermal performance according to standards, they are often oversized to always ensure thermal comfort, even if the moments of thermal discomfort might only occur momentarily and seasonally. However, allowing for thermal variation wouldn't only cut energy use but could lead to higher thermal satisfaction and health [84]. While these narrow temperature ranges have often been able to show coherent comfort results in steady-state laboratory studies, they show a large discrepancy when transferred to real-world or dynamic environments both in thermal comfort perception, thermoregulation, and energy use. More recent literature has tied this discrepancy in comfort evaluation to not accounting for temporal information in the data acquisition, like thermal history [85] and time-of-day [86] as well as accounting for a performance gap caused by human adaptation behavior [87]. In other words, instead of an active building and passive users, we should encourage active users in an otherwise passive building. The less energy we put into the conditioning of a building (or if the amount of energy is not sufficient), the more energy our body has to utilize to compensate, following the orderly recruitment by physiological cost and adaptive behavior [88].

Research into thermal comfort has, therefore, evolved significantly from static models to dynamic approaches that account for the complex and varying nature of human thermal experiences throughout the day [64, 84, 89-92]. Various models focusing on dynamic thermal contexts have been proposed as cited by Zhang et al. (2004) [93]:

- Equivalent Homogenous Temperature (EHT): Introduced by Wyon et al. (1989), this model considers different upper and lower body segments in non-uniform environments.
- Haginos Model (1992): Uses a weighted average of local comfort perceptions across different body parts.
- Fiala's Regression Model (2002): Accounts for transient environments by measuring skin temperature, rate of change in skin temperature, and core temperature.
- Guan et al. Model (2003): Combines static skin temperature with dynamic heat gain rates.
- Zhang et al. Model (2004): Validates a model using mean skin temperature from multiple body parts to represent the overall thermal state in non-uniform and transient environments.

In another more recent discovery that underlined the importance of time in thermal comfort research Parkinson and de Dear proposed considering the affective component of thermal perception through alliesthesia [94]. Alliesthesia, a physiological phenomenon first described by Michel Cabanac in 1971, involves modifying conscious arousal in response to environmental stimuli [95]. It suggests that individuals seek pleasant stimuli and avoid unpleasant ones. Parkinson and de Dear identify two types: Temporal, which involves sequential changes in thermal environments influencing overall body perception, and spatial, which relates to local stimuli impacting comfort perception despite overall body thermal symmetry [96]. Understanding alliesthesia can potentially inform strategies that optimize both energy sufficiency and human comfort, adapting to dynamic environmental conditions throughout the day. But models or indexes are also needed that account for the dynamic nature of individuals' thermal boundaries and preferences in real-time. This approach involves understanding individual thermal profiles to tailor energy consumption more precisely. This can involve wider acceptable temperature variations within indoor environments while focusing energy expenditure on decentralized and localized heating and cooling solutions. Warthmann's research illustrates the efficacy of this approach. Reducing energy consumption should not compromise occupants' comfort, health, or productivity [60]. Research by Kolarik et al. demonstrates that temperature shifts beyond the standard comfort range can be accommodated without negatively impacting thermal perception, provided they occur gradually within acceptable rates [97].

Early research predominantly focused on long-term adaptive measures over months, overlooking the variations in adaptation occurring within minutes, hours, or even years. The concept of thermal endurance investigates how individuals adapt to and perceive thermal environments over varying time scales. Roaf's study in 1988 [98] examined vernacular architecture in Iran, highlighting how occupants move between different rooms throughout the day to select preferred thermal environments. This adaptive behavior underscores the importance of understanding both the temporal evolution of indoor thermal landscapes and the pathways individuals take through them over time, as noted in subsequent publications by Humphreys, Nicol, and Roaf [39]. Recent studies, such as the 2019 research by Ryu et al. [99], introduced new temporal dimensions to analyze discomfort and adaptation behaviors related to air conditioning use. Key temporal metrics include *Discomfort Capacity,* which measures the duration until an occupant expresses discomfort and subsequently adjusts behavior, calculated based on cumulative indoor air temperature and cooling base temperature per minute, and *Comfort Restoration,* which indicates the time required for an occupant to restore comfort after behavioral adaptation, reflecting a lag despite swift solutions. Findings suggest that the psychological adjustment to discomfort delays behavioral adaptation despite the availability of rapid comfort solutions. [99]

Next to behavioral adaptation, temporal delays are also observed in human thermoregulation. In a 2013 study, Liu et al. [100] evaluated the skin temperature and surface temperatures of garments under steady-state conditions as well as under ramps of rising and falling radiant temperatures. The study concluded that in all cases, the skin temperature change occurs with a longer temporal lag than the surface temperature change of the clothes. Also, it was found that quicker radiant temperature change rates caused the disparity between those two temporal delays to become more pronounced [100]. An experiment conducted in 2016 by Xiong, et al. [101] also demonstrated the significance of the heat exposure history. Subjects were exposed to three successive temperature step changes in a transient laboratory environment from a temperature increase of 5 K, 11 K, or 15 K to 37°C, followed by a decrease in temperature of the same magnitude. The experiment demonstrates that following a 15 K step-down in air temperature, there are significant temporal lags – more than 45 min – in the adjustment of skin temperature to reach a steady state. Most of the subjects' thermal satisfaction and perspiration were not equal during the same air temperature exposure when separated by a step-change and temperature exposure of 37°C for one hour between the two sessions, leading the authors to further suspect a psychological and physiological adaptation to the thermal conditions [101]. This temporal lag can also be seen in the comfort sensation as thermal alliesthesia, which offers the possibility of non-uniform surroundings through spatial divergence of local and mean skin temperature trends [80]. But while the sensation vote in large temperature steps in transient environments might also be due to a cold sensation overshoot in thermal sensation vote (TSV), temperature transitions of up to 8 K show large discrepancies between the psychological sensation and physiological thermoregulation [102]. Making it more evident that these differences between the comfort vote and thermoregulatory processes need further investigation.

While temporal variations in temperature exposure result in a temporal difference in thermoregulation, spatial variations in radiant temperature have been found to elicit spatial differences in skin temperature. A study by Kurazumi, et al. (2018) [103] found significant differences in the mean temperature of the skin when comparing the sun-facing side of the body and the shade-facing side of the body in outdoor environments. Furthermore, the authors concluded spatial differences in body areas depending on the posture and, therefore, exposure to direct short-wave radiation. [103] This was also evident in the 2022 indoor laboratory study by Yuyao, et al., which shows these spatial differences increasing with increasing distance from the radiation heat source [104]. The various body parts and regions, as well as between like body sections, can all exhibit these spatial variations in skin temperature even in steady-state conditions. These differences can be as large as a 12 K differential in skin temperature between different body parts under spatial cooling systems [105] and a 3 K differential between the hand using the computer mouse and the non-dominant hand during steady-state conditions [106]. The acceptability of vertical temperature gradients between the ankle (0.1 m) and the neck (1.1 m) have shown to be as high as 3 K, or 5 K under circumstances of personal control and in tropical climate zones with acclimatized subjects. Local and spatial cooling systems like face cooling were able to raise the acceptable indoor temperature range by 4.5°C in a 2007 study by Zhang and Zhao [107]. The effect of spatial variation on thermoregulation also offers insight into rephrasing thermal comfort standards, with more fundamental research needed.

In the realm of building operations and energy management, the focus has shifted from traditional comfort and productivity concerns to encompass broader issues such as energy consumption and long-term health impact. Standards like ASHRAE 55 and ISO 7730 have traditionally guided HVAC system development and operation, but current models often oversimplify and lead to an overestimation of thermal comfort in high temperatures, resulting in unnecessary homogeneous cooling of entire buildings [108]. This not only drives up energy consumption but also exacerbates ecological concerns related to greenhouse gas emissions. For instance, Germany's ambitious sustainability goals aim for greenhouse gas neutrality by 2045, necessitating significant reductions in emissions from the building sector [109].

Chapter Three

Abstract. Amid the climate change and the worldwide catastrophes, witnessed on a daily, we find ourselves in a time in which we need to start justifying any recourse and energy consumption, at least of which is not truly renewable. While the outside temperatures become more extreme, the inside environment becomes more relevant. The way we design and operate our buildings is directly influenced by current building standards and as we spend almost all our time indoors, our comfort, wellbeing and health are crucially affected by such. The last five decades have seen many approaches in establishing guidelines for a comfortable indoor environment. But while current standards favor the narrow temperature ranges of static homogeneous environments, they have been criticized for their high energy consumption and long-term health implications. This chapter compares a typical office space with mechanical cooling with that of a passive strategy, by evaluating the energy consumption and health over comfort. The results show a 64% cooling potential within the mechanically cooled scenario as well as the passive strategy complying to standard without any cooling energy.

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3. Mitigating Climate Change through Healthy Discomfort

3.1 Introduction

According to the German government, the building sector is one of the main emitters, accounting for 14% of the total CO_2 emissions in Germany. If emissions from the production of electricity and district heating as well as building materials are included, this figure doubles to 28%. On the other hand, the necessary reduction of greenhouse gas emission according to the Paris agreement assumes 66 - 67% until 2030, compared to the values of 1990. [110] An essential part of this target lies in the responsibility of the energetic building renovation and more concretely in the reduction of the mechanical cooling and heating energy. The required energy demand for indoor cooling is gradually rising at an average pace of 4%/year since 2000 and makes up roughly 16% of the total building sectors energy consumption worldwide. This has led to a doubling of the respective CO_2 emissions between 1990 and 2020. [15] With the advancing climate change and most recent predictions of a warming of 1.5°C in the next 20 years compared to 1990 [111], indoor cooling has become a focus of necessary adaptation [112-114]. Air conditioning, being one of the most common strategies of indoor cooling, is therefore expected to grow by 40% more units worldwide until 2030. [15] This trending development of mechanically regulating the indoor temperature poses real challenges to the energy sector and its necessary reduction of greenhouse gas emissions.

3.2 Problem Statement and Hypothesis

One, often-overlooked reason for the high energy consumption of Air Conditioners (A/C) is the usage according to the current building standards of indoor environments. The thermal indoor environment is evaluated by comfort and addressed by standards like the ASHRAE 55 [37] in the USA, the DIN EN 16798-1:2021-04 [51] in Germany, or the International Organization for Standardization (ISO) 7730 [38]. The standards thereby define the acceptable temperature range of indoor environments to meet the average comfort perception of users. Most standards accept temperature ranges between 2-9°C, depending on typology and season. While maintaining a relatively tight range of acceptable indoor temperature demands a relatively high energy consumption, accepting a wider range does the opposite. Besides saving resources when allowing for larger variation in indoor temperature, it might also benefit our health and wellbeing. Recent studies show a significant correlation between a uniform thermal exposure and cardiovascular diseases [115] as well as type 2 diabetes [116]. When evaluating the energy efficiency within the building sector we must therefore address the question why we are heating and cooling buildings as strictly as we do.

This chapter is made up of two parts. The first reviews how we evaluate indoor environments nowadays and briefly summarizes more recent findings towards the negative impacts of current standards on our health and wellbeing. The second part evaluates the potentials towards energy-efficiency and health when rethinking the current standards, with a simple simulation of five scenarios. The hypothesis of this chapter is that future climate mitigation can be achieved through (more) passive strategies that allow for wider temperature ranges within indoor environments, therefore reducing the energy demand and leading to healthier indoor environments.

3.3 Evaluating Comfort

Many human responses are coherently related to environmental stimuli, so that increasing exposure to light or noise, for example, elicits a similar positive or negative response. The louder the environment, the more unpleasant. The same is true for the lack of light in any given environment. This relationship between stimulus and response does not apply to temperature, where a linear increase in temperature leads to an inverted U-curve in comfort. [42] While a moderate thermal environment is considered comfortable by most people, the extremes of a cold or hot environment lead to dissatisfaction and, in the worst cases, extreme physical reactions like hypothermia or hyperthermia [117]. This sensitivity towards small variations in body temperature can offer insight into the state of human well-being, health, stress, and productivity [32].
It has long been known that weather can have a major impact on our behavior and psychological wellbeing. But more recent literature shows that this influence on humans, can be observed not only in outdoor weather, but also in indoor climate. [33] The fact that humans spend more than 90% of their time indoors [83] makes it essential to study the possibilities and limitations of thermoregulation and possible adaptation. Many indexes have been proposed to quantify and predict indoor thermal comfort. As the PMV/PPD and later the adaptive comfort theory have found their way into current standards, norms and recommendations, they will briefly be introduced in the following.
The Predicted Mean Vote (PMV) was first introduced by Ole Fanger in 1970, when evaluating data from field studies as well as laboratory studies done by himself [45]. He concluded the magnitude of discomfort as the function of the six parameters: Air temperature (Ta), Radiant temperature (Tr), Relative Humidity (rH), Air velocity (v), Clothing factor (clo) and metabolic rate (MET). With this Fanger went on predicting the thermal perception of hypothetical subjects in any evaluated environment on a scale from Hot +3 to Cold –3; 0 being without any discomfort. Furthermore, he constructed the Predicted Percentage Dissatisfied (PPD), as the relation between the mean vote and the people uncomfortable with the environment [43], as seen in Figure 4 [37].
The adaptive comfort theory was introduced in 1976 by Humphreys and Nicol explaining a shift of people's indoor comfort temperature preference according to the outside climate, allowing not only for seasonal shifts of preference within one location but also shedding light on differences dependent on climate zones. [118] The adaptive comfort, as used for passive buildings (buildings without mechanical cooling) by almost all standards nowadays, relates the comfort indoor temperature to the outdoor temperature by exponential averaging of the running mean outside temperature.

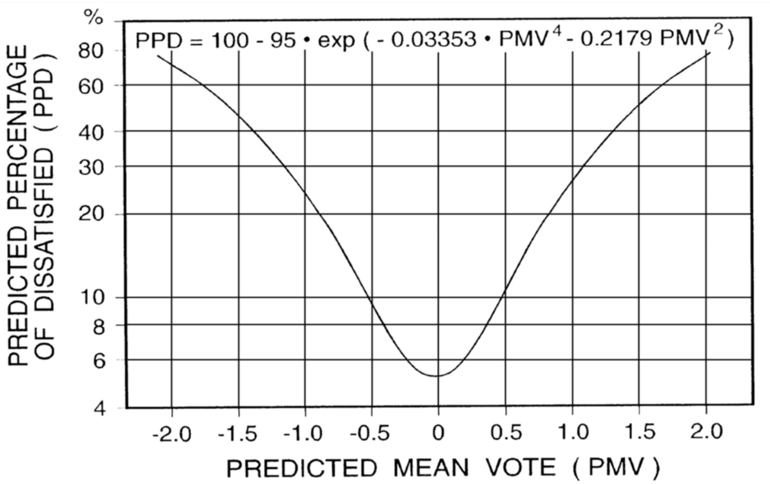

Figure 4 – PMV-PPD relation according to Fanger as seen in [37].

Standards like the DIN EN 16798-1 in Germany take both indexes into account when evaluating the indoor environment. While the acceptable indoor temperature range for passive buildings adjusts according to the outdoor temperature as established by the adaptive theory, the range for mechanically ventilated buildings is defined by four categories according to the PMV/PPD as seen in Figure 5. [51]

I	< 6	−0,2 < PMV < +0,2
II	< 10	−0,5 < PMV < +0,5
III	< 15	−0,7 < PMV < +0,7
IV	< 25	−1,0 < PMV < +1,0

Figure 5 – Acceptable PMV/PPD for indoor mechanically ventilated environments according to DIN EN 16798-1:2021-04. From left to right: Category, PPD and PMV [51].

Following the concept of the PMV/PPD the standard assesses an indoor environment close to PMV=0 as most desirable and therefore encourages narrow temperature variations, with the maximum indoor operative temperature to be ≤25.5°C (Category I), ≤26°C (Category II), ≤27°C (Category III), ≤28°C (Category IV) during the cooling period. [51]

Passive buildings (without mechanical cooling) are assessed only through the adaptive comfort theory by relating the indoor operative temperature to the moving average value of the outdoor air temperature. It thereby also differentiates between three categories (I,II,III) with varying temperature ranges (5°C, 7°C, 9°C), that are shifted asymmetrically as seen in Figure 6. While the assessment of passive buildings allows for overall wider temperature ranges, compared to that of active buildings, it also favors the tightest temperature ranges.

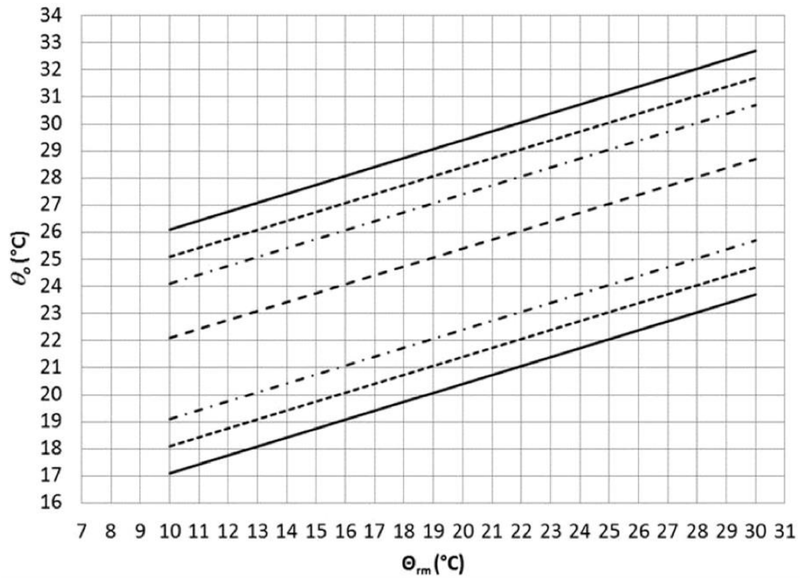

Figure 6 – Adaptive comfort range for passive indoor environments according to DIN 16798-1 with the X-axis describing the outdoor mean running temperature and the Y-axis describing the indoor operative temperature [51]. From outermost lines inwards: Category III, Category II, Category I and optimum indoor operative temperature.

3.4 Evaluating Health

When addressing the indoor thermal environment, standards as shown focus on the terminology of comfort and discomfort. Comfort thereby describes the feedback of how people feel within a certain static environment or as described by ASHRAE 55 [119] as "the condition of mind that expresses satisfaction with the (thermal) environment and is assessed by subjective evaluation." The underlying studies represent an individual's perception of a time and place, that are then scaled and averaged to fit all people's needs. This subjective feedback of a homogeneous sample, represent only a small percentage of the worldwide population with comparable preference. The PMV/PPD for example shows big variation in accuracy when comparing different ages [116], sex [120] or climate zones [121]. This is further critical as this narrow range is becoming even more homogeneous on a global scale and throughout seasonal weather shifts. [23] One reason may be the worldwide growing use of Air Conditioners that allow for consistent indoor environments independent from the outside. [28] Furthermore, there is strong evidence, that perceived thermal comfort has little to do with what are healthy conditions for the human body. Studies done by Yao, et al. (2007) conclude the subjective vote of the PMV to be correlated closely to the skin temperature and more specifically to single regions of the body. Therefore "the overall thermal comfort will closely follow the parts of the body that feel the most uncomfortable in a cool or warm environment." [122]

More recent technical advances enable literature to focus on analyzing stress. From a physiological standpoint stress can be defined as a reaction to various environmental stressors triggering alarm, resistance and exhaustion. Stressors are thereby defined as „exogenous or endogenous stimuli, events or conditions that are able to elicit the stress response. “ [68] All mammals contain biologic systems like the nervous system, cardiovascular system, musculoskeletal system, or the immune system, that are in constant communication with themselves or their environment through changes in electrical activity, pressure, chemical concentration, temperature and more. [61] The human peripheral nervous system consists of the somatic (conscious) and the autonomic (unconscious) system (ANS). During stressful periods the body utilizes more sympathetic activity, that derives from the ANS, produces stress hormones, increases the heartrate and forces an increase in heart contractions. While eustress describes the human body successfully coping with these reactions and returning to a decreased level of activity, distress, occurs in situations where the body can’t recover from this increase in neuroendocrine reaction and sympathetic dominance of the ANS function. [70] While it is nearly impossible to quantify thermal comfort as it is an abstract concept of various parameters, it is possible to objectively measure and compare the ANS responses to environmental stressors. [123] As stress is a measure of how much the body is working it can also indicate its long-term wear and tear effects on the persons health. [124] While the relation between stress and health has been ongoing research for many decades in the fields of medicine, neurology, physiology, psychology, etc. [125] it is more recently occurring within the building industry, which has led to new insight into the health implications of thermal environments.

Current studies show that the energy expenditure, brown fat activity and obesity, skeletal muscle metabolism, insulin sensitivity, blood pressure cardiac output and the immune system of humans are all linked to the influence of our individual temperature profile. Metabolic syndrome is thereby amongst the most researched and widespread health issue around the world. It accounts for obesity as well as type 2 diabetes, cardiovascular disease and certain types of cancer. [23] While a positive energy balance is necessary to counteract obesity, most recent research assumes that long exposure to thermal neutral environments, does the exact opposite. [23, 28, 126-128] Several studies were able to show that cold and warmth both effect the metabolic health and mild colds to positively increase the energy metabolism without shivering. This non-shivering thermogenesis (NST) increases energy expenditure in temperatures between 14-16°C for lightly clothed, lean adult, and in temperatures as high as 19°C and regular exposure for two hours per day for six weeks to 17°C, as shown in a study done by Yoneshiro, according to Lichtenbelt, et al. (2017) [23]. Not only did the temporary exposure to cold conclude a health benefit but an increasing capacity for NST in all age and health groups examined. The same temporary exposure profiles also demonstrated an increase in insulin sensitivity and improvement in cardiovascular stability. Even more surprising the studies showed not only the necessity of thermal fluctuation as a health benefit but a change in comfort perception as well. Van Marken Lichtenbelt, et al. (2017) state that “with respect to thermal (dis)comfort, it was shown that during the experiments involving 10 days of cold acclimation, thermal comfort changes from uncomfortable to just comfortable.” [23] Another study done by Ivanova, et al. (2021) was able to show higher energy expenditure and activity levels when the participants were exposed to a drifting temperature of +2.58°C/h in the morning and –2.58°C/h in the afternoon and overall range between 17–25°C, in alliance to the maximum fluctuation of ISO 7730. Within the study, the PMV vote drifts accordingly from slightly under -1 to slightly above +1 in the morning and from slightly above +1 to slightly under -1 in the afternoon, indicating little correlation between perceived comfort and health. The authors furthermore refer to similar result in increased energy expenditure in a study with a higher temperature range of 22-27°C. [128]

All studies to the knowledge of this research, conclude that a temporary exposure to heat and cold outside of the comfort zone (PMV= 0) can benefit our metabolic health, insulin sensitivity, cardiovascular and immune system, while trends in the last decade show an increasing homogeneity in indoor temperatures throughout the year. [23] While it’s crucial for the body to maintain a stable core temperature, literature suggests a constant indoor temperature to be counterproductive. Or in other words, while too much stress is not so good for our health, neither is too much comfort. As this seems to be closely related to the temporal dimension of thermal stress, the physiological reaction of the body depends highly on the time of exposure as well as the time of the day [123]. As the human body follows a circadian rhythm, it will tend to react more strongly to heat in the afternoon as it will in the morning. [123, 129, 130] Even though there is more research needed to understand the boundary conditions of such healthy temperature fluctuations, it is vital to address the accompanying standards. Kramer et al. (2016) were able to calculate a 63% reduction of a museum’s total energy demand with an increase of ±1°C temperature fluctuation compared to the current uniform conditioning. As this still complies to the ASHRAE standard it exemplifies the enormous saving potential of indoor conditioning. [131]

While comfort and wellbeing are often subject of evaluation, it may be more appropriate to evaluate the inflicted health implications. Considering the current necessity to sustainably minimize recourse consumption as well as the new gained knowledge of possible health implications by the strictly uniform climatization of the indoor environment, subjective comfort perception can no longer be justified as the main evaluation metric. Comfort has always been a luxury that we can no longer, and may have never been able to, afford.

3.5 Thermal and Energy Simulation

Rather than aiming for PMV= 0 (Category I), as shown in the standard DIN EN 16798-1, the accompanying simulation explores the possibility of focusing on the cooling energy saving potential within the absolute necessary comfort range (Category IV). Subject of the simulation is an office space with common usage boundary conditions defined in several European standards.
The simulation consists of five scenarios; the four categories of PMV/PPD as described in the standard (Figure 5), represented by actively cooling the operative room temperature to the respective upper temperature limits, and one passive scenario without any active cooling but elevated air speed (ceiling fan) instead.

The simulation uses the predicted weather data for Mannheim as the most extreme summer temperature scenario within Germany. The weather data, obtained from the German Weather Service (DWD, dt.: Deutscher Wetterdienst), is provided in form of a test reference year (TRY), representing averaged but typical meteorological conditions [132]. These can either reflect past measurements as well as climate forecasts of the year 2045, showing higher summer temperatures, due to the current and predicted climate change. As the simulation aims to analyze the limitations of the energy saving potential and thermal comfort range the most extreme weather situation was chosen. The simulation therefore depicts the week with the highest 24h-mean ambient temperature within the TRY2045 summer scenario.
The simulated office space is 6.5 m wide, 5 m deep and 2.75 m high. The south facing façade has a window-to-wall ratio of 60%. These geometrical assumptions are based on [133]. The heat capacity of the room's components are assumed according to DIN 4108-2 and DIN EN ISO 13786 as a "medium-weight construction". The insulation quality of the outside wall (U-value of 0.19 $W/(m^2*K)$) represents current German standards [134]. Assumptions regarding internal gains, such as people, equipment and light, as well as necessary air change rates and other usage-related inputs are based on Swiss standard SIA 2024:2015 and German standard DIN V 18599-10. Specific measures for all scenarios include external sun protection (radiation-controlled) and nighttime ventilation to reduce the operative temperature effectively during user absence.
The investigated office space represents a common building standard, incorporating already effective measures for reducing extreme heat stress in summer. The scenarios only distinction lies in the upper temperature limit according to DIN 16798-1. Scenarios 1 to 4 are limited to 25.5, 26, 27 and 28°C operative temperature respectively through active cooling. The passive scenario 5 does not provide any mechanical cooling.

3.6 Results

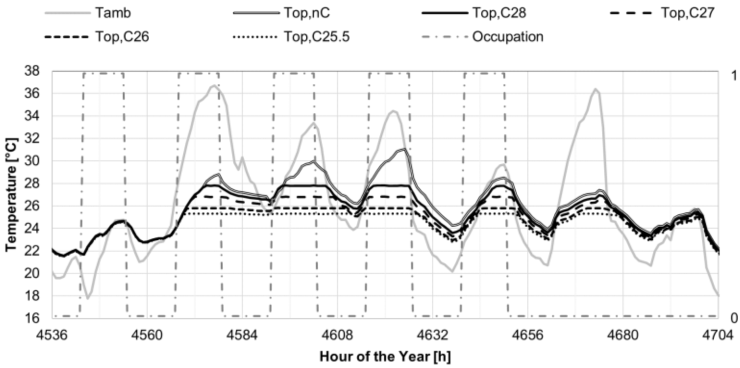

Figure 7 – Temperature Profile of the five scenarios for the warmest week of the TRY2045 data prediction.

Figure 7 depicts the temperature profile of the ambient outside temperature (Tamb) and the operative indoor temperature (Top) of the five scenarios as well as the occupation periods with 1 being occupied and 0 not occupied. Due to effective nighttime ventilation, external shading and decent thermal mass, even operative temperatures in scenario 5 stay below outside temperatures for most of the occupied time. The highest indoor temperatures and therefore also highest cooling loads occur after two nights of ambient nighttime temperatures never dropping below 24 °C (between hour 4584 and 4632).

Scenario 1 (C25.5)- Scenario 4 (C28) depict the necessary temperature cap through mechanical cooling according to the categories I-IV of DIN 16798-1 respectively. Scenario 5 (nC) doesn't use any mechanical cooling, with the Top ranging between 22-31°C (acceptable after Category II), with a maximum range of 5°C per occupation and day.

The temperature profiles manifest themselves in the cooling energy demand for the investigated summer week, as seen in Figure 8. An increased upper temperature limit can therefore reduce cooling demand within periods of extreme heat significantly. Limiting the allowed operative temperature to 28 instead of 25.5°C therefore reduces the energy demand by 64%, while still complying to the standards Category IV maximum operative indoor temperature. This suggested maximum temperature range within mechanically ventilated buildings, that are simulated as the scenarios, rely on the assumed PMV/PPD range as seen in Figure 5. The passive scenario also aligns to the necessary requirements utilizing no cooling energy at all.

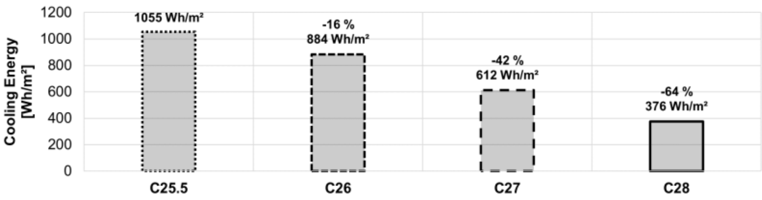

Figure 8 – Cooling energy demand of scenarios 1-4, with mechanical cooling.

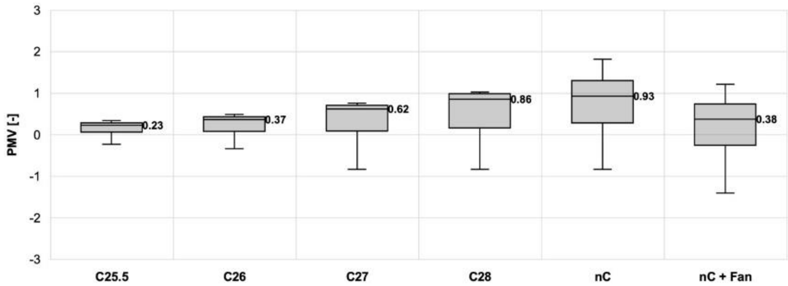

Figure 9 – PMV values of the scenarios 1-5 and scenario 5 (nC) + Ceiling Fan with v= 0.25 ms-1.

Figure 9 comprises the range of all hourly PMV values during occupation throughout the simulated week. Next to the five known scenarios, a sixth scenario (nC + Fan) depicts the PMV range of scenario 5, when equipped with a ceiling fan that provides 0.25 ms-1 elevated air speed (v) at all times of occupation. The boxplot indicates the PMV range by depicting the upper and lower quartile (boundary of the grey box), extremes (top and bottom horizontal line) and median value (shown also as number). While scenarios 1-4 show most values in the positive (warm) range of the PMV they seem to be fairly in line to the respective categories I – IV of the DIN 16798-1.
Even though the passive scenario 5 (nC) depicts rather high perceived discomfort, when including a light air breeze through a fan, into the PMV calculation, the median value shifts by -0.55 as seen in scenario 6 (nC + Fan). This comes to show that even though the Top of the scenario without mechanical cooling ranges beyond the acceptable ranges set for active buildings, the underlaying limits of PMV can still be complied with, even in the passive scenario. When introduced to even higher air speeds this range keeps shifting further to the negative spectrum of the PMV range, even though it should be noted that air speeds over 0.8 ms^{-1} start to become a problem within office environments, as these speeds can blow away loose paper.

While energy intensive adaptation like change of temperature is often used to assess the *right* thermal environment, this simulation raises the question if passive adaptation could be an equally successful way of climate mitigation. Even though the DIN 16798-1 offers a compensation of increased air temperatures through air velocity [51], this may also be relevant to other behavioral adaptions like change in clothing or accounting for the overall exposure time. While not surprising, the passive scenario 5 (nC) in Figure 7 shows that the highest temperatures occur at the end of the workday between 4 and 6 p.m., due to the accumulated solar gains throughout the day. While these temperatures might cause thermal stress to the body, it is important to assess this as not being a constant but rather a temporary exposure, shortly before the occupants leave the building. This aspect of exposure time must therefore be more closely evaluated, as mentioned in 3.4 Evaluating Health.

3.7 Conclusion / Further research

Current norms focus on the air and operative temperatures as the main indication of the thermal environments effect on human comfort and as a justification for a uniform steady environment to be a healthy and satisfying indoor environment, whilst accepting enormous energy consumptions. By contrast recent literature shows this goal of achieving a uniform optimum temperature to be counterproductive to our health and wellbeing. The simple simulation depicts the energy saving potential of an office room by allowing for passive temperature fluctuation and adaptation through air velocity, while still following the maximum acceptable range of standard and achieving similar PMV values. Following research by the authors will focus on recreating this as well as other passive adaptation strategies (i.e., clothing factor) in real laboratory experiments, to understand the thermal stress and overall physiological processes during different environmental conditions within similar PMV ranges.

Achieving energy efficient systems and at the same time embracing healthy environments by changing the operation of the buildings HVAC- systems provides a fast and cheap opportunity for climate mitigation in the building sector. It is vital to address the PMV/PPD and adaptive comfort theory as a momentary subjective response to a thermal environment that includes many biases and can't indicate healthy environments. More research is needed to understand the upper temperature exposure limit to an individual's health, considering the time of exposure as well as the age, sex and overall health conditions. Achieving better insight into the medical consequences of thermal exposure, can help us design solutions where we embrace thermal fluctuations of passive environments by having the indoor environment work with the human body instead of against it. Gaining more knowledge in the relation of individual physiological processes, adaptive behavior and our indoor environment is a crucial research foundation for the needed design solution of our time and that to come.

Chapter Four

Abstract. Thermal comfort research lacks continuous data collection on thermoregulation and adaptive behavior in real-world environments. This paper presents the findings of a field study that aimed at understanding the temporal and individual differences between humans' thermoregulation and adaptation within a dynamic thermal environment. The dataset contains a 6-week long summer field study of 2022 observing nine participants in a naturally ventilated office without a cooling system. The data collection comprises a total of 43 measurement days (22,776 data points at 60s frequency). The results indicate that the overall trend in clothing insulation deviates from standard assumptions (0.5 clo), especially above air temperatures of 26°C. The mean clothing insulation was 0.29 clo ±0.08, overall ranging from 0.20 - 0.73 clo. The data showed significant sex differences in tonic levels of electrodermal activity, the low-frequency to high-frequency heart rate variability ratio, and clothing insulation. Other heart rate variability data, like the root mean square of successive differences and beats per minute, as well as the distal skin temperature of the wrist, show significant sex differences and time-of-day variations in morning-to-afternoon comparisons. The findings indicate a nuanced relationship between air temperature and thermoregulatory responses, highlighting the need for future research with larger, more diverse participant cohorts and enhanced environmental monitoring to strengthen the validity and generalizability of the findings.

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4. Thermoregulatory Differences in Sex and Time-of-Day within Naturally Ventilated Office Environments

4.1 Problem statement

Naturally ventilated buildings that utilize passive cooling strategies are crucial in the need, also identified by the IPCC Climate Change Mitigation Report, to decarbonize the building sector [135]. On the contrary, the global trend is moving towards more uniform and tighter control of the indoor environment, as air conditioning has become one of the fastest-growing HVAC systems worldwide, with a growing energy consumption rate of 4%/yearly since 2000 [15]. One reason for this uniformity of indoor conditions is the thermal comfort standards that allow for limited flexibility in thermal variety, even in naturally ventilated buildings, in which narrow temperature thresholds are less easily achieved. Standardized thermal comfort indices or metrics (i.e. PMV/PPD or adaptive model) aim to maintain near-neutral indoor temperatures to minimize heat transfer and avoid physiological adaptation through thermoregulation, while still relying on steady-state conditions when assessing the influence of indoor environments on the predicted thermal comfort. In summer and for naturally ventilated offices, national and international standards like DIN 16798-1 [51], ISO 7730 [38], and ISO 17772-1 [136] recommend an optimal operative indoor temperature depending on the running outdoor mean air temperature, with a temperature range tolerance defined by categories I (5K range) II (7K range) and III (9K range). A study by Arens, et al [137] concluded little difference in thermal comfort and acceptability when comparing field study data of these different thermal categories (by overall PMV range) according to current standards.

That individual behavioral adaptation can impact human thermoregulation and our perception of thermal comfort beyond the environmental conditions alone, is well established [56]. Despite advancements in thermophysiological models that have proven reliable in predicting thermal sensation [89-91, 138] and thermoregulation [139, 140] even under dynamic and severe environments, current standards merely correct this mismatch by allowing for slight adjustments in the thermal comfort evaluation when adaptation, like changes in the air velocity and clothing, are to be expected [141, 142].
ASHRAE 55 [37] allows for higher temperature thresholds when greater air velocities are expected. However, these assumptions frequently require project-specific justification in real-world scenarios since passive airflow through window ventilation [143] or active air velocity through ceiling fans [144] is highly uneven and non-uniform across the room. Few field studies show significant air movement in office environments at all, as cross-examination of 5653 observations by Toftum, et al. (2002) concluded only 8% of the studies show air velocities higher than 0.2 m/s, underscoring the lack of this adaptation potential [145]. In addition to the non-

uniformity in distribution, the window and fan operation are also influenced by individual behavior. This behavior pattern is most often correlated with indoor environmental parameters like air quality, air temperature, humidity levels, and air velocity [146, 147] or outdoor environmental parameters as Ming, et al. (2020) point to seasonal differences in window usage, with late spring and early autumn exhibiting the highest frequency of window opening [146].
Clothing modifications are often the primary tool for adaptation in office environments with studies showing occupants successfully adapting to operative temperatures up to 29°C through clothing adjustments alone [92]. In 2013, Liu et al. were able to demonstrate an adjustment in the neutral-comfort temperature of -0.4°C and -0.7°C in winter and summer, respectively, per increase in clothing insulation of 0.1 clo and a total variation in clothing insulation of 1.3 clo between the maximum insulation of 1.7 clo in the winter and 1.6 clo in the spring and a minimum insulation of 0.5 clo in the autumn and 0.3 clo in the summer [100]. Similarly to the behavioral adaptation through a window or fan operation, the adaptation of the clothing insulation is often only correlated to the physical parameters of the indoor and outdoor environment and assumes a constant, uniform effect on every person [148-151]. These methods of adjusting for behavioral adaptation do not consider temporal or individual differences in thermal perception and needs, by merely assuming the average and constant mean of all people.

The challenge of decarbonizing the building sector and demanding more active users in an otherwise passive building has therefore led recent thermal comfort research to include methodologies that focus on quantifying this temporal and dynamic relation of the environment on the thermoregulation (capabilities), thermal perception, and adaptive behavior of users [152]. An example of this is research quantifying the effect of the human circadian rhythm on thermal comfort [80, 153-155]. Introducing a temporal variation to thermal comfort on an hourly basis could significantly change how we evaluate and condition our buildings and offer the potential to decarbonize the building operation as well as improve individual thermal comfort. Zmeureanu and Doramajian [156] were able to calculate this temporal potential with an HVAC energy reduction of 11% in office settings when allowing for temperature increases after 3 pm in summer, while still complying with the 80% acceptability range and a maximum set point temperature of 27°C. Many studies have presented a circadian variation in thermal response as well as sex differences in physiological data under climate chamber conditions. Grivel and Candas [157] reported lower average rectal temperatures in men and in the morning (both 0.3°C difference). Temporal differences were also discovered in the behavioral adaptation of clothing changes under dynamic conditions, with slower adaptive behavior in the afternoon towards cooling [158]. Terai et al. [159] show a higher water temperature preference when submerged in water under a rising than declining core body temperature period. Vellei et al. [84] similarly suggest a higher chance of warming discomfort during the declining phase. In a 2021 review, Vellei et al. [152] only identified 21 studies addressing the temporal influence on thermal perception of which only 4 simulated changing (thermal dynamic) conditions.

Very few studies have conducted continuous data collections in free-running environments to understand how individual differences and adaptation behavior influence the potential of temporal thermal fluctuations and adaptation possibilities. Whereas steady-state settings show more or less coherent results when comparing simulated/calculated predictions and measured feedback, real-world dynamic environments have proven to show significant discrepancies both in higher thermal discomfort feedback and higher energy consumption than expected [64, 92, 93, 154]. Karyono [160] compared the subjective feedback of 596 office workers in Indonesia under naturally ventilated, air-conditioned, and hybrid buildings. The temporal analysis showed a significant increase in subjects' neutral operative temperature when comparing the time frames 9-10 am and 3-4 pm, with an afternoon increase of +3.1°C. Similar findings are presented in a study by Wagner, et al. [161], which found temperature comfort levels to differ between morning and afternoon, as the afternoons felt cooler, with a median "just right" temperature of 25.2°C compared to 24.9°C in the morning for "slightly warm", with morning temperatures generally 1.3°C lower for the same comfort level [161].

4.2 Research Statement

This study aims to gain further insight into the individual and temporal differences in thermoregulatory processes in a real-world naturally ventilated office environment, to formulate a more sustainable framework for indoor climate regulations following objective thermoregulatory boundaries to behavioral and thermoregulatory adaptation. The hypothesis of the study can be phrased as follows: Physiological thermoregulation, especially in dynamic thermal environments, shows high temporal interdependencies and individual variations.

4.3 Method and Experimental Set-Up

The field study was conducted within a naturally ventilated office space on the fifth floor of the Technical University of Munich, in Germany. A total of 9 participants were included in the study, over a total observation period of 28 workdays (between 28.06.2022 - 04.08.2022). The participants' anthropometric characteristics are listed in Table 1.

	Sex	**Age**	**Height (cm)/ Weight (kg)**	**BMI (kg/m^2)**	**Daily Start Time**	**Daily End Time**
Participant 1	F	34	176/66.0	21.3	11:11 ± 02:47	17:54 ± 01:29
Participant 2	M	36	190/82.7	22.9	10:02 ± 02:54	17:32 ± 01:29
Participant 3	M	31	180/72.0	22.2	08:54 ± 00:20	17:28 ± 00:17

Participant 4	M	35	176/61.2	19.8	09:50 ± 01:19	17:22 ± 01:34
Participant 5	M	31	185/81.0	23.6	08:58 ± 00:49	17:02 ± 01:14
Participant 6	M	38	167/67.2	24.0	09:21 ± 00:14	17:48 ± 00:34
Participant 7	F	31	180/73.5	22.7	08:36 ± 00:10	17:10 ± 03:25
Participant 8	F	39	166/56.1	20.3	09:13 ± 00:30	18:29 ± 01:35
Participant 9	M	26	190/82.0	22.7	09:17 ± 00:49	16:59 ± 01:09

Table 1 – Anthropometric characteristics of participants n=9, including sex, age, height, weight, BMI, daily mean start and end time.

All participants remained at their usual office space and underwent their usual schedules with no regard to the study. On randomized days participants' physiological data as well as the immediate climatic conditions were measured. The collected data is listed in Table 2. The climatic conditions were measured using an IoT sensory system developed by and described in detail in Banihashemi, et al. [162] and placed on the desk just beside the participants (as seen in Figure 10), with the globe sensor at 1.1 m height (head level according to ISO 7726 [163]). The physiological parameters were measured using the Empatica E4 wristband [164].

Data domain	Data	Unit	Sensor/Method	Resolution / Accuracy	Sampling Rate
Climate	Air temperature	°C	Thermocouple shielded from radiation/ Thermocouple Bricklet 2.0. Tinkerforge.	0.01 °C / ±0.15% (a)	1 min
	Globe temperature	°C	Thermocouple in a blackened sphere (ø 70 mm) / Thermocouple Bricklet 2.0. Tinkerforge.	0.01 °C ±0.15% (a)	1 min
	Relative Humidity	%	Humidity Bricklet 2.0 Tinkerforge	0.01% 14bit / ±2.0% (a)	1 min

	Air velocity	Volts & °C	Wind Sensor Rev. P	±0.5 ms^{-1} (b)	1 min
	CO_2 concentration	ppm	CO_2 Bricklet 2.0 Tinkerforge	0.01 ppm / ±30 ppm (a)	1 min
	Outdoor Air temperature	°C	Weather station data by the Meteorology Institute Munich, LMU. Measured at a height of 30m above ground [165]	-	1 min
Biometric	Electroderma l activity (EDA)	µS	Electrodermal activity sensor, Empatica E4.	1 digit ~900 pSiemens (c)	4 Hz
	Photoplethys mography (PPG) /Blood volume pulse (BVP)	nano Watt	PPG sensor	0.9 nW/Digit (c)	64 Hz
	Distal skin temperature	°C	Infrared Thermopile	0.02 °C (c)	4 Hz
	Motion-based activity	g	3-axis Accelerometer	8 bits (c)	32 Hz
Psycholog ical	Adaptive behavior and clothing insulation	-	Manual mark-up through continuous monitoring (on-site observation)	-	-

Table 2 – Collected data, methods, and resolution. According to technical specifications by (a) Tinkerforge [166], (b) Research study [167] (c) Empatica [164].

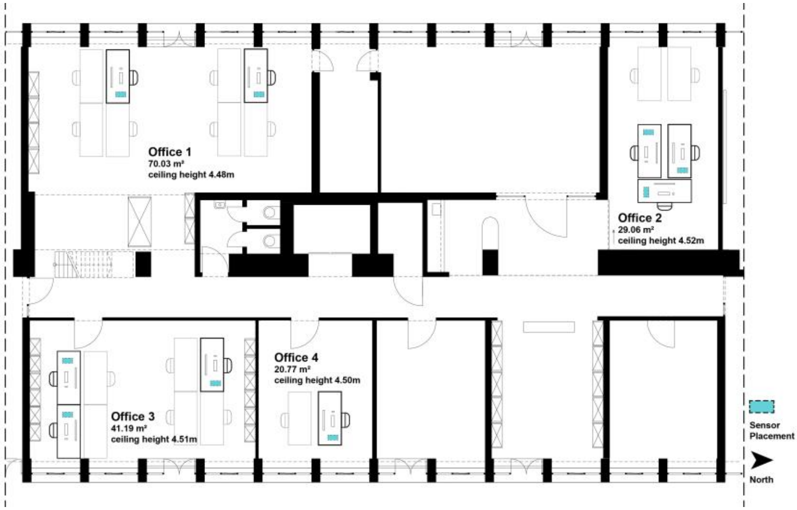

Figure 10 – Floorplan of all 4 monitored environments (Office 1-4) and sensor placement (turquoise) within the naturally ventilated offices at the Technical University Munich.

All participants were monitored for at least 6 days but only days with a continuous occupancy of at least 3 hours within the monitored office space were considered, reducing the overall data set to 43 days of usable data collection with participants monitored on 4.8 days on average with one participant only showing three usable measurement days.

Ethics. The study protocol was approved by the Ethics Committee of the Technical University of Munich. All participants were informed of the data handling in written and oral form, and consent was given in written form prior to the study.

4.4 Data Analysis and Findings

4.4.1 Climate Data

Figure 11 depicts all air temperature data points (resolution: 1min) grouped by the respective participant and in relation to the outdoor air temperature (data provided by [165]). We assumed equal values for air temperature, mean radiant temperature, and operative temperature, but to ensure the validity of the results against the air velocity sensors' potential inaccuracy, all relevant data analyses were also conducted using the raw globe temperature data (summarized in *Appendix 1-Appendix 5*) that showed little variation in the overall conclusion. While the indoor conditions varied substantially, with a mean range of 8.0K ±1.0 difference, the outdoor conditions showed little variation during the times of occupancy (mean: 1.5K SD: ±0.3). This is most likely due to the LMU weather station's height of 30 m above ground level [165]. This data was chosen over the more commonly used climate data at 2 m height, as the observed office space with operable windows is located on the 6th floor at an elevation of ~30 m.

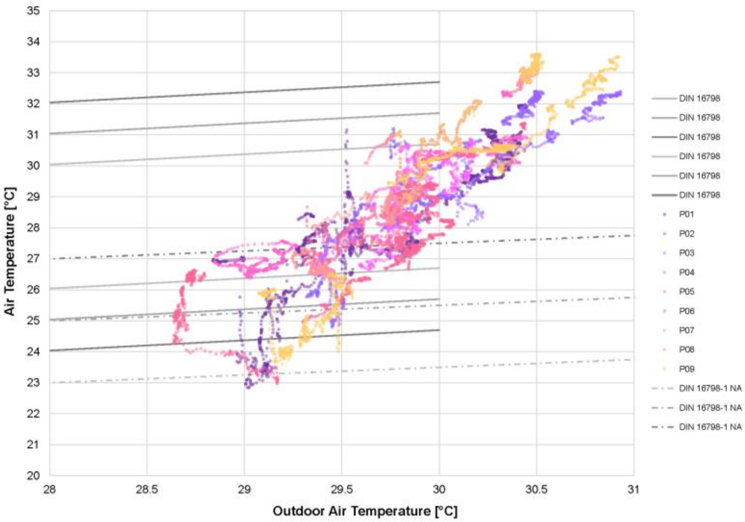

Figure 11 – Air temperatures during desk occupancy in relation to the adaptive comfort categories by DIN 16798 and DIN 16798-1 NA and color-coded participants.

The variation and mean of the indoor temperatures as well as other climatic parameters (relative humidity, air velocity, outside air temperature) are displayed in Figure 12.

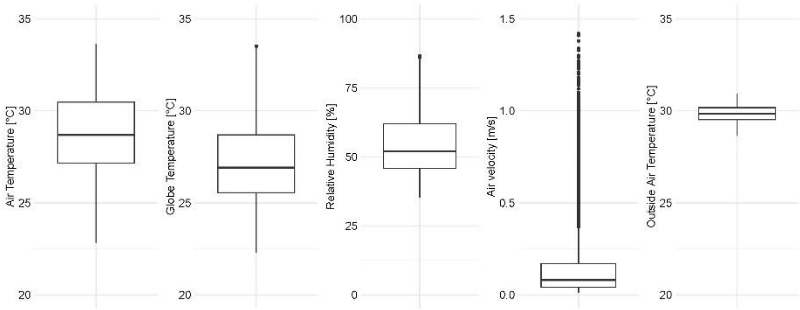

Figure 12 – Mean indoor climate data and outside air temperature for all participant sessions as boxplots.

4.4.2 Behavioral Adaptation

In office environments where climate control is limited, behavioral adaptations such as allowing air movement through window openings or utilizing ceiling fans and changes in clothing can significantly alleviate thermal stress. To understand the influence of such behavioral adaptation, changes in clothing were monitored. At the beginning of each session, participants collaborated to document the clothing insulation, adhering to ISO 7730 Table C.2 [38] and ISO 9920 Table B.2 [47]. Dedicated study assistants stationed in each office space monitored clothing changes throughout the day, documenting them along with updated clothing calculations and timestamps. Figure 13 depicts the combined clothing data and trend against the air temperature. While most standards assume a fixed clothing insulation of 0.5 clo during summer, the polynomial regression fitting of the findings shows this to not hold true above air temperatures of ~25°C (intersecting 0.5 clo) or above ~26°C (intersecting 0.4 clo) when also accounting for the office chair (0.1 clo according to ISO 7730 Table C.3) [38]. In true observation, no participant wore ≥ 0.5 clo above 28.7°C or above 29.8°C (when accounting for the office chair: 0.1 clo), with an overall mean and standard deviation in clo value of 0.29 ±0.08, throughout all 43 measurement days.

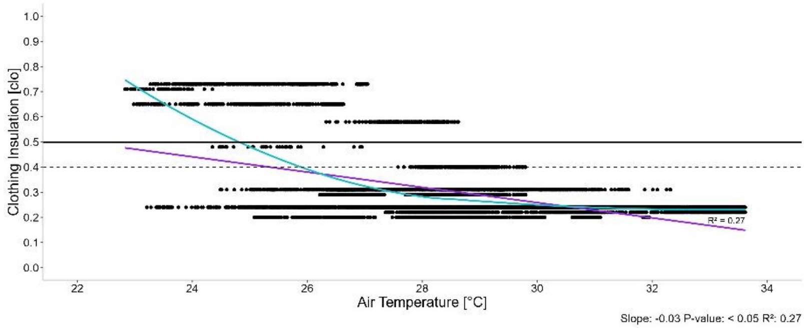

Figure 13 – Trend in clothing insulation [clo] against air temperature [°C] for all participants data with a linear regression curve (method = lm) in purple (Slope: -0.03, p-Value: <0.05, R^2:0.27) and a local polynomial regression curve (method = loess) in turquoise (R^2:0.27).

4.4.3 Temporal differences in thermoregulation

Studies on heart-related biosignals commonly use heart rate or heart rate variability (HRV). HRV, indicated by R-R or N-N intervals, represents the variation in successive heartbeat durations, while heart rate is measured in beats per minute [168]. The cardiovascular system's response to stress and maintenance of homeostasis relies on the intricate and dynamic oscillations of a healthy heart [169]. HRV signals are crucial in stress assessment research, particularly due to the sensitivity of the nervous system to temperature changes [170]. Environmental temperature influences vagal and sympathetic nerve activity [171]. In stressful conditions, sympathetic activity prevails, while comfortable conditions stimulate vagal activity. The analysis of HRV components, such as low-frequency (LF) and high-frequency (HF), provides insights into sympathetic and vagal nerve activity. The activation of the sympathetic nerve in response to thermoregulation prompts an increase in the LF-HF ratio and a decrease in HF power [172]. Studies consistently show that a higher LF-HF ratio correlates with unpleasant thermal sensations and discomfort [61]. RMSSD (Root Mean Square of Successive Differences) is another metric derived from heart rate variability (HRV) analysis. It specifically quantifies the variation in time intervals between successive heartbeats, reflecting the activity of the parasympathetic nervous system. RMSSD is closely related to the HF component of HRV and is considered a sensitive marker of parasympathetic activity. Higher RMSSD values indicate greater parasympathetic (vagal) modulation and are often associated with states of relaxation and recovery. Lower RMSSD values, on the other hand, suggest reduced parasympathetic activity and may indicate stress or physiological imbalance [173]. In the context of thermal stress, RMSSD provides additional information about autonomic nervous system modulation. A decrease in RMSSD during thermal stress could indicate a shift towards sympathetic dominance or reduced vagal activity [173], which may impair the body's ability to adapt to temperature changes effectively. BPM (beats per minute) also serves as a fundamental metric in assessing the dynamic fluctuations of heart activity. In the context of thermal stress, rising BPM readings (several minutes of bpm > 180 bpm – 0.65 x participants' age) can indicate an elevated physiological response. Conversely, declines in BPM readings toward the individual resting rate may suggest a more relaxed state with reduced sympathetic activity, potentially indicating a greater level of well-being [174].

Human skin is another vital source of data for understanding physiological reactions to the environment. Acting as the primary sensory organ, skin sensations reflect both internal biological processes and responses to external stimuli [175]. Skin temperature (Tsk), similar to heart rate variability (HRV), offers insights into autonomic nervous system (ANS) activity [176]. Skin temperature is the most extensively studied among these biosignals, offering direct insights into human thermal sensation and comfort estimation with cost-effective sensors [177]. Constant thermocouples, in both real-world and laboratory settings, have been demonstrated in various studies for predicting thermal sensation. However, it's worth noting that the use of thermocouple sensors involves the placement of electrodes on the skin, which can make the data-collection process somewhat obtrusive. [61] In this study, one infrared thermopile sensor was used to measure the distal wrist skin temperature (Tskw) at 60-second intervals.
The second important skin variable is Electrodermal Activity (EDA), also known as galvanic skin response, which reflects the electrical conductivity of the skin, primarily influenced by sweat gland activity. Tonic EDA refers to the baseline level of skin conductance, which reflects sympathetic nervous system activity. During thermal stress, sympathetic activation can lead to changes in tonic EDA readings, indicating increased arousal or stress response. Monitoring tonic EDA can provide insights into the psychological and physiological stress response to thermal stimuli, complementing measures like heart rate variability.

Analyzing the temporal effect on the thermoregulation, Figure 14 compares the time frames Morning (defined as the start of the day until lunch break) and Afternoon (defined as all-time after the lunch break). As the lunch break was the same period for all participants this was simplified as the time frame (12:00-13:00) in the data handling.

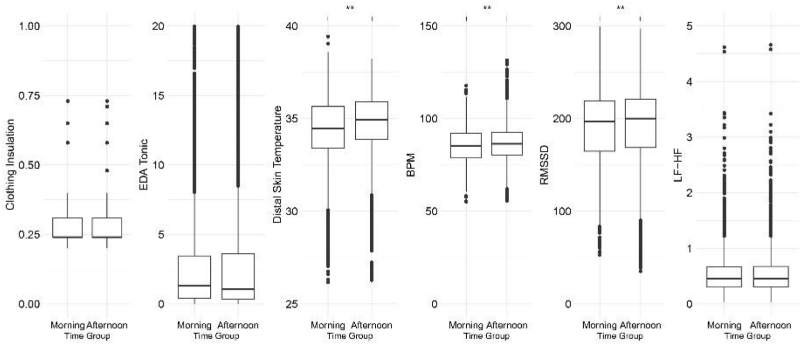

*Figure 14 – Combined participants data grouped by time (Morning 07:00 – 12:00; Afternoon 12:00 – 19:00) for clo, eda, bpm, rmssd, lf hf. Independent t-test comparison with assumed equal variances between the two temporal datasets: ** P-values <0.05.*

The comparison in Figure 14 reveals no significant temporal differences in clothing, EDA Tonic as well as in the heart rate data of LF-HF. A slight though significant ($p<0.05$) increase in the BPM, and RMSSD values from morning to afternoon can be observed, giving somewhat contradicting findings towards the thermal state of the participants. While the increased BPM can indicate a potential increase in heat stress, most studies show hot environments significantly reduce RMSSD values [178]. A more pronounced temporal difference is seen in the distal skin temperature readings with the afternoon showing significantly higher values.

4.4.4 Sex differences in thermoregulation

There is growing literature evidence on sex differences playing a crucial role in how individuals respond to thermal stress, with significant implications for health, safety, and well-being in various environments [179]. These differences can stem from both physiological and hormonal factors that show a large individual variety but are mostly simplified by sex categories of Male and Female [180]. One of the primary drivers of sex differences in thermal stress response is the hormonal profile. For instance, estrogen has been shown to enhance vasodilation and increase peripheral blood flow, which aids in heat dissipation and can lead to a lower core body temperature in females compared to males [180]. Moreover, hormonal fluctuations throughout the menstrual cycle can further influence thermal response in females. Estrogen and progesterone levels fluctuate across the menstrual cycle, affecting factors such as core body temperature (+ 0.3 - 0.5°C during luteal phase), suggesting that women may experience variations in thermal comfort and stress tolerance to heat depending on their menstrual phase [180]. This effect on thermoregulatory capacity has also been shown during other instances of hormonal fluctuation, like during menopause or pregnancies [179]. Additionally, differences in body composition between males and females can contribute to variations in thermal response. Females generally have a higher proportion of body fat and lower muscle mass compared to males, which can affect heat production and dissipation mechanisms [181].

Thermophysiological models such as JOS-3 include sex as a variable in the Harris-Benedict model equation for determining heat production (metabolic rate) but do not automatically account for the proportion of body tissues or other physiological sex differences like sweat activity. However, this can be adjusted individually when predicting specific group types [139]. Women also generally possess a higher density of sweat glands and utilize a greater percentage of them, resulting in a more efficient sweating process which may decrease wasted sweating, particularly in humid environments; however, despite this efficiency, female marathon runners tend to produce only 68-73% of the absolute sweat rates observed in males due to lower metabolic heat production stemming from lower body mass and slower pace [181]. Furthermore, it is not hard to suspect societal, and cultural factors to also influence how males and females experience thermal comfort. Occupational settings, clothing choices, and behavioral adaptations to environmental conditions may vary between sexes, affecting exposure and response to thermal stressors. However, it should be noted that these differences are more likely addressed by gender differences as they concern socio-cultural rather than bio-physiological or hormonal differences.

To understand the sex differences Figure 15 compares the thermoregulatory responses and clothing data. Differences in the effect of the menstrual cycle on thermoregulation couldn't be assessed due to the limited data amount and variation. An analysis of the difference of BMI on thermoregulation in correlation to sex is understood to have a significant impact on thermoregulation [182] but showed no significance in our data. This is most likely due to the similarity of all subjects BMI (Total Mean: 22.17, Males Mean: 22.53, Female Mean: 21.43).

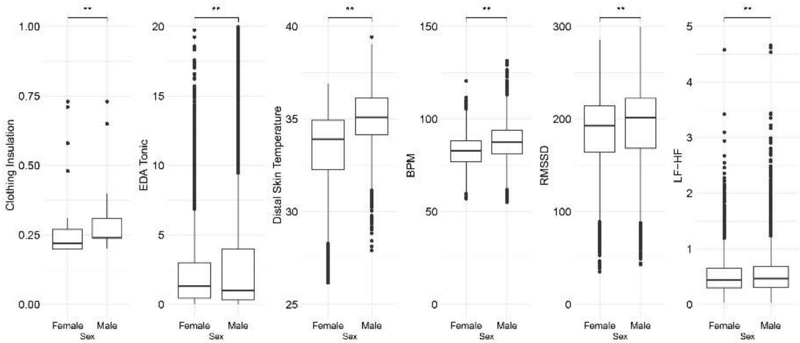

*Figure 15 – Combined participants data grouped by sex (Female, Male) for clo, eda, bpm, rmssd, lf hf. independent t-test comparison with assumed equal variances between the two temporal datasets: ** P-values <0.05.*

All comparisons show a significantly higher overall mean value in Males except the Tonic EDA levels. Tskw shows the most prominent difference in the overall trend, and more so than in the temporal comparison. Figure 16 visualizes the Tskw data as a scatterplot grouped by sex (Male in pink and solid trendline and Female in purple and dashed trendline) against the air temperature (Tair). The gap between Tskw differences in sex is larger with lower Tair, whereas air temperatures of 32.5°C depict little to no difference in Tskw between Male and Female participants.

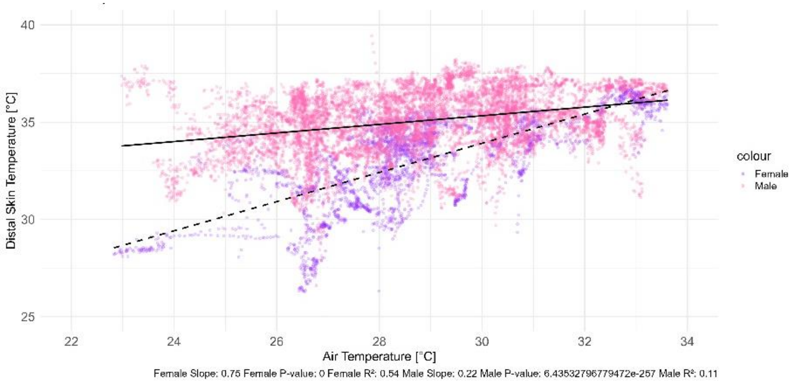

Figure 16 – Scatter plot of distal skin temperature (wrist) against the air temperature grouped by Sex (Male in pink and solid trendline, Female in purple and dashed line).

Similarly, Figure 17 and Figure 18 visualize the differences in the regression line between time and sex groups respectively against the air temperatures. The difference is calculated by subtracting the average male or afternoon trendline (linear regression slope) from the average female or morning trendline (linear regression slope) respectively. Negative values therefore denote lower values in the average trend of female or morning data compared to male or afternoon data at the respective Tair, whereas positive values denote higher female or morning average trendlines.

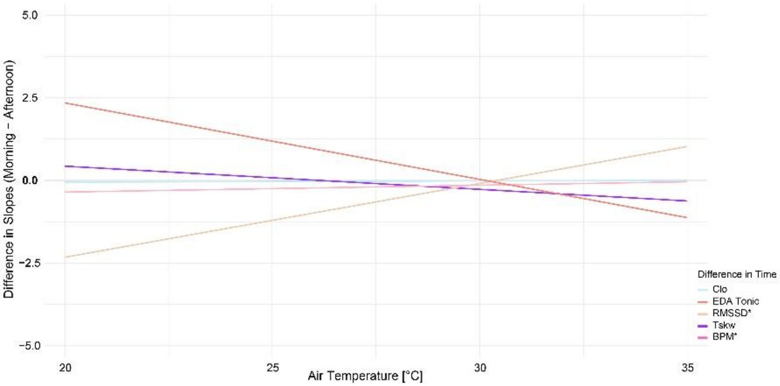

*Figure 17 – Absolute difference between the time group linear regression slopes by air temperature. *RMSSD and BPM values were scaled by a factor of 10 to fit the scale of the y -axis.*

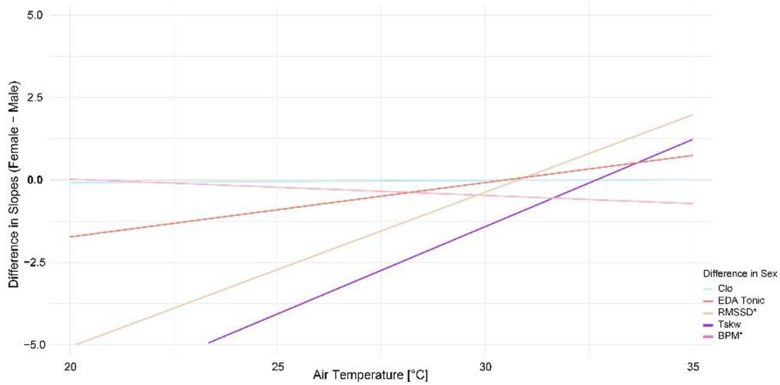

*Figure 18 – Absolute difference between the sex group linear regression slopes by air temperature. *RMSSD and BPM values were scaled by a factor of 10 to fit the scale of the y -axis.*

Clothing changes seem to show no meaningful shift in their relationship due to the air temperature. BPM shows overall lower trendlines for morning and female groups independent of the Tair. RMSSD trendlines suggest lower values for female or morning groups when air temperatures were below 31°C or 30°C respectively, but higher values in those same groups when temperatures exceeded those thresholds. EDA Tonic trendlines are higher in females when Tair > 31°C. While other studies have found EDA Tonic levels to be lower in the morning compared to the afternoon at similar temperatures [129, 153], the EDA tonic levels in this study are only lower in the morning compared to the afternoon when air temperatures were above 30°C. The wrist skin temperature trend also shows a tipping point around 27°C in the time groups, and around 33°C in the sex groups, with higher afternoon and female trendlines at higher temperatures.

4.5 Conclusion

The data analysis concludes the following findings, with findings 2-4 confirming the initial hypothesis:

1. The overall trend in clothing insulation deviates from the standards assumption above air temperatures of 26°C when accounting for the insulating properties of the office chair, with no participants wearing >0.5 clo above 28.7°C, and a mean clo value of 0.29 ± 0.08 across 43 measurement days.
2. Temporal variations are evident in thermoregulatory responses, with morning-to-afternoon comparisons showing increases in overall mean Tskw, BPM, and RMSSD values.
3. Sex differences in thermoregulatory responses are pronounced, with higher overall mean values observed in males across various parameters but overall higher mean Tonic EDA levels in females.

4. At air temperatures below 31°C female EDA and RMSSD data showed lower overall values compared to Males, whereas this relation switches with higher Tair above that threshold. The same relation is seen in Tskw with a tipping point at ~33°C. This suggests a nuanced relationship between the air temperature and differences in thermoregulatory responses, with a potential tipping point above 30°C.

4.6 Limitations and Discussion

The study and conclusion consist of and should be interpreted only with the following limitations in mind:

- **Small and Imbalanced Dataset:** The dataset's size, particularly the limited number of female participants and period of measurement poses a challenge in drawing statistically robust conclusions. This imbalance may skew the findings and hinder a comprehensive understanding of the suggested conclusions, especially regarding sex differences in thermoregulation (i.e. due to hormonal changes).
- **Study context and period:** The study is constrained by a limited observation period (6 weeks) confined to the summer season and focused solely on the specific climatic conditions of Munich, which needs to be extended for less contextual reasoning of the findings.
- **Lack of Environmental Context:** Participants had freedom of movement and engaged in their typical daily activities, introducing variability in their environmental exposures during breaks and meetings. While the climate around the desk was monitored and only those timeframes were used in the analysis, the absence of recorded environmental conditions during participants' activities beyond that introduces uncertainty of a difference in thermal history in the quality of the readings. This lack of contextual data may affect the accuracy and reliability of the observed thermal responses.
- **Accuracy in Air Velocity:** Although the air velocity sensor (Wind Sensor Rev. P) exhibits high data resolution, a research study (referenced in Table 2) identified its lack of accuracy (± 0.5 ms^{-1}) under specific directional conditions. As part of an already established sensory system, the air velocity sensor was nevertheless adopted and utilized. To understand the impact of uncertainty in the air velocity readings, all findings were cross-examined using air temperature and globe temperature. Given slight disparities observed across various data analyses, air velocity is considered a source of uncertainty in the overarching conclusions.
- **Single Measurement Point for Tskw:** The study solely measured skin temperature at the wrist, providing insights into distal skin temperature. However, this is not a standardized method for understanding heat loss dynamics or to conclude the mean skin temperature. The inclusion of proximal measurements, such as infraclavicular, thigh, and stomach areas, by following standardized procedures recommended by international standards (i.e. ISO 9886), could have facilitated the assessment of the mean skin temperature, offering a more comprehensive understanding of heat loss mechanisms.

- **Additional Factors:** The study couldn't conclude variations in age and BMI, which are known to influence thermoregulation. Incorporating these factors would provide a more nuanced analysis, potentially revealing larger differences in thermoregulatory responses. However, addressing age and BMI differences necessitates a more diverse participant group to capture a representative range of physiological characteristics.

Overall, while the study sheds light on differences in thermoregulatory responses in a free-running office environment, these limitations underscore the need for future research with larger, more diverse participant cohorts and enhanced environmental monitoring to strengthen the validity and generalizability of our findings. To reliably validate our conclusions, skin temperatures should be measured according to ISO 9886 and with more accurate air velocity sensors. Additionally, incorporating factors such as age and BMI would enrich our study's findings. Integrating these metrics allows for a comprehensive assessment of the body's adaptive mechanisms, helping to optimize thermal comfort, mitigate the risk of heat-related illnesses, and enhance overall well-being in challenging environmental conditions. Even the limited dataset of this study underlines the importance of understanding temporal and sex differences in thermal stress response as crucial when advocating for a thermal variety of free-running buildings rather than fixed set point temperatures of steady-state environments.

Abstract. This paper focuses on how the existing sealed office typology can adapt to a warming world while minimizing the high energy demand for space cooling, through Dynamic Cooling, by adjusting the cooling temperature profile towards the average human circadian rhythm to mitigate heat stress during times of heightened thermal sensitivity. This concept is explored through a study in which we compared the effects of Dynamic Cooling, constant cooling, and no cooling on the core body temperature of 21 participants as well as a thermal dynamic simulation of 270 office space configurations under the same cooling profiles, comparing the total energy demand, peak loads, and overall hours of discomfort. The results of the study suggest the different conditioning profiles have no direct impact on the overall change in core body temperature throughout the day (difference<0.04K) but do influence the overall range throughout (from 0.37K under constant cooling to 0.53K under Dynamic Cooling). Additionally, there is no clear correlation between elevated indoor temperatures and CBT during the morning hours, questioning the necessity and effectiveness of pre-lunch cooling. This is underlined by the simulation findings, which reveal a non-linear relationship between savings in cooling demand and a decline in thermal comfort, with a 51.3% reduction in ideal cooling energy demand and a 25.2% - 36% increase of Over-Temperature-Kelvin-Hours, from a steady state cooling profile to a profile of Dynamic Cooling. The results of the study and simulation challenge traditional cooling standards and highlight the need for a balance between minimizing thermal discomfort and the necessary cooling energy demand.

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Chapter Five

5. Dynamic Cooling – A concept of time-sensitive thermal regulation to cut cooling energy demand in office buildings

5.1 Problem statement

Addressing carbon emissions in buildings is crucial for climate mitigation and adaptation. Buildings account for 30% of global energy consumption and 26% of energy-related emissions [183]. While studies predominantly focus on the residential sector and new construction, it's crucial to note that existing commercial buildings have significantly higher specific energy consumption [184]. The need to decarbonize this building stock, as identified also by the IPCC Climate Change Mitigation report, makes it furthermore necessary to retrofit existing buildings, particularly office typologies, that are prone to more repurposing and renovation [135]. Over the past 70 years, office buildings have been energy-intensive, relying on HVAC systems within sealed facades. The existing office typology's operational energy consumption is becoming more problematic for owners, tenants, and society due to climate change and policy initiatives [185]. These buildings at the same time hold significant embodied energy, making demolition impractical for carbon reduction goals [186]. Therefore, re-thinking comfort and use practices, façade conditions, and mechanical systems retrofit is the only viable option. Decarbonizing mechanical systems and comfort strategies in existing structures is a complex problem with few simple answers. Our approach to thermal comfort relies on standards, which use measures like Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) to assess occupant satisfaction. Low PPD indicates near-neutral thermal conditions (PMV=0) and higher satisfaction [37]. These standards aim to minimize heat transfer and avoid physiological adaptation through thermoregulation like sweating by maintaining indoor temperatures close to thermal neutrality. Compared to the steady state comfort evaluation of the PMV/PPD model, the adaptive comfort model adjusts the indoor set temperature according to seasonal outdoor temperature changes but in practice is often reduced to fixed temperature set points, limiting the overall possible range of adaptation [187]. This leads to narrow and rigid daily temperature ranges, particularly in mechanically ventilated buildings, resulting in overall higher heating and cooling loads. To ensure the set point temperature during work hours, most standards recommend conditioning the indoor environment at least one hour before the arrival of the occupants. Most standards assume mechanical systems in German office buildings run eleven hours every workday. [51]

Recent studies in the field of thermal comfort attempt to highlight the role of circadian rhythmicity in thermoregulation [153, 188], based on the already existing body of literature from chronobiology [189, 190]. Maintaining a constant temperature has furthermore become questionable, as some occupants may prefer deviations from thermal neutrality [191]. Exposure to thermal stimuli can also elicit pleasure, a phenomenon known as thermal alliesthesia [96, 192]. Varying indoor temperatures throughout the day can cater to the desire for diverse thermal sensations [191, 193] and align with circadian rhythms, potentially benefiting thermal perception [84, 152], thermal resilience, cardiovascular health, and metabolic well-being [194, 195]. This knowledge reframes the traditional narrative of thermal comfort and exposes an uncharted realm of energy-saving possibilities.

5.2 Research aim

The concept of *Dynamic Cooling* is to reframe the conventional paradigm by emphasizing the conditioning of spaces sufficiently rather than efficiently. In essence, time-dependent conditioning shifts the focus from continuous, energy-intensive heating or cooling of entire building masses to targeted conditioning of occupied spaces, guided by physiological and temporal markers. The aim is to reduce the cooling and heating time to a few critical hours when needed the most instead of uniform conditioning throughout the whole workday. This study primarily focuses on air-conditioning due to its prominence as the fastest-growing technical equipment in the building sector that produces excessive carbon emissions. The required energy demand for indoor cooling has been gradually rising at an average pace of 4% every year since 2000 and makes up roughly 16% of the total building sector's energy consumption worldwide [15]. Air conditioning units, being one of the most common strategies of indoor cooling, are therefore expected to grow by 40% worldwide until 2030. [2]
Dynamic Cooling suggests a new approach toward thermoregulation that aligns with our circadian rhythms, energy efficiency goals, and human well-being. Like investigations of weather-predictive conditioning, Dynamic Cooling delves into the prospect of managing energy consumption and, consequently reducing CO_2 emissions, by breaking down conditioning demand into hourly evaluations rather than relying on seasonal assessments. Studies exploring this potential of temporal constraints to cooling, show promising results in energy demand and CO_2 emission reduction [196, 197], most notably when considering the dynamic emission factor of most electricity networks [198]. By exploring the nuances of this concept, this paper hopes to contribute to a growing body of research that seeks to revolutionize the way we think about and approach thermal comfort in the built environment and how to mitigate future heat stress. Understanding the relevance of this concept towards time-dependent heating profiles seems equally relevant in the long term and should be addressed in further research. Two hypotheses can be articulated as follows:

1. Cooling indoor spaces according to a dynamic temperature profile can function as a viable alternative towards heat stress mitigation.
2. Cooling indoor spaces according to a dynamic temperature profile can function as a viable sufficiency strategy to cut energy use in already existing office buildings while complying with current standards.

To answer these hypotheses this paper is structured into two main sections: Part 1 compares the intricate interplay between *Dynamic Cooling*, a conventional cooling strategy, and a scenario of no cooling and human physiology. For this purpose, we conducted a comprehensive data acquisition study analyzing the impact of these three conditioning profiles on the core body temperature of 21 individuals. Part 2 explores the limitations and opportunities that these cooling profiles present within the context of sufficient building technology. A parametric study, involving dynamic-thermal simulations, compares 270 models of an office space, varying in size, window-to-wall ratio, thermal mass, and orientation. The analysis focuses on the properties of energy demand and thermal comfort under these three distinct conditioning profiles.

5.3 Part I – Interdependencies of Dynamic Cooling and thermal resilience

5.3.1 State-of-the-art

The thermoregulatory mechanisms of the human body are active when the body temperature deviates from a state of equilibrium known as the thermal neutral zone (TNZ). Within the TNZ, the body attempts to regulate its temperature through thermogenesis, the production of heat, using minimal energy to achieve thermal homeostasis. The location of the TNZ depends on several factors, including individual metabolism, clothing, and ambient climate. For example, as physical activity increases and the body generates more heat, increased heat output is required and consequently shifts the TNZ to cooler temperature ranges.

In general, the TNZ for resting, unclothed people is between 28 and 30°C, depending on the environmental conditions, while for clothed, resting people it is between 20 and 22°C [199]. The position of the TNZ can also vary slightly throughout the day due to the circadian rhythm of the core body temperature. In addition, the threshold of the thermoregulatory set point always deviates slightly from the core body temperature, which is called load error and is described as $T_{rect} – T_{set}$ (Temperature of the core body – thermoregulatory set point temperature) [200]. At rest in an ideal TNZ, the load error is negative, and the core body temperature varies slightly during the day between -0.05 K and -0.07 K from the thermoregulatory set point. During activity, like office work, the load error shifts into the positive range and is expressed cyclically in a circadian rhythm, with the lowest load error occurring in the morning and the peak in the afternoon. The maximum load error occurs between 12 and 2 p.m., which indicates an increased tolerance of the thermoregulatory system to heat [200]. Additional research on the preferred temperature to touch on the neck has shown that it varies by 2.5°C over the course of the day, approaching a trend that corresponds to the inverse of the body core temperature [200]. Studies by Attia et al. have shown differences in preferred room temperature throughout the day, with the highest preferred room temperature being reached around 2 a.m. [200]. However, in studies by O. Fanger et al. (1973), only small variations in preferred room temperature were found to occur during sedentary behavior [201]. Consequently, a comparison of studies by Vellei, et al. (2021) assessed the existence of daily patterns in thermal perception. The result suggested that there is no clear evidence for the presence or absence of these daily patterns. [152]

The increase in energy turnover after food intake also influences metabolic activity. Both resting energy expenditure (circadian rhythm) [202] and changes in energy expenditure after eating (diet-induced thermogenesis) [203] vary throughout the day. After a meal, energy expenditure increases significantly in the morning and afternoon but returns to baseline levels after about four hours at the latest. This coincides with a study done by Weststrate et al. (1989), which also depicts this process to be slightly slower in the afternoon compared to morning hours [204]. Furthermore, thermal perception depends not only on absolute temperature values but also on the fluctuations and temporal course of temperatures. The perception of temperature changes, such as temperature ramps, temperature steps, and temperature cycles, are described in standards like ANSI/ASHRAE Standard 55 and ISO/DIS 7730. In such transient temperatures, fluctuations in daily building conditions are evaluated using the Predicted Percentage of Variance (PPV). Smaller temperature variations result in more favorable categories and lower PPV ratings, with Category I in office buildings allowing a maximum fluctuation of ±1.0K, while Category IV permits ±3.5K fluctuations [51]. Excessive temperature fluctuations exceeding 1K [38] / 1.1K [37] or occurring at a rate faster than 4.0K [38] / 2.2K [37] per hour compromise thermal comfort, highlighting the essential role of air conditioning in meeting these strict temperature limits. A method for a more detailed evaluation of the extent of these deviations has not yet been defined in current standards but research studies into thermal alliesthesia offer some insights. Thermal alliesthesia describes the subjective evaluation of thermal comfort in relation to the changes in load error caused by temperature changes. The subjective evaluation of thermal comfort thus depends on whether the load error is reduced (positive alliesthesia) or increased (negative alliesthesia) by the temperature change [96]. Another important component is the adaptability of the human body to different temperatures over short or long periods, also known as acclimatization. People who are used to air conditioning adapt less well than those who are used to natural ventilation [205, 206]. In addition to the well-documented effects of psychological adaptation (alterations in expectations and perceptions of the environment) and behavioral adjustments (such as changing clothing and using fans) identified first by de Dear and Brager (1998) [52], recent research by Yu et al. indicates that occupants of air-conditioned buildings, who are typically exposed to consistently neutral environments and thus lack environmental stimulation, may gradually lose their thermal adaptability [206]. Finally, the individual regulation of air conditioners plays an important role in the duration of tolerance to thermal stress, with adaptation to rising temperatures (temperature ramp) being easier than to falling temperatures (temperature drop) [99]. The acclimatization capacity is also more effective the more active the person is during the adaptation phase. When active in hot environments adaptation takes place more quickly and lasts longer than with sedentary activity [199, 207].

In summary, physiological measurements have shown that certain physiological signals fluctuate throughout the day, even when environmental conditions are kept constant. In particular, increased values of core body temperature and sweat activity are observed in the afternoon, indicating a dependence of the thermal perception towards the circadian rhythm. Other factors for the increase in thermoregulatory activity could be food intake and increased bodily activity. This raises the question if mechanical cooling of indoor spaces is sufficient when only applied in those human timeframes of heightened thermal sensitivity. A recent field study summary by Vellei et al. (2022) examined daily temperature preferences using data from 10,000 Canadian households and 22,000 samples of thermal comfort data from 7,000 subjects. It analyzed how occupants adjust their setpoint temperatures throughout the day, with most decreasing it midday and increasing it in the morning and early evening. Neutral temperatures were found to dip around 14:00 and rise thereafter, with an estimated 2°C difference between morning and midday, and midday and evening [208].

5.3.2 Methods

Experimental Set-Up. To understand the sufficiency of time-restricted cooling towards human physiology, a dynamic temperature profile according to the reviewed literature and standards, as seen in Figure 19, was tested on participants over the course of seven workdays, in an office space at the Technical University of Munich, in June 2023.

On these days of dynamic cooling (DC), the air conditioning only ran between 12:30 p.m. and 2:30 p.m., at a 26°C set point temperature. This two-hour cooling period is based on Vallei et al.'s (2022) study, which found that people's neutral temperature vote is lowest at 14:00. Additionally, it considers the effects of changes in both resting energy expenditure (circadian rhythm) [202] and energy expenditure after eating (diet-induced thermogenesis) [203]. Figure 19 qualitatively illustrates these factors, showing how the peak positive load error and diet-induced energy expenditure accumulate most significantly during this period.

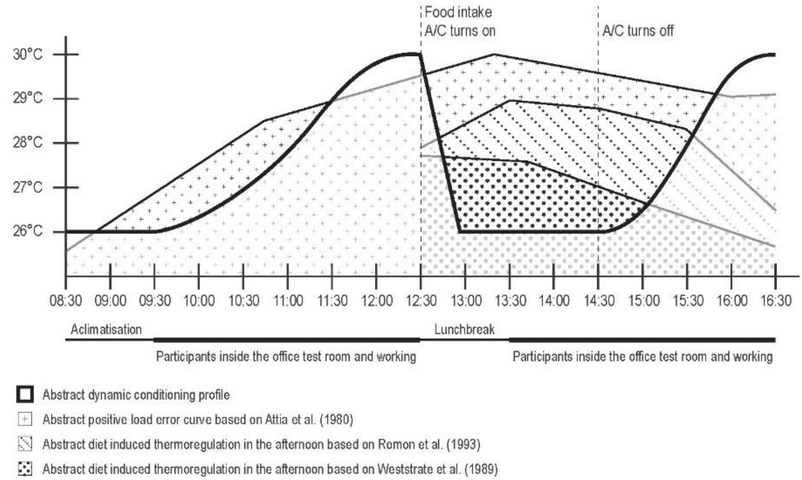

Figure 19 – Temperature profile as an inverted and simplified curve to the mean positive load error and diet-induced thermoregulation.

Temperatures were not regulated but only observed outside of this time window. The participants were not permitted to change the A/C settings, but at CO_2 concentrations above 1000 ppm, natural ventilation (tilted window) was used to regulate the air quality. This did not occur during times that were subject to the data analysis presented. The detailed room layout is described in Figure 20.

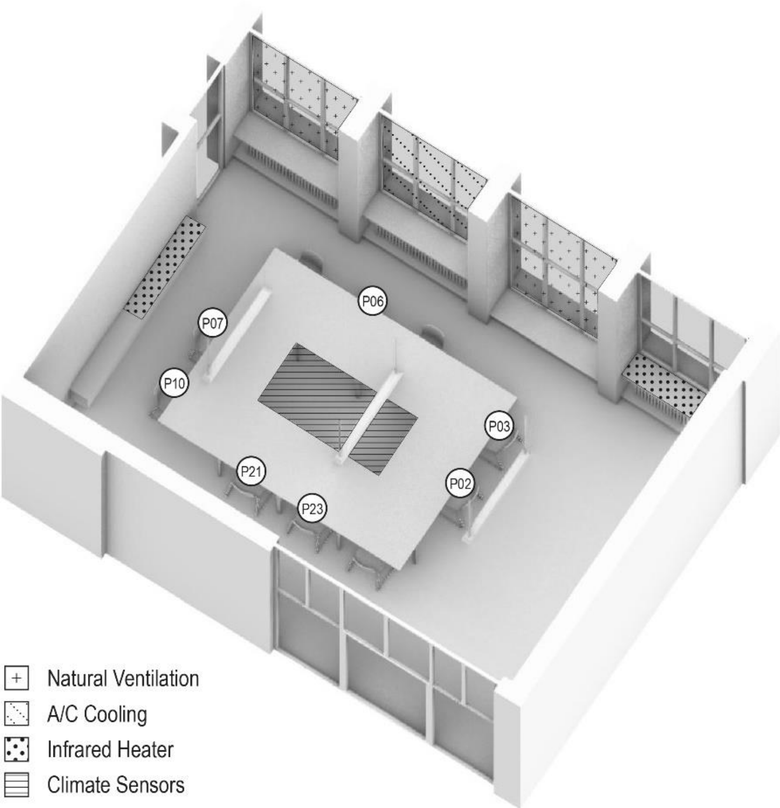

Figure 20 – Axonometric view of the office room layout with the natural ventilation intake, the placement of the façade air conditioning unit (A/C Cooling), the infrared heaters as well as the climate sensors at the center of the room, and the seating arrangement of the participants.

Every day began at 9:00 a.m., however participants were instructed to arrive 30 minutes early and take their assigned seats in the room at 9:00 am. The participants sat at their desk for 6.5 hours on each day, with an additional hour-long collective outdoor lunch break beginning at 12:30 p.m., in which the participants were exposed to outdoor conditions. They could leave the room whenever they needed to use the restroom or for short breaks of < 10 minutes. The seating arrangements remained unchanged throughout all days.

Control groups. To assess the impact of Dynamic Cooling on participants' physiology, two control scenarios were introduced for comparative analysis: Constant Cooling (CC), adhering to established standards, and a Free Running (FR) scenario without any cooling measures. In the CC scenario, a consistent set point temperature of 26°C was maintained using air conditioning, with no natural ventilation but indoor breaks with lunch served to them inside the office space. This was to ensure consistent exposure to temperatures in alignment with the most prominent standards (DIN 16798 [51] and DIN 4108-2 [142]). On the other hand, the FR scenario lacked active heating or cooling mechanisms but provided ceiling fans and operable windows for participants to manage their comfort as needed. Both scenarios followed the same protocol as Dynamic Cooling (DC).

Participants. A total of 21 people took part in the study, including 12 female and 9 male participants. They were recruited via flyers and posters hung around the university campus as well as through social media outlets. Their ages ranged from 20-36. All participants were healthy, had no chronic or acute illness, no ongoing medication use throughout the experiment, lived in Munich for at least a year, were non-smoking, did not regularly consume alcohol in large amounts, and were not pregnant. During the test days, the participants were free to choose their clothing factor. During the study period, they were told not to make drastic lifestyle changes regarding diet, exercise and sleep. Before the test days, they were instructed to rest well and refrain from consuming stimulating drinks.

Scenario	**Age**	**Height (cm)/ Weight (kg)***	**BMI (kg/m^2)**	**Body muscle percentage***	**Body fat percentage***
DC (n=7)	25 (±5.2)	169.6/74.8 (±8.3/±22.5)	25.7 (±5.45)	76.5% (±9.2)	19.6% (±9.7)
CC (n=6)	26 (±2.5)	171.7/63.4 (±10.5/±18.3)	21.2 (±3.5)	75.8% (±4.3)	20.6% (±5.3)
FR (n=8)	27 (±3.2)	168.3/63.3 (±9.7/±14.0)	22.1 (±2.9)	75.9% (±2.5)	19.8% (±2.4)

*Table 3 – Anthropometric characteristics of participants n=21, including sex, height, weight, BMI and BSA, muscle percentage, body fat percentage, and body fat distribution grouped by scenario. Data shows the mean value and one standard deviation. *Data was collected with a bioimpedance scale by Withings, with a resolution of 0.05kg [209] and an accuracy of ±0.25kg body weight [210].*

Measurements. During all days, the environmental conditions as seen in Table 4 were monitored. Only during the first and last of the seven-day exposure the Core body temperature was monitored through the biometric sensor as seen in Table 4. Within this paper's analysis, the average of the two measurement days was used for each scenario amounting to a total of 42 measurement days of data.

Data Domain	Data	Unit	Sensor/Method	Resolution / Accuracy	Sampling Rate
Climate	Air temperature (Tair)	°C	Thermocouple shielded from radiation/ Thermocouple Bricklet 2.0. Tinkerforge.	0.01°C / ±0.15 % (a)	1 min
	Globe temperature (Tr)	°C	Thermocouple in blackened PVC sphere (ø 120 mm) / Thermocouple Bricklet 2.0. Tinkerforge.	0.01°C / ±0.15 % (a)	1 min
	Relative humidity (rH)	%	Humidity Bricklet 2.0 Tinkerforge	0.01 % 14bit / ±2.0 % (a)	1 min
	Air velocity	ms^{-1}	Wind Sensor Rev. P. Modern Device	- / ±0.5 ms^{-1} (b)	1 min
	CO_2 concentration	ppm	CO_2 Bricklet 2.0 Tinkerforge	0.01 ppm / ±30 ppm (a)	1 min
Physiology	Core body temperature	°C	eCelsius Performance electronic capsule BodyCAP	0.01°C / ±0.2°C (d)	1 min
	Movement	g, step count	Shimmer EXG/IMU sensors, worn on the chest	1000 LSB/g at +/-2g	256Hz

Table 4 – Collected data, methods and resolution. According to technical specifications by (a) Tinkerforge [166], (b) Research study [167] (c) iButtonLink [211] (d) BodyCAP [212].

Ethics. The study protocol was approved by the Ethics Committee of the Technical University of Munich. All participants were paid for their attendance, independent of study completion, and were informed of the participation protocol and data handling in a written and oral form. All consent was given in written form prior to the study.

5.3.3 Data Analysis and Findings

The following Table 5 summarizes the indoor climate data and outdoor air temperature as a combined mean and standard deviation (±SD) as well as three separate mean values of the time frames 09:45-12:30, 13:30-14:30, and 14:30-16:30 in the DC scenario. The mean outdoor air temperature during the time of occupation was 23°C with a maximum air temperature of 34°C.

Scenario	Air Temperature [°C]	Operative Temperature [°C] (a)	Relative Humidity [%]	CO_2 [ppm]	Outdoor Air Temperature [°C] (b)
DC	29.01 ± 0.82	28.69 ± 0.77	47.86 ± 6.30	617.73 ± 94.14	29.72 ± 0.37
CC	27.54 ± 0.98	26.88 ± 0.84	43.73 ± 4.57	660.27 ± 66.75	29.72 ± 0.45
FR	28.60 ± 1.06	28.20 ± 1.09	40.34 ± 2.86	607.30 ± 80.17	29.70 ± 0.46
$DC_{Morning}$ (09:45-12:30)	29.29 ± 0.48	28.88 ± 0.46	51.85 ± 5.84	669.84 ± 35.83	29.56 ± 0.34
DC_{Noon} (13:30-14:30)	27.87 ± 0.57	27.68 ± 0.56	43.96 ± 5.19	565.52 ± 51.86	29.78 ± 0.10
$DC_{Afternoon}$ (14:30-16:30)	29.51 ± 0.59	29.19 ± 0.62	44.75 ± 4.51	633.75 ± 105.51	29.87 ± 0.39

Table 5 – Measured indoor climate data and outdoor air temperature as mean value and one standard deviation. (a) The operative temperature was calculated using the pythermalcomfort library in accordance with ISO 7726, following the mixed convection [44] with ε = 0.95 and D = 0.07 m and regarding the measured air velocity. The air velocity was only used for the calculation of operative temperature but showed few values above 0,1 m/s and is therefore regarded to have had no impact on the participants. (b) The outdoor air temperature was provided by the inner city weather station of the Meteorology Institute Munich, LMU [165].

To mechanically cool the office rooms of DC and CC, portable A/C units were used with a maximum cooling capacity of 4.6 kW (16,000 BTU). During the lunch break of DC (12:30-13:30), two A/C devices were employed to enhance the overall capacity and quickly lower the room air temperature. During periods of occupancy, only one device was used in each room to minimize significant air movement. While the indoor air temperature set point in the CC scenario was fixed to 26°C, the afternoon saw higher overall temperatures due to the west facing façade and therefore higher solar heat gains, that couldn't be combated properly. This can also be seen in the other two scenarios (DC and FR) in a higher overall operative temperature (Top) in the afternoon, as depicted in Table 5, and a steeper rise in temperature in the afternoon of DC compared to the morning hours. Furthermore, the cooling in DC never reached the set point temperature of Top = 26°C as intended but showed a rather consistent 27.68°C (DC Table 5) during the time of occupancy and cooling, between 13:30-14:30. While the required cooling demand was calculated using a load duration curve simulation before the study, deeming the A/C units sufficient, the simulation assumed that the sun shading would be fully closed when necessary. However, during the experiment, the sun shading was only lowered halfway to ensure adequate natural light and eliminate the need for artificial lighting, which led to higher indoor temperatures than expected. CC also didn't keep the set point temperature of 26°C consistently, and reached as high as 27.8°C exposure temperature in the afternoon, as seen in Figure 21. The exposure temperature was used as a comfort indicator to account for the experienced change from the indoor to outdoor environment by the participants in scenarios FR and DC. While indoors the exposure temperature (Texp) is equal to the scenario respective operative temperature, during the lunch break in DC and FR, Texp is equal to the adjacent outdoor air temperature as provided by the inner city weather station of the Meteorology Institute Munich, LMU [165].

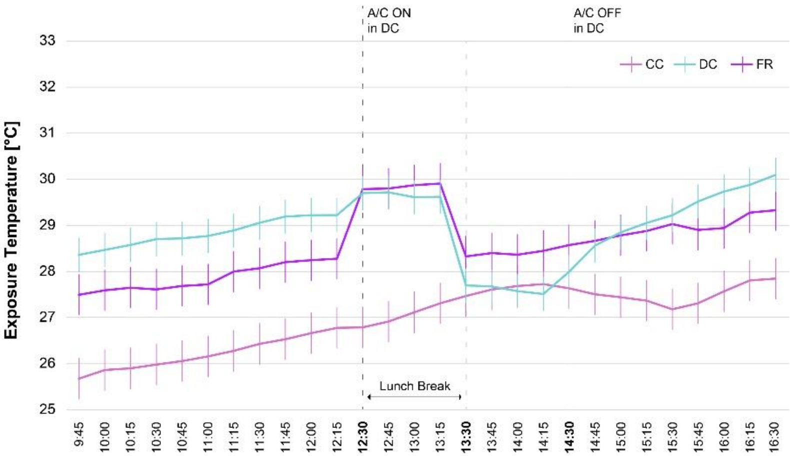

Figure 21 – Averaged mean exposure temperatures of the three scenarios as experienced by the participants. The whiskers represent one standard deviation.

The main analysis to answer the first hypothesis concentrates on overall differences in the core body temperature trend between DC, CC, and the FR as well as temporal differences within the change rate. To understand this the core body temperature was compared.

Core body temperature (CBT). Core body temperature is a direct indicator of the body's thermal state. While rectal thermometer measurements are often used as a reference method in laboratory settings, there is no standardized agreement in research for measuring core body temperature in ambulatory subjects, however, ingestible telemetry systems seem to offer a reliable alternative with convincing agreeability with gold standards [213].

As our measurements lasted several hours each day, we measured the temperature in the gastrointestinal tract to ensure comparatively low invasiveness and allowed the participants to remain ambulatory. The core body temperature was measured using an electronic capsule by

BodyCAP, and an eViewer Performance monitor by BodyCAP that logged the temperature readings at 60-second intervals. The sensor was ingested prior to entering the office, typically between 8:30 and 9:00 am. The data analysis begins at 9:45 to ensure the CBT pill has sufficient time to adjust and the body has acclimated to the sedentary work conditions and office climate.

Data handling. The data included two experimental days involving 21 participants for a total of 42 participant days that were aggregated to reduce the influence of previous exposures in different room conditions. Furthermore, the movement throughout the session was controlled with the IMU sensors the participants were wearing, and the minutes where more than 5 steps were recorded were tagged as movement. These minutes and the following 2 minutes were excluded from the CBT data analyses. The CBT data was checked for anomalies by several measures: 1. Checking for data points where the value is below 35°C, and tagging them as anomalies; 2. Checking for consecutive data points where the difference in values is larger than 0.5K, and tagging them as anomalies; 3. Removing the anomalies by interpolating the adjacent values, and finally; 4. Applying a smoothing median filter by a rolling window with a size of 30 samples. The resulting dataset was summarized in 15-minute steps for further modeling. Data handling and cleanup was done in Python. Statistical analysis was done using RStudio version 2023.03.1+446. Initial examination of the relationship between Texp and CBT data outcomes and thermal conditions (not presented in the analysis) as well as further detailed evaluation of differences between each scenario was done by performing an independent t-test with assumed equal variances. The significance threshold was set at 0.05 for all tests and adjusted using the Bonferroni correction to mitigate the risk of Type I errors arising from multiple comparisons, with outcomes below this threshold considered statistically significant.

Figure 22 illustrates the time series graph for the estimates and standard error bars of CBT of all participants presented as a time series for all three scenarios: CC, DC, and FR. The estimates are calculated using a mixed effects model, where the participants were introduced as random effects in order to account for inter-individual variability. Notably, variability in individual subjects can be observed, as evidenced by the broad range of standard errors. The most significant individual disparities in CBT are during the morning hours, specifically within the first two hours after the ingestion of the sensor. This phenomenon is most likely attributed to the sensor's position in the stomach, exerting a pronounced influence on water intake as accounted for but not eliminated completely in the data handling.

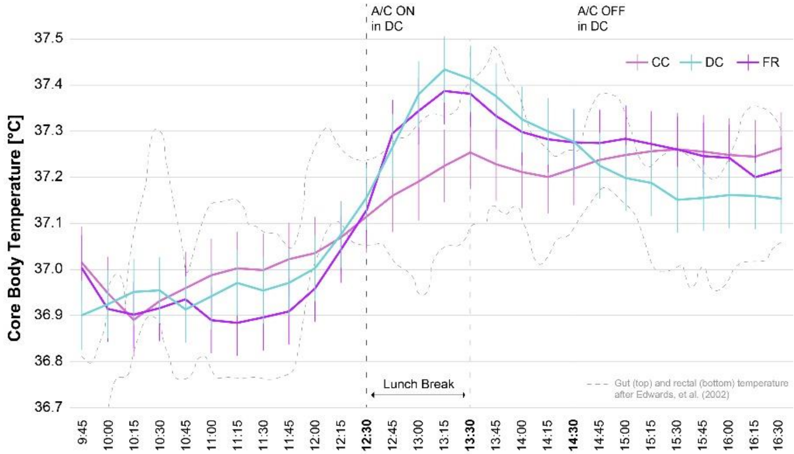

Figure 22 – Time series of 15-minute averages of mean CBT of the participants (n=21) grouped by scenario (CC, DC and FR). One standard deviation is indicated by the whiskers. Dashed grey trendlines display the comparative gut (top) and rectal (bottom) temperature data in a typical subject of a field study conducted by Edwards, et al. (2002) [214].

In general, all scenarios show an upward trend of CBT throughout the day. Based on the literature, we assume CBT to increase as such throughout a workday, reflecting the body's continuous heat-gain mode until late evening, manifesting anywhere from an approximate 0.3K elevation between 8 a.m. and 8 p.m., according to a cross-sectional analysis of single core body temperatures throughout a 24h cycle, in a hospital setting by Harding, et al. (2019) [215], up to an approximate 1.1K elevation within the same time frame according to a continuous 24h field study measurement by Edwards, et al. (2002) [214].

While the CBT steadily rises throughout the day in CC, the FR and DC scenarios show the highest CBT values during the outdoor lunch break between 12:30 – 13:30, before declining throughout the afternoon session, similar to the findings of Edwards, et al. (2002) natural circadian rhythm [214]. The overall difference in change in CBT between the first and last averaged and mean datapoints are +0.25K (CC), +0.21K (FR), and +0.25K (DC). We conclude the scenarios have little effect on the overall heat gain throughout the workday, though they do show differences in the magnitude of change throughout.
The DC scenario shows a steeper decline in CBT, then CC and FR, after participants return to the office (13:30), that extends far beyond the cooling period (12:30 - 14:30) until the conclusion of the measurement period (16:30). As this decline in CBT is also visible in FR, yet not as pronounced, one possible explanation for this rapid drop may be the magnitude in Texp step difference experienced following Lunch. Given that Texp in DC is partially higher and partially lower than that in FR, the CBT trend necessitates further contextualization within the varying environmental conditions.

Figure 23 compares the absolute variation, difference, and change in Texp, for all three scenarios. Figure 24 compares the same in core body temperature (CBT). The data is grouped by the time frames: Morning (9:45-12:30), Lunch (12:30-13:30), DC Cooling (13:30-14:30), and Afternoon (14:30-16:30). DC Cooling refers to the cooling in the DC scenario but was kept as an individual timeframe in both FR and CC, for the overall temporal comparability. The mean average and variation in data are represented through the boxplots, where CC shows the absolute variation and FR and DC are normalized against CC. The Boxplots of FR and DC therefore represent the difference against the underlying trend of CC. The absolute change of Texp and CBT from the start to the end of each time group is represented through the purple points. Positive values denote an overall rising Texp or CBT, and negative values showcase an overall declining Texp or CBT, within each time group.

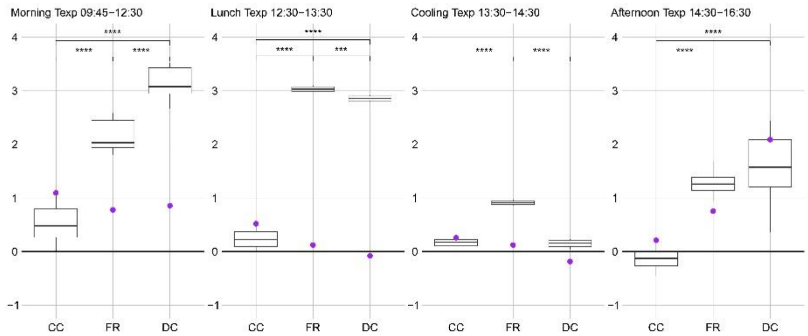

*Figure 23 – Absolute variation and difference in exposure temperature (Texp), normalized in FR and DC as differences against CC (Starting value=0), within each time-group, in [K]. Purple points depict the absolute change the data shows within each scenario and time-group. * p<0.1; ** p<0.05; *** p<0.01; **** p<0.001.*

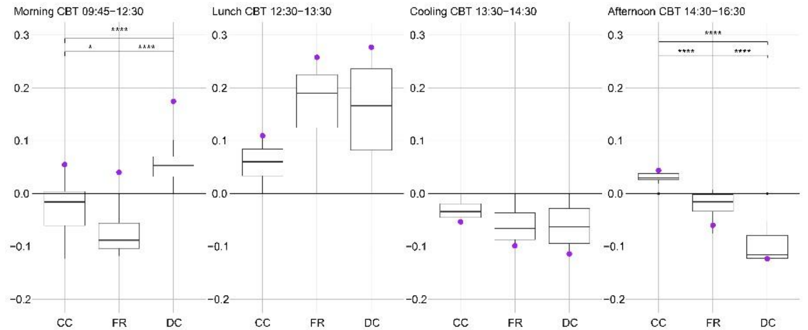

*Figure 24– Absolute variation and difference in core body temperature (CBT), normalized in FR and DC as differences against CC (Starting value=0), within each time-group, in [K]. Purple points depict the absolute change the data shows within each scenario and time-group. * p<0.1; ** p<0.05; *** p<0.01; **** p<0.001.*

Upon scrutinizing the data comparison, several noteworthy observations emerge. The discrepancies between Texp and CBT within each time-group show an expected relation during Lunch but an inverse correlation during Afternoon. While during Lunch higher exposure temperatures lead to a higher heat gain (rising CBT) as seen in the absolute change (purple point), during Afternoon higher exposure temperatures lead to higher heat losses (declining CBT). This phenomenon is particularly evident in the DC Afternoon dataset, where Texp increases by ~ 2K while CBT decreases by 0.12K. The most substantial increase in CBT occurs during Lunch across all scenarios, whereas the most significant surge in Texp is observed during Afternoon in FR and DC, and during Morning in CC. Conversely, the most considerable decrease in CBT arises during Cooling in CC and FR, but during Afternoon in DC. The Texp never decreases throughout the time-groups in CC, whereas the Texp in FR decreases during Lunch and DC most significant declines during Cooling. It should be noted that this doesn't account for the immediate step change between two time-groups, when reentering the office after Lunch (-1.57K in FR; -1.91K in DC). The CBT in DC shows a significant difference ($p<0.001$) from the other scenarios exclusively during Morning (higher) and Afternoon (lower). Although all scenarios demonstrate a decline in CBT during Cooling after an increase during Lunch, no significant differences are observed in CBT during Lunch and Cooling among the individual scenarios. Significant variations in CBT during Afternoon are likely influenced by sustained differences in cooling strategies. Furthermore, DC exhibits a more pronounced fluctuation, with the largest overall range in Texp (2.57K) and CBT (0.53K) data, throughout the day (with CBT range of CC: 0.37K and FR: 0.50K). When contrasting CC and FR, an inverse relationship between Texp and CBT is evident across all time-groups (lower Texp correlates with higher CBT) except during Lunch, where lower Texp coincides with lower CBT. Conversely, comparing CC and DC reveals a consistent relationship between Texp and CBT in all time-groups (lower Texp corresponds with lower CBT) except during Afternoon, where lower Texp aligns with higher CBT.

We also compared the differences in PMV across various scenarios and time groups (Appendix 6), which demonstrates consistent findings. It is important to interpret the PMV evaluation with caution, as we assumed constant values for clothing insulation (clo = 0.5) and metabolic rate (met = 1.1). Additionally, since there was minimal variation in humidity and air velocity and the primary factors influencing PMV variation were therefore fluctuations and differences in air and mean radiant temperature, both analyses yield similar comparisons.

5.3.4 Conclusion

These findings suggest a substantial impact of indoor conditioning profiles on our heat loss in CBT, that can be summarized as follows:

1. The findings indicate no clear relationship between the conditioning scenarios and the overall change in CBT throughout the day, confirming the first hypothesis, but seem to influence the range and trend within certain time frames.

2. The findings indicate no clear relationship between elevated indoor temperatures and the CBT during Morning, especially when comparing CC and FR, which questions the necessity and effectiveness of cooling Pre-Lunch.
3. The findings indicate the *Dynamic Conditioning* profile to affect the CBT in the Afternoon, exemplified by DC's continuous decline in CBT against both FR and CC despite rising exposure temperatures, and the cessation of air cooling after 14:30.

5.4 Part II – Simulated energy reduction potential of Dynamic Cooling strategies in an exemplary office building in Germany

This part addresses the second hypothesis in this paper. To understand whether Dynamic Cooling can serve as a viable strategy to reduce cooling energy consumption in pre-existing office buildings while adhering to current standards and remaining within the operational capabilities of contemporary mechanical systems, a comprehensive simulation analysis of thermal comfort, energy peak load and -demand within typical office environment typologies was undertaken and subsequently validated.

5.4.1 Boundary Conditions.

The thermal-dynamic simulation was conducted using TRNSYS 18, employing the parametric simulation tool TRNLizard, and executed within the graphical programming environment Grasshopper in Rhinoceros 7. TRNSYS 18 has been validated in accordance with ANSI/ASHRAE Standard 140 Section 5.2 [30]. The simulation encompasses 270 scenarios of an office space, characterized by variations in dimensions, window-to-wall ratio, thermal mass, orientation, and cooling strategy. The parameters of the simulation are outlined in Table 6.

ConstructionType [C_{wirk} / A_G] (a)	**OfficeType**	**WWR***	**Orientation**	**Cooling strategy**
Light < 50 Wh/(Km²)	Single 9 m² (b); 1 person (c)	60%	East	Conventional (S_{CC}) Set point temperature: 26°C (d)
Medium ≥ (50 Wh/(Km²); ≤ 130 Wh/(Km²)	Double 25 m² (b); 3 people (c)	90%	South-East	Dynamic (S_{DC}) Set point temperature: 30°C (during 12:30-14:30: 26°C)
Heavy > 130 Wh/(Km2)	Open 64 m2 (b); 10 people (c)	-	South	Passive (SP) Set point temperature: 40°C (e)
-	-	-	South-West	-
-	-	-	West	-

*Table 6 – Simulation parameters (total simulation variants: 270). *Window to wall ratio; (a) According to DIN 4108-2:2013-02 [142]; (b) According to DIN V 18599-10 [216]; (c) According to German office safety requirements ASR-A.1.2 [217]; (d) According to Category I DIN EN 16798 [51]; (e) Even though the scenario is assumed passive it has a mechanical cooling set point of 40°C to simulate a realistic passive environment and thus an energy demand at high indoor temperatures.*

Each simulation constitutes a unique combination within the matrix of Table 6. Most importantly the simulations are categorized into three cooling strategies. The first represents a constant cooling (S_{CC}) conforming to German standards. The second temperature profile aligns with ideal physiological considerations, mirroring the findings of our preliminary study in Part I (S_{DC}). The third serves as a reference to a passive environment (S_P) with no cooling below 40°C indoor air temperature. All cooling types are conceptualized as ideal cooling with no upper limit to the peak load of the system, to understand the necessary energy load and demand necessary to adequately fulfill the prescribed profiles.

The simulation is based on predicted weather data for the year 2045 in Mannheim, reflecting the location with the hottest summer scenario in Germany, utilizing open-source weather data from the German Weather Service (DWD). The data comprises a test reference year (TRY), predicting averaged yet representative meteorological conditions, based on historic conditions between 1995 and 2012 and climate change predictions according to the RCP-4.5 scenario [132]. Figure 25 depicts the underlying weather data used.

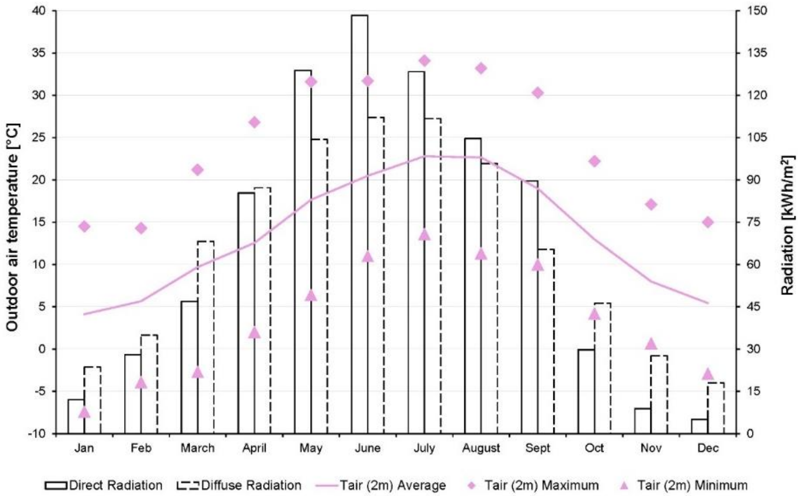

Figure 25 – Average, maximum, and minimum outdoor air temperature, and direct and diffuse horizontal radiation per month in Mannheim 2045 according to the RCP-4.5 scenario TRY by DWD [132].

The primary objective of the simulation is to quantify the limitations of the peak capacity of the mechanical system, assess energy-saving potential, and define the thermal comfort range in the context of extreme weather conditions. The room dimensions and volume are classified into three categories (single office, double office, and open office) with height excluded as a metric for volume change. The room components' heat capacity adheres to DIN 4108-2 standards, categorized as "light-, medium-, or heavy-weight construction" [142]. The outside wall insulation quality (U-value of 0.19 W/(m²*K)) aligns with current German standards [134], presenting an optimistic scenario to eliminate building physics and condition as influential parameters in the simulation's overall performance. The wall to window ratio (WWR) is set to 60% and 90% glazing share, representing the typical architypes of the modernist ribbon window and curtain wall configurations, most often represented in the office typology posing the highest risk of overheating

[218]. Five orientations are considered, following the highest radiation exposure and consequent maximum solar gains [219]. Assumptions about internal gains, air change rates, and other usage-related inputs follow the Swiss standard SIA 2024:2015 and German standard DIN V 18599-10. Consistent measures against overheating across all scenarios include external sun protection (radiation-controlled) and nighttime ventilation to effectively lower the operative temperature during user absence. The studied office space encompasses various iterations of plausible building typologies with existing measures to mitigate extreme heat stress in summer. The primary goal of the simulation is not to determine the sizing of HVAC systems based on dynamic cooling profiles in new constructions but, rather, to understand the feasibility of temporally restricting cooling operations in existing office buildings reliant on mechanical conditioning.

5.4.2 Analysis and Findings

Figure 26 illustrates the results of the simulation, clustered by shape according to the cooling strategy and further visualized in a trend line combining the annual energy demand for cooling in kWh per square meter and the Over-Temperature-Kelvin-Hours (OTKH).

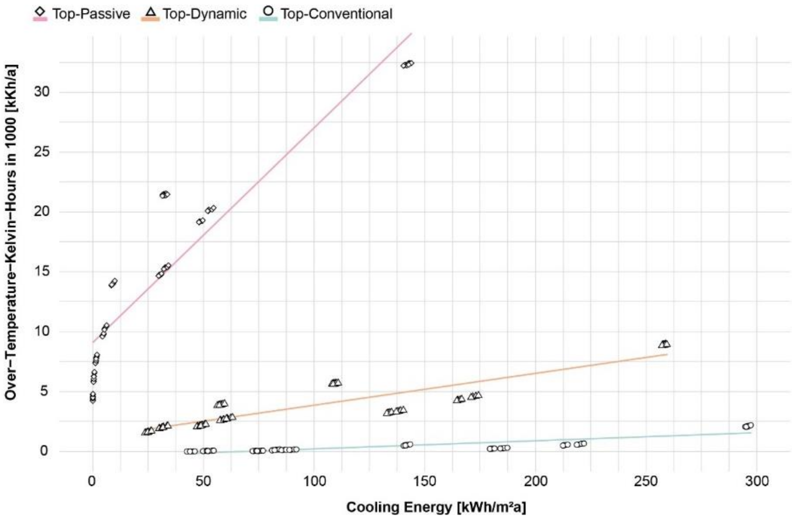

Figure 26 – Scatter plot of the cooling energy demand and Over-Temperature-Kelvin-Hours according to DIN EN 4108-2 of all simulation variants, clustered into the conditioning strategy (Passive = S_P, Dynamic = S_{DC}, Conventional = S_{CC}).

OTKHs occur when the indoor operative temperature exceeds the threshold temperature defined by DIN 4108-2 [142]. In the case of the Mannheim weather data (categorized as climate region C), this threshold is 27°C operative temperature.

Furthermore, the OTKH calculation takes the degree of exceedance into account through the difference in indoor and threshold temperature, as described in the following equation while $T_{i,\text{indoor}} > T_{\text{threshold}}$:

$$OTKH = \sum_{i=1}^{n} \left(T_{i,\text{indoor}} - T_{\text{threshold}}\right)$$

$T_{i,\text{indoor}}$: Indoor operative temperature at time i
$T_{\text{threshold}}$: Threshold temperature according to DIN 4108-2
n: Number of hours during which the indoor temperature $T_{i,\text{indoor}}$ exceeds the threshold temperature $T_{\text{threshold}}$

To ensure the comparability of simulations, all scenarios incorporated mechanical ventilation for the required air exchange, including the passive scenario. Consequently, the passive strategy also exhibits a cooling demand in the variants of high discomfort (> 5000 kKh/a). These instances initiate cooling at an indoor air temperature of 40°C, offering an alternative to insufficient air exchange through infiltration or window operation. Overall observations indicate that dynamic cooling variants exhibit a closer correspondence to conventional cooling variants than to passive variants. Despite all variants of the Ideal Dynamic Cooling (SDC) category displaying discomfort levels above the annual threshold requirements of 500 OTKH for office buildings, as defined by DIN 4108-2 [142], ranging between 1522 and 8968 Kh/a, their comparison with conventional cooling variants is more pronounced than with passive variants.

Understanding the temporal distribution of these OTKH is crucial when considering the temporal variability in the impact of environments outside the TNZ on the cardiovascular system, as seen in Part I of our findings. Conventional calculation methods for discomfort often fail to differentiate temporal variations in the hours of discomfort. In Figure 27, the daily temperature profile of all cooling scenarios is depicted within the most effective scenario (heavy construction, 60% wall-to-window ratio, south-facing, single office) for alleviating discomfort during the hottest week of the TRY from August 5th to August 9th. While in the S_{CC} all hours of discomfort (temperatures exceeding 27°C, as defined by DIN 4108-2 [142]) are concentrated in the afternoon (after 2 p.m.), the S_{DC} maintains temperatures above 27°C throughout, demonstrating a more evenly distributed pattern of discomfort, with 35% of the OTKH occurring before 2 p.m.
Figure 27 also visualizes the absolute difference in specific cooling demand between S_{CC} and S_{DC} (calculated $S_{CC} - S_{DC} = \Delta$ Specific Cooling Load). While the S_{DC} scenarios are designed to limit cooling time to two hours per day, simulation results indicate that this objective is seldom achieved, occurring only in a few simulation variants. Overall, the A/C cooling hours per day vary within the DC variants anywhere between 2.55 h/d (SD: 4.25) to 8.02 h/d (SD: 5.06). In the simulation variant with the overall highest cooling demand (Light construction, 90% WWR, South-West facing, Open office), cooling is required throughout the entire occupied period (11 hours, as per DIN 16798-1) on 43 days, compared to 4 days in the simulation variant with the

smallest cooling demand (Heavy construction, 60% WWR, South facing, Single office). This is primarily due to the air temperature frequently reaching 30°C outside the designated cooling period (12:30-14:30), thereby activating a cooling demand and extending the two-hour-per-day schedule. Nevertheless, both the cooling peak load and overall energy demand are notably lower than those observed in the S_{CC} scenarios. A normalized reduction in cooling energy demand of 51.3% is illustrated in Figure 28 when considering the conventional and passive cooling demands as the maximum range. Concurrently, the OTKH only increases by either 25.2% or 36% (both normalized against S_{CC} and S_P) depending on the calculation method, following either DIN 16798 or DIN 4108-2, respectively.

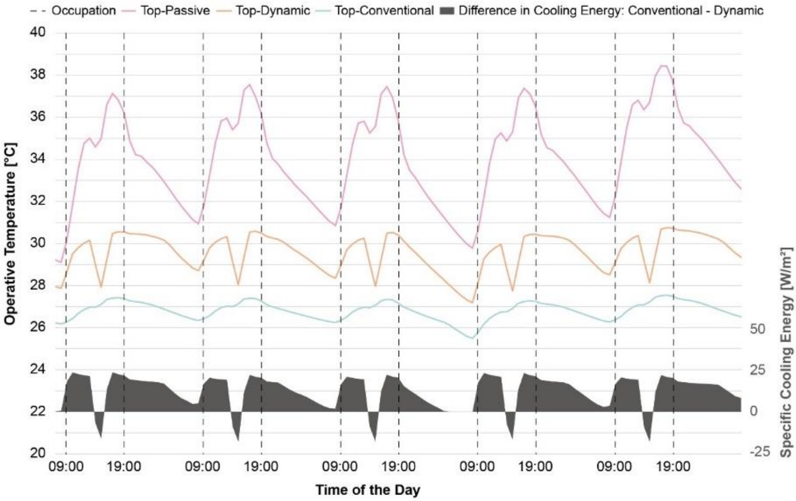

Figure 27 – Daily temperature profile of all cooling scenarios (Passive, Dynamic and Conventional) and absolute difference in cooling energy demand (Calculated by subtracting the energy demand of S_{DC} from S_{CC}) for an extreme summer week (August 05.-09.) in the scenario Heavy construction, 60% WWR, South facing, Single office.

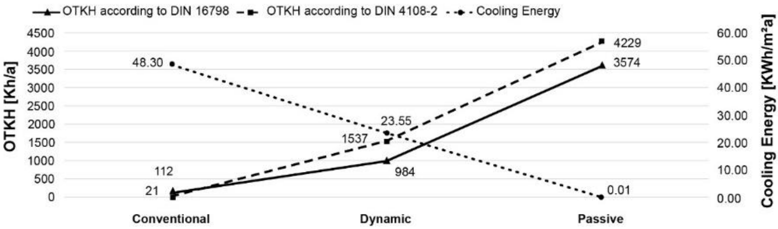

Figure 28 – Comparison of the energy demand and discomfort (measured in over-temperature-kelvin-hours) in the scenario Heavy construction, 60% WWR, South facing, Single office.

In evaluating the maximum peak loads for cooling across the 270 scenarios, categorized by conditioning scenario as outlined in Table 7, it is apparent that the scenarios S_{CC} and S_{DC} exhibit minimal differences. Specifically, the maximum, minimum, and mean specific peak cooling load of S_{DC} are slightly lower than those of S_{CC} scenarios, a trend also evident in the variation in cooling load during the extreme week illustrated in Figure 27. This observation suggests that the Dynamic Cooling profile may represent a viable option for the majority of existing office environments that are currently equipped with and adequately conditioned by a mechanical Heating, Ventilation, and Air Conditioning (HVAC) system.

Scenario	**Max. Peak Cooling Load [W/m²]**	**Min. Peak Cooling Load [W/m²]**	**Mean (SD) Peak Cooling Load [W/m²]**
Conventional	179.9	88.6	127.7 (± 31.4)
Dynamic	177.3	86.3	123.9 (± 33.4)
Passive	134.1	7.6	64.4 (± 37.1)

Table 7 – Max., Min., and Mean (± standard deviation) of the Peak Cooling Load of all simulation variants, clustered into the conditioning strategy (Conventional = S_{CC}, Dynamic = S_{DC}, Passive = S_P)

The simulation suggests that the savings in cooling demand and the reduction in the maximum cooling load do not consistently exhibit a linear relationship with the corresponding decline in thermal comfort. The reduction in energy demand demonstrates a similar (negative) linear trend as the increase in Over-Temperature-Kelvin-Hours (OTKH) when comparing conventional to passive cooling profiles. In contrast, comparing the relationship between the conventional and dynamic profiles reveals a more moderate increase in OTKH at the same linear regression of cooling energy. Additionally, comparing the dynamic to passive profile shows a steeper increase in OTKH compared to the linear decrease in cooling energy demand (Figure 28).

This potential of energy savings is further evident in the visualization of the summer hours of occupancy within the adaptive comfort band according to DIN 16798 in Figure 29. It should be noted that this is an atypical evaluation of a mechanical system, which are usually assessed against fixed temperature thresholds (i.e. 26°C, category II, DIN 16798). However, given that dynamic conditioning represents a hybrid system and the adaptive comfort band has proven to be more accurate in depicting observed thermal comfort and preference votes [220], all three scenarios are compared within the adaptive comfort band. In such context, the S_{CC} shows few hours above the category I threshold, often leaning closer to the bottom threshold than the top. Conversely, the S_{DC} spans the entire range of the comfort band, with only a few points above the category III threshold. S_P shows values well beyond the upper thresholds. Recognizing this correlation between energy demand and thermal comfort also emphasizes the considerable potential in addressing the presumed discomfort of category III. Any deviation between the operative temperature and the upper limit of category III underscores a deliberate prioritization of thermal comfort over energy consumption.

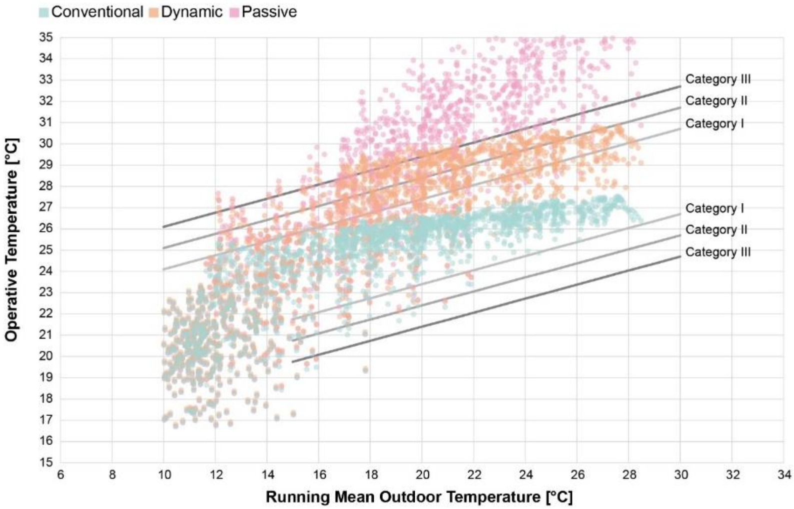

Figure 29 – Hourly performance according to the adaptive comfort range of DIN EN 16798 for conventional, dynamic and passive cooling in the scenario Heavy construction, 60% WWR, South facing, Single office. Every point represents one hour during occupancy and summertime (running mean outdoor temperature >10°C). (Passive = S_P, Dynamic = S_{DC}, Conventional = S_{CC})

While the objective of all comfort standards is to minimize the occurrence of OTKHs, the building industry's overarching goal should be to achieve this with the utmost energy sufficiency. The critical juncture in this relationship is apparent in the threshold of comfort category III within the results of S_{DC}. However, it should be noted that these are the ideal assumptions of the simulations, devoid of considerations for the performance gap between simulated and real usage profiles. Nevertheless, the aim of the building standard to prioritizing as little thermal discomfort as possible must be questioned in light of the analysis presented in Part II and the imperative to save resources.

5.4.3 Conclusion

These findings suggest a substantial potential of indoor conditioning profiles on the overall energy use and simulated thermal comfort, which can be summarized as follows:

1. The findings indicate a clear unused potential of cooling energy reduction, more specifically there seems to be a more favorable relation between the energy demand and the resulting hours of thermal comfort in the Dynamic Cooling than within the common practice of constant cooling, confirming part of the second hypothesis, that Dynamic Cooling can function as a viable sufficiency strategy to cut cooling energy.
2. The second part of the hypothesis couldn't be presented and confirmed, as none of the simulation variants of Dynamic Cooling were able to show results in accordance with

the standards, when only conditioning to 30°C outside of the cooling period of two hours. However, it should be noted that an adjustment of the temperature setpoint outside the cooling period (<30°C) would, in theory, be able to reduce the hours of discomfort substantially at the price of more energy use, as proven by the CC variants.

5.5 Limitations and Discussion

5.5.1 Part I

The study elucidates several challenges and limitations that warrant careful consideration when interpreting the findings. One notable aspect is, due to the nature of the study not being conducted in a lab environment, the fluctuating temperature differences observed in the outdoor weather conditions as well as indoor conditions, showing large discrepancies between the first and second measurement day as well as between the scenarios, potentially leading to a bias in comparability and interpretation of tendencies in the data. Another limitation is determined by the limited days of measurements. The participant sample size and homogeneity (while offering consistency) also limit the generalizability of the results. Individual variations in cardiovascular activity, core body temperature and metabolic rate, particularly due to fitness level, could not be addressed in this study. The menstrual cycle phase of female participants that is assumed to influence the core body temperature and perceptions of indoor environments, was documented but showed no relevant significance. Understanding the effect of the menstrual cycle on the thermal resilience capacity of the body, especially for participants experiencing heat stress during the luteal phase, would be important for further research. While the core body temperature was normalized and analyzed by its differences in trend and magnitude, this dataset alone doesn't conclude the underlaying thermoregulatory processes that might have influenced the identified patterns. A more in-depth analysis on the thermoregulatory processes could help explain the moments of fast heat transfer. Since the thermal conditions in mechanically conditioned office environments are kept steady in a tight range throughout the day, the dry heat loss mechanisms are more efficient in the morning and the loss in efficiency in dry heat loss in the afternoon might be initiating an earlier sweat onset. The body's second act of defense against heat stress is increasing blood flow to the skin's surface to facilitate heat dissipation through radiation and convection. This increased blood flow requires an increase in heart rate to maintain adequate circulation and oxygen delivery to the body's tissues. As the gradient between the human and ambient environment grows smaller over the day, a larger thermoregulatory load in HRV could be assumed. As such, skin temperature and heart rate variabilities are subject to further analysis by the same authors in accordance with this study. The room configuration and the placement of the cooling devices are assumed to have a significant effect on the experiment's outcome. In particular, the positioning of devices may not have accurately reflected real-world scenarios, potentially causing variations in the conditions experienced by participants. This is especially true for the height of the A/C cooling (~1.5 m above ground) and position at the facade. The seating arrangement is also considered a potential source of uncertainty, considering participants were seated within different proximities to each other and towards the entrance, showing high traffic with researchers entering and exiting the room at least every hour. Lastly, it is essential to note that the Dynamic Cooling profile was tailored as an inverted and simplified curve to the mean positive load error and diet-induced thermoregulation. Individual variations in sleeping patterns, sleeping temperature preferences, and food intake would shift this assumed cycle in starting time and potentially duration. Consequently, a more in-depth investigation into these individual factors is needed.

5.5.2 Part II

While simulations inherently involve abstract calculations and simplifications of complex real-world uncertainties, specific limitations in these simulations need further investigation. Although the intention was to compare cooling systems and establish coherent boundaries, this approach is highly theoretical and diverges from the reality of building operation, most importantly, considering the influence of human adaptation. General building standards classify two main types of building operation: mechanically ventilated and naturally ventilated. The former is evaluated through steady temperature boundaries, while the latter is assessed using the adaptive comfort band and/or solely by over-temperature hours. In this simulation, the constant cooling was initially set according to the boundary condition of 26°C air temperature, aligning with recommendations for most standards addressing mechanically conditioned spaces. However, it was later evaluated using the adaptive comfort band, as typically suggested for naturally ventilated spaces. While this approach is not inherently incorrect, it underscores the need for further investigations. These include research into the expectancy bias of thermal comfort perception in sealed offices and into hybrid scenarios or scenarios based on different set point temperatures, such as 28°C (category IV) according to DIN 16798 for mechanically ventilated spaces. The later investigation would likely reveal energy demand reductions similar to the Dynamic Cooling scenario. This aspect, was intentionally excluded from the scope of this study, given a parallel study by the same authors in 2022 that delved into the potential of temperature set points and alternative low-energy systems like ceiling fans [221]. When further investigating the potential of DC, it is advisable to explore its performance across varying climate zones and different architectural typologies, including structures with larger air volumes (e.g., libraries) and diverse usage patterns (e.g., schools).

Overall the study in Part I and the simulation in Part II encountered multifaceted challenges and limitations that should be recognized for future research endeavors.

5.6 Conclusion

This work introduces the concept of Dynamic Cooling and provides a comprehensive examination of the viability of function as a sufficient strategy to reduce the energy demand in existing sealed office buildings, with a particular focus on its impact on core body temperature. Part I of the study provided valuable insights into the temporal significance the exposure temperature poses on the core body temperature. Notably, the examination of CBT differences under varying conditions suggests high independence of temperature exposure pre-lunch but suggests it significantly affects the CBT in a close inverse relationship in the afternoon. Furthermore, Dynamic Cooling seemed to have no impact on the overall change in CBT over the course of the day but showed an increase in fluctuation magnitude, confirming the first hypothesis. The results of the dynamic-thermal simulation, underscore the significant potential of Dynamic Cooling in reducing overall energy demand, at similar peak loads, when compared to constant cooling scenarios. However, the nuanced nature of the trade-offs between thermal comfort, as indicated by Over-Temperature-Kelvin-Hours (OTKH), and energy savings is evident, revealing that reductions in energy consumption do not consistently correlate linearly with a decline in thermal comfort. This could be further illustrated by connecting the findings to a dynamic emission factor, highlighting the additional advantage of energy flexibility, by having a high electricity demand during hours characterized by statistically the lowest possible percentage of emissions. As both simulations and human studies, as conducted for this paper, inherently simplify complex real-world uncertainties, there is still a need for further investigations into hybrid scenarios, alternative set point temperatures, and cooling timeframes, as well as their applicability across diverse building types and in combination with alternative passive, or low-energy cooling strategies. As a concept paper, this study not only advances our understanding of the intricate dynamics between cooling strategies and the human heat balance, thermal comfort, and energy efficiency in office environments but also sets the stage for future research endeavors that delve deeper into the physiological and operational complexities of implementing Dynamic Cooling strategies in real-world settings.

Chapter Six

6. Conclusion

In the domain of building operations and energy management, priorities have evolved from focusing solely on comfort and productivity to addressing broader concerns, such as energy consumption and long-term health impacts. The first study explored this shift by examining the influence of standards like ASHRAE 55 and ISO 7730, which guide HVAC system development and operation. While these standards aim to ensure thermal comfort, current models often oversimplify strategies for managing high temperatures, leading to unnecessary and uniform cooling across entire buildings.

A key insight from the first study of this thesis is that reducing cooling demands by embracing wider thermal ranges and thresholds can significantly lower energy demand. However, these standards aim to minimize thermal discomfort, not energy consumption, leading us to cool buildings towards thermal neutrality rather than allowing the human body to adapt. This approach neglects the potential for any adaptive behavior, especially at higher temperatures, which was highlighted in the second study, which demonstrated the shortcomings of equal air temperatures to achieve equal thermal equilibrium, revealing substantial individual differences in thermoregulation, even within the so-called comfort zone. The findings from these first two studies align with recent research literature and suggest that exploiting energy flexibility by reducing the extent of cooling can significantly lower energy use. For example, higher cooling setpoints or even eliminating cooling in certain situations could be effective when sufficient adaptation is possible. While some studies have observed temporal variations in thermal comfort throughout the day, influenced by the circadian rhythm, current research has yet to consider the implications of dynamic setpoint temperatures aligned with these temporal changes in heat sensitivity. To address this gap, the third study focused on understanding occupants' thermal needs rather than solely catering to subjective comfort expectations.

The overarching goal of this thesis was to evaluate whether dynamically cooling indoor spaces could offer an effective and adaptive strategy for mitigating heat stress while promoting energy sufficiency in existing office buildings, all within the framework of current standards. Four research questions were analyzed through the studies presented in chapters 3–5 to answer this hypothesis. As stated, the three research studies conducted all encountered multifaceted challenges that limit the scalability and certainty of conclusions. These mainly include small and imbalanced datasets, lack of environmental context and long-term measurement periods, sensor accuracy, and non-standardized measurement methodologies. Despite these limitations, the research provided valuable insights. In the following, a detailed summary of the findings is presented in alignment with the research questions outlined in Chapter 1.2.

6.1 RQ 1: Potentials for Energy-Saving and Health Improvements

Chapter 3 explored the potential for energy-saving and health improvements when rethinking current thermal comfort standards. It was found that increasing the upper-temperature limit to 28°C from 25.5°C could significantly reduce cooling demand by 64% within the hottest week of the year while still complying with the Category IV maximum operative indoor temperature following DIN 16798-1. Introducing passive adaptations such as air velocity via fans further shifted PMV values to acceptable ranges, demonstrating that even passive scenarios without mechanical cooling can achieve compliance with thermal comfort standards.

The findings of Chapter 3 challenge the necessity of uniform temperature environments – especially as the literature review shows the benefit of broader temperature ranges on our metabolic health, insulin sensitivity, cardiovascular and immune system – suggesting that passive adaptation strategies like increased air velocity and behavioral adjustments (e.g., clothing changes) can mitigate thermal discomfort, long-term health implications and reduce energy consumption.

6.2 RQ 2: Influence of Individual Differences and Adaptation Behavior

Chapter 4 addressed how individual differences and adaptation behaviors influence the potential of temporal thermal fluctuations and physiological adaptation. The study revealed significant deviations in clothing insulation from standard assumptions at higher air temperatures, with no participants wearing more than 0.5 clo above 28.7°C. Temporal variations in thermoregulatory responses were evident, with significant differences in skin temperature (Tskw), heart rate (BPM), and root mean square of successive differences (RMSSD) between morning and afternoon. Pronounced sex differences were observed, with males showing higher mean values across various parameters but females exhibiting higher mean Tonic EDA levels. Notably, female EDA and RMSSD values were lower than males at air temperatures below 31°C, but this relationship reversed at higher temperatures, indicating a complex interaction between air temperature and individual thermoregulatory responses.

The findings of Chapter 4 suggest a large potential for adaptative behavior that we often don’t account for (i.e., clothing insulation < 0.5 clo), especially in higher temperatures. It furthermore questions the performance of steady set point temperatures to achieve thermal equilibrium, as we see large individual discrepancies between individuals' thermoregulation even at equal air temperatures.

6.3 RQ 3: Effect of Dynamic Cooling on Human Thermoregulation

The first part of Chapter 5 investigated the impact of dynamic temperature profiles on human thermoregulation. The study found no clear relationship between conditioning scenarios and the overall change in core body temperature (CBT) throughout the day. However, dynamic conditioning profiles affected the overall range of fluctuation in CBT during specific time frames. In the Morning no clear relationship between elevated indoor temperatures and the CBT was found, especially when comparing CC and FR, which questions the necessity and effectiveness of cooling Pre-Lunch. In the Afternoon, the dynamic conditioning profile led to a continuous decline in CBT, despite rising exposure temperatures, suggesting that the cessation of air cooling in the early afternoon effectively influenced thermoregulation.

The findings of Chapter 5 Part I suggest that while the dynamic temperature profiles influence the magnitude of thermoregulation, particularly during certain periods of the day, the body can successfully dissipate heat during and after the one hour of cooling exposure, therefore questioning the necessity of constant cooling throughout the day.

6.4 RQ 4: Effect of Dynamic Cooling on Energy Demand

The second part of Chapter 5 examined the impact of dynamic temperature profiles on the overall cooling energy demand. The study demonstrated a significant potential for reducing cooling energy demand through dynamic temperature set points, achieving a 51.3% reduction in energy demand with only a 25.2% to 36% increase in Over-Temperature-Kelvin-Hours (OTKH). The relationship between energy demand reduction and thermal comfort decline is not linear, with dynamic profiles showing moderate OTKH increases per increase in energy demand, compared to conventional profiles. However, none of the dynamic cooling variants met standards when conditioned only to 30°C outside the two-hour cooling period, suggesting that adjustments to temperature setpoints outside the cooling period could further reduce discomfort hours at the cost of increased energy use. The dynamic scenarios showed slightly lower peak cooling loads than the respective conventional scenarios, showcasing the viability of existing HVAC-equipped office environments.

The findings of Chapter 5 Part II suggest a favorable relationship between energy demand and thermal comfort in dynamic cooling scenarios compared to constant cooling and passive scenarios. Furthermore, the potential of reducing the amount of overcooling in office environments alone can significantly reduce the overall energy demand, even in existing buildings.

Beyond the studies conducted and research questions posed within this thesis, recent research findings further complement the findings of Chapter 5, showcasing the overall relevance of Dynamic Cooling as a concept.

6.5 Relevance of Dynamic Cooling Beyond This Thesis

In a recent publication by Reitmeyer, et al. [222], analyzing cognitive performance and thermal comfort perception under the same three different conditioning profiles examined in *Chapter 5 Dynamic Cooling – A concept of time-sensitive thermal regulation*, we were able to show no significant difference in the cognitive test performance (Creyos test) and no relationship between indoor air temperature and average cognitive performance. These results align with recent research done by Porras-Salazar, et al. in a meta-analysis in 2021 [223] and a simulated study in 2024 [224].

Reitmeyer et al. also found no significant difference in thermal comfort vote between DC and CC (both "comfortable") but a significant tendency in FR towards "slightly uncomfortable." The thermal sensation also differed slightly, with a significant tendency from "slightly cold" (CC) to "Neither hot nor cold" (DC) and "slightly warm" (FR) [222]. Especially when analyzing the temporal distribution of the thermal comfort vote, it is apparent that the tendency toward "slightly uncomfortable" only occurs after lunch and in the afternoon, as can be seen in the excerpt (B) of Figure 30. The excerpt also displays the temporal distribution of thermal sensation (A), showcasing a similar trend of increasing heat sensation after lunch and in the afternoon. The thermal sensation vote also exemplifies the overcooling in mechanically ventilated buildings in summer, a phenomenon quantified by Zhong et el. (2023) [225] and Alnuaimi et al. (2022) [108], in this case not as an overperforming A/C but overperformance in thermal sensation towards "Slightly cool".

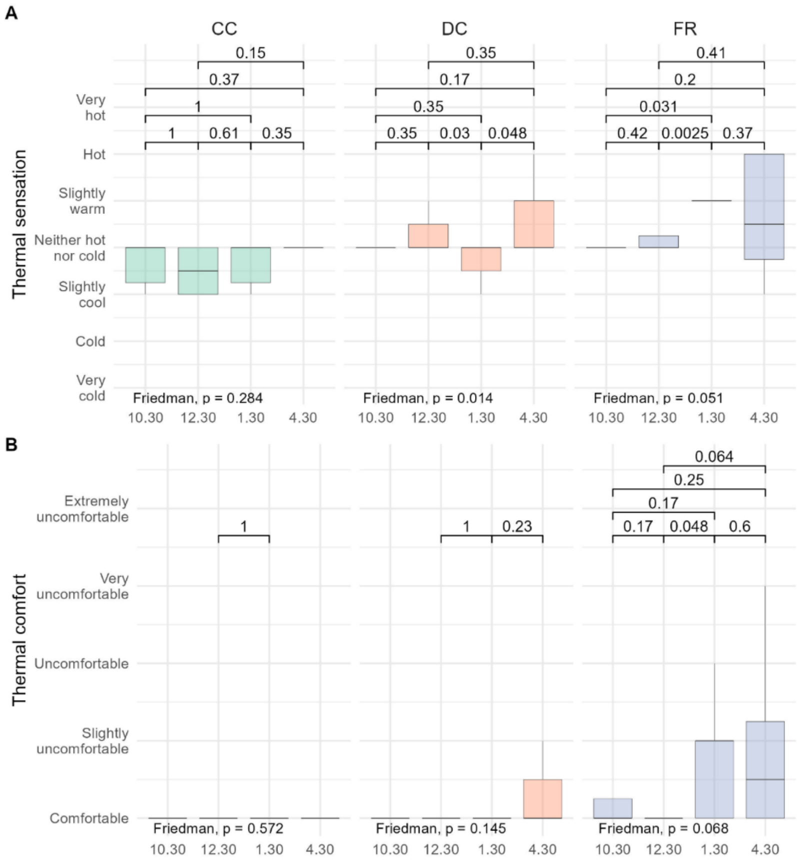

Figure 30 - Excerpt from [222] showing the temporal distribution of (A) thermal sensation and (B) thermal comfort vote in the three scenarios, from left to right: CC, DC, FR.

6.6 Connecting the Dots

Summarizing the main findings of the relevant literature and the results conducted within this thesis, the following conclusions for Dynamic Cooling suggest relevant advances in how we should evaluate thermal conditions in office environments:

1. Dynamic Cooling might benefit our metabolic health, insulin sensitivity, and cardiovascular and immune systems, as it influences the magnitude of thermoregulation without affecting the overall change in core body temperature (CBT) throughout the workday.

2. Dynamic Cooling and, in general, air temperature doesn't impact overall cognitive performance [222-224].
3. Dynamic Cooling can improve the overall thermal sensation compared to constant cooling and free-running environment and the overall thermal comfort compared to free-running, especially in the afternoon, showing similar results as constant cooling [222].
4. Dynamic Cooling shows no significant effect on our CBT or thermal comfort before lunch but elicits positive effects after lunch.
5. Dynamic Cooling can significantly reduce cooling energy and potentially eliminate overcooling at similar peak loads that are shifted towards times of highest global radiation and potential photovoltaic gains.

While the generalizability of the findings needs to be tested against all aforementioned limitations, the conceptual implications on current thermal comfort standards could be a dynamic adjustment to the adaptive comfort standard. Instead of generalizing the classification of indoor environments by the boundaries of categories I-III, the temporal diversity of these thresholds should be encouraged. Based on the results of this thesis and in reference to recent literature, we understand certain time intervals throughout the workday to affect our capabilities in mitigating heat stress. We can define a *High Tolerance Phase* in the morning ($HTP_{Morning}$) and in the late afternoon ($HTP_{Afternoon}$), according to the findings of this thesis, as well as a *Low Tolerance Phase* (LTP), according to literature and as proposed by the concept of Dynamic Cooling in Chapter 5. Both phase types represent the respective ability to mitigate heat stress at different times of day, contrary to current standards that suggest a steady state of thermal equilibrium (and preference) throughout the day. Figure 31 illustrates a times series of these three phases as a scale of tolerable heat stress within the adaptive comfort boundaries of category I-III and, therefore, in relation to the outdoor running mean temperature.

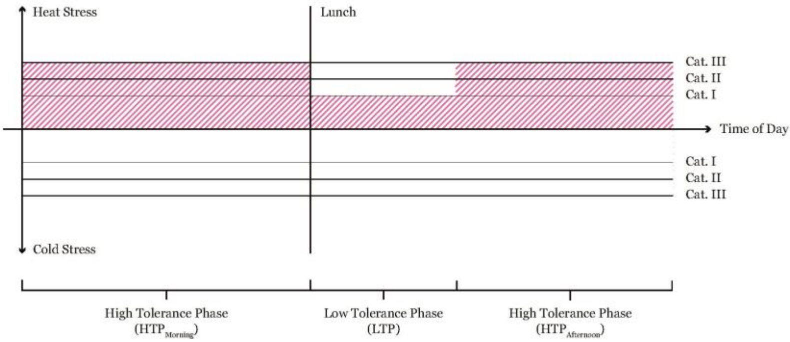

Figure 31 – Temporal distribution of High-tolerance zones (HTZ) and low-tolerance zones (LTZ) throughout a workday using Categories I-III of the adaptive comfort standard as thermal heat stress thresholds.

While exposure to higher air temperatures within the acceptable range of category III has little to no effect on our heat balance and thermal preference in the morning and late afternoon, the effects of changes in both resting energy expenditure (circadian rhythm) and energy expenditure after eating (diet-induced thermoregulation), as well as the temporal dynamics of people's neutral temperature vote, are considered in the LTP, by ensuring air temperatures within the category I boundaries. The length of this LTP remains uncertain, based on the findings of this thesis, but should be defined to start after food intake (highest cumulated energy expenditure) and should reach as far as 2 p.m. (lowest mean neutral temperature vote). Following those markers, the total time of cooling towards a temperature set point of category I can be ideally estimated at a maximum of 2-3 hours per day, or 8 – 13% of the time, compared to 10h/day or 42% of the time.

6.7 Dynamic Adaptive Comfort

Adding a temporal component to the adaptive comfort standard, as illustrated in Figure 32, involves implementing High- and Low-Tolerance Phases (HTP and LTP) into current standards. The proposed *Dynamic Adaptive Comfort* simplifies the standard into two thresholds, incorporating the third dimension of time of day. The HTP thresholds (previously Cat. III) outline acceptable indoor operative temperatures for the morning hours until lunch and afternoons, starting no earlier than 2 p.m. or 2 hours after lunch. Meanwhile, the LTP thresholds (previously Cat. I) specify acceptable indoor operative temperatures for a minimum of two hours following lunch.

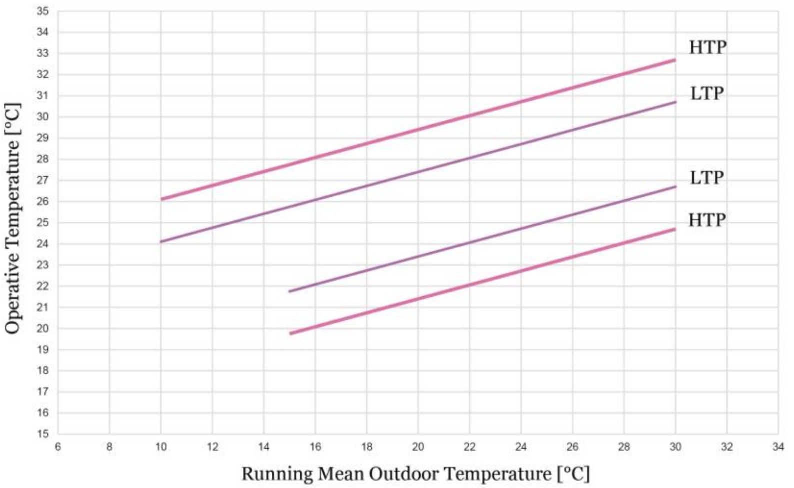

Figure 32 – Dynamic adjustment to the adaptive comfort standard by defining High-tolerance zones (HTZ) and Low-tolerance zones (LTZ).

Following the Swiss standard SIA 2024:2015 and German standard DIN V 18599-10 for typical occupation times in office environments, a temporal division might suggest HTP to account for the timeframes 08:00 – 12:00 as well as 14:00 – 19:00 and LTP to account for 12:00 – 14:00. Consequently, evaluations through simulation and the analysis of discomfort hours would need to account for this temporal differentiation, ensuring varying levels of comfort quality throughout the day.

6.8 Research Outlook

While this thesis offers several advances and methodologies in the realm of thermal comfort research, it should be seen as an argument for future research to focus on refining thermal comfort standards to incorporate temporal dynamics of human thermoregulation, moving away from single optimum conditions. These conclusions drawn in this thesis all suggest the benefits of a missing temporal metric to thermal comfort, of which one possible solution was suggested in this Chapter.

Independent of the final conclusion, this thesis, in all its studies, suggests environments with larger temperature variations and the role of adaptive opportunities as a viable alternative to constant and steady-state cooling. While many studies still focus on subjective comfort perception, this thesis showed vast individual differences in thermoregulation at the same temperatures. Advancements in sensing technology and biomedical data acquisition should be leveraged to develop reliable physiological metrics for assessing thermal health boundaries beyond computer simulations to understand individual thermoregulatory variance and healthy thresholds better and to verify the conclusions drawn within this thesis.

This research is also valuable to the building industry as it offers a sufficiency approach to managing the rising energy demand for mechanical cooling while reducing the hours of overcooling. By understanding the impact of thermal environments on human thermoregulation and adaptation capabilities, building designs can optimize indoor environments for energy efficiency and occupant health, ultimately contributing to more sustainable practices in building management.

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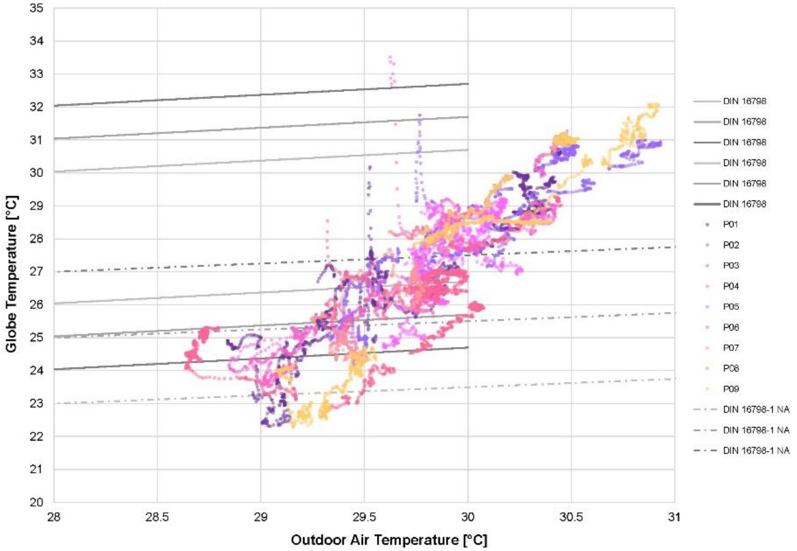
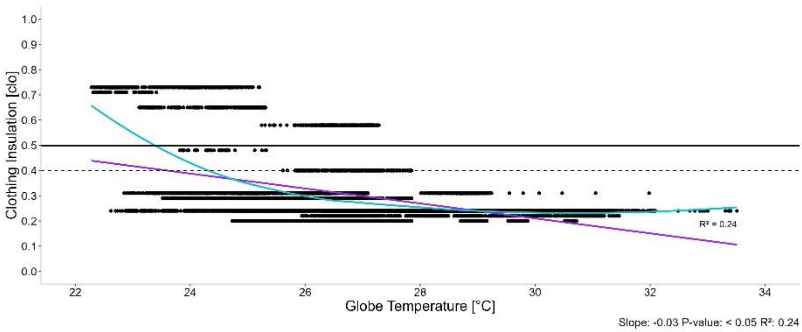
Appendices

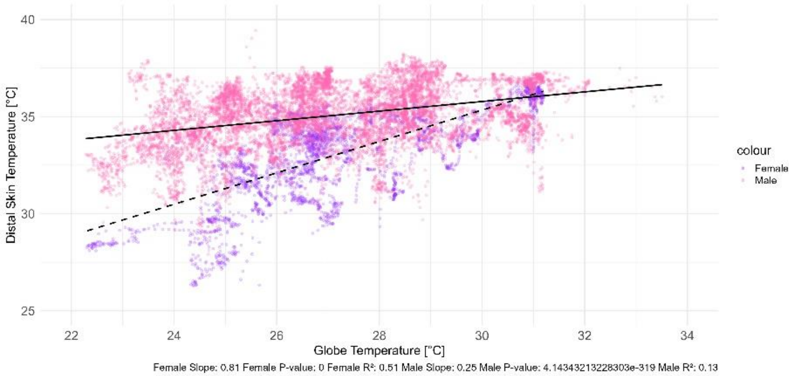
Chapter Four



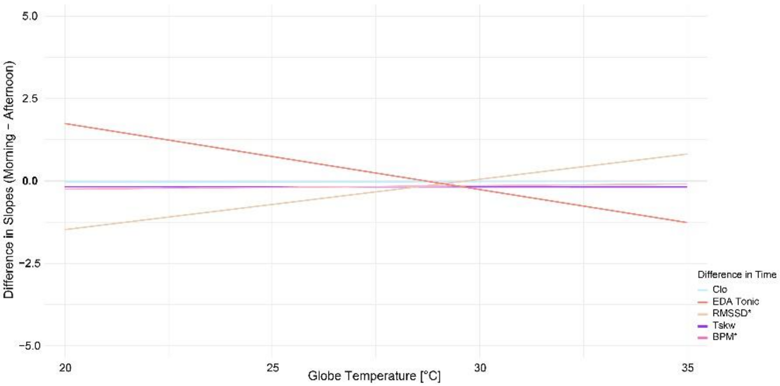
Appendix 1 - Data comparison of Figure 11 using globe temperature [°C]



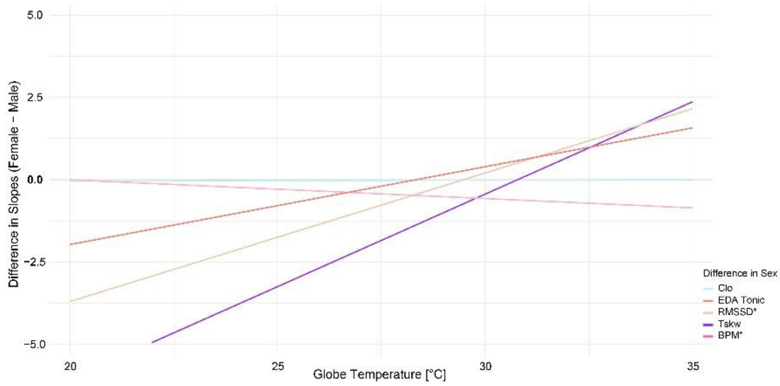
Appendix 2 - Data comparison of Figure 13 using globe temperature [°C].



Appendix 3 - Data comparison of Figure 16 using globe temperature [°C].

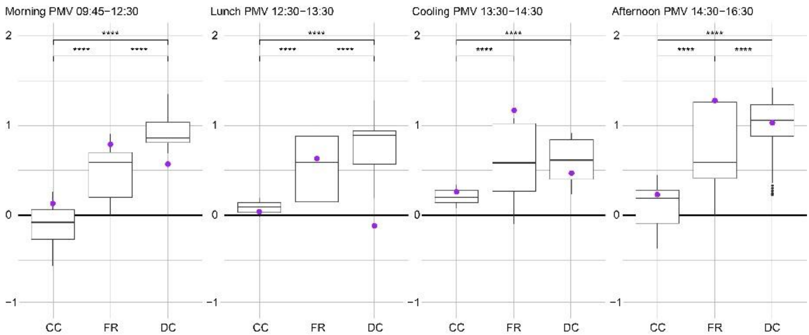


Appendix 4 - Data comparison of Figure 17 using globe temperature [°C].



Appendix 5 - Data comparison of Figure 18 using globe temperature [°C].

Chapter Five



*Appendix 6 – Absolute variation and difference in Predicted Mean Vote (PMV), within each time-group. Purple points depict the absolute change the data shows within each scenario and time-group with **** equal to p<0.001.*

List of Publications

Journal Publications:

Reitmayer, A., **Koth, S.C.**; Kobas, B.; Johnstone, K. R.; Cook, M. M.; Madigan, C.; Auer, T. (2025) Effects of dynamic thermal conditioning on cognitive load and performance in an office environment. Applied Ergonomics, 2025. 122: p. 104395.

Koth, S.C.; Kobas, B.; Reitmayer, A.K.; Hepf, C.; Auer, T. (2024) Dynamic Cooling – A concept of time-sensitive thermal regulation to cut cooling energy demand in office buildings. Energy and Buildings, Volume 322, 114734

Koth, S.C.; Kobas, B. Thermoregulatory differences in sex and time-of-day within naturally ventilated office environments. Building and Environment 2024, Volume 261, 111759. https://doi.org/10.1016/j.buildenv.2024.111759

Hepf, C.; Overhoff, L.; **Koth, S.C.**; Gabriel, M.; Briels, D.; Auer, T. Impact of a Weather Predictive Control Strategy for Inert Building Technology on Thermal Comfort and Energy Demand. Buildings 2023, 13, 996. https://doi.org/10.3390/buildings13040996

Hepf, C.; Bausch, K.; Lauss, L.; **Koth, S.C.**; Auer, T. Impact of Dynamic Emission Factors of the German Electricity Mix on the Greenhouse Gas Balance in Building Operation. Buildings 2022, 12, 2215. https://doi.org/10.3390/buildings12122215

Kobas, B.; **Koth, S.C.**; Nkurikiyeyezu, K.; Giannakakis, G.; Auer, T. Effect of Exposure Time on Thermal Behaviour: A Psychophysiological Approach. Signals 2021, 2, 863-885. https://doi.org/10.3390/signals2040050

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Peiman, P.H.; Schweiker, M.; Kobas, B.; **Koth, S.C.**; Auer, T. Variations in subjective psychological responses to similar but distinct thermal environments. Healthy Buildings 2023 Europe, p. 772-773.

Deghim, F.; Banihashemi, F.; **Koth, S.C.**, Lang, W. A data-driven approach for predicting occupant thermal comfort in offices. 33. Forum Bauinformatik 2022, Munich, pp. 257-264, 10.14459/2022md1686600

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Kobas, B.; **Koth, S.C.**; Auer, T. Towards a multivariate time-series approach with biosignal datasets for the global thermal comfort database. Proceedings of 2022 European Conference on Computing in Construction 2022. https://doi.org/10.35490/EC3.2022.201

Scoping Papers:

Koth, S.C.; Auer, T.; Werkhausen, W. Bausteine der Bauwende Scoping Paper des Fachforums Nachhaltige Bauwirtschaft. Scoping Paper des FachforumsNachhaltige Bauwirtschaft 2024. Grüner Wirtschaftsdialog e.V., Berlin. https://gruener-wirtschaftsdialog.de/scoping-paper-bausteine-der-bauwende/

Book Chapters:

Auer T.; **Koth, S.C.**; Kobas, B.; Sharmin, S.; Uslu E.; Schweiker, M.; Peiman, P.H. Raumklimalabor. Pages 224-227, Zukunft Bau Pop-up Campus Aachen. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR), 2023, Bonn. ISBN 978-3-98655-049-3

Göttig, R.; Mayer, A.J.; **Koth, S.C.** Büro und Behaglichkeit - Normen, Vorschriften und thermischer Komfort. Pages 55-66, Putz, A.; Rung, H. Hochhaus Bestand 2023. DETAIL Business Information GmbH, Munich. ISBN: 978-3-95553-615-2