Assessment of occupants' comfort expectations related to the adoption of personal environmental control systems

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I, Romina Paula Rissetto, confirm that the present thesis is solely my own work. Where information has been derived from other sources, I confirm that this has been indicated in the work.

"Currently comfortable buildings may be entirely unsuited to the conditions of the future (. . .) much also depends upon whether and how people's understandings of comfort evolve."

- Heather Chappells & Elizabeth Shove

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Abstract

Rising global temperatures have increased the need for research into human adaptability and comfort in buildings. To reduce comfort-related energy demand, low-energy alternatives for space cooling, such as Personal Environmental Control Systems (PECS), are being investigated. However, the implementation of personal adaptive control strategies should be accompanied by a relaxation of comfort requirements. Shifting occupants' comfort expectations may increase thermal acceptability and facilitate the implementation of PECS in buildings. This research aims to extend the thermal comfort criteria to support the use of PECS and in line with occupant expectations. Therefore, the role of occupants' comfort expectations in office buildings and their influence on the adoption of a ventilation PECS is investigated.

Firstly, a performance evaluation and a cost-benefit analysis of a type of ventilation PECS, an embedded personal ceiling fan (PCF), were conducted through an experimental study in a test chamber and building simulation. To define expectations in the built environment, and based on existing theories of psychology and human behavior, a theoretical framework of expectations was proposed and tested using data from a nationwide survey. A series of laboratory and field studies were conducted to investigate the influence of occupants' comfort expectations on thermal comfort and satisfaction with the PCF. The analyzed PCF is a low-energy strategy capable of meeting occupants' thermal comfort requirements in warm indoor environments. The effect of air movement on specific body parts, the physiological response and the effect of personal control on psychological adaptation are the main features of the PCF in improving occupants' thermal comfort. However, thermal perception is strongly related to expectations, decreasing occupants' thermal comfort if experiences do not match expectations. Cognitive psychological constructs can characterize comfort expectations, which are mainly influenced by warm indoor temperatures and known environments. Occupants' expectations can be aligned with the adoption of ventilation PECS by activating normative motivations through tailored information, increasing occupants' thermal satisfaction and PCF acceptance.

Findings suggest that it is possible to identify occupants according to their individual expectations by assessing social-psychological factors. Shifting comfort expectations, for instance, through normative messaging and personal control, could shape more resilient occupants toward the adoption of low-energy control strategies. Thus, implementing ventilation PECS could improve occupants' thermal comfort and energy efficiency in buildings.

Kurzfassung

Steigende globale Temperaturen führen zu einem Forschungsbedarf hinsichtlich Anpassungsfähigkeit und Nutzerkomfort von Personen in Gebäuden. Zur Reduktion des Energieverbrauchs von Raumkühlungen werden energiesparende Alternativen wie Personal Environmental Control Systems (PECS) untersucht. Die Einführung persönlicher Kontrollstrategien sollte mit einer Lockerung der Komfortanforderungen einhergehen, da eine Verschiebung der Erwartungen an Behaglichkeit die thermische Nutzerakzeptanz erhöhen und die Einführung von PECS erleichtern könnte. Ziel dieser Arbeit ist es, Kriterien für thermischen Komfort zu definieren, die den Nutzererwartungen entsprechen und die Implementierung von PECS unterstützen. Es wird untersucht, welche Rolle die Komforterwartungen der Nutzenden in Bürogebäuden spielen und wie sie die Einführung eines Lüftungs-PECS beeinflussen.

Mittels experimenteller Studien und Gebäudesimulationen wurden eine Leistungsbewertung und Kosten-Nutzen-Analyse für einen integrierten persönlichen Deckenventilator (PCF) durchgeführt. Basierend auf psychologischen und Verhaltenstheorien wurde ein theoretisches Erwartungs-Framework vorgeschlagen und anhand von Daten aus einer landesweiten Umfrage getestet. In Labor- und Feldstudien wurde der Einfluss der Nutzererwartungen auf thermischen Komfort und Zufriedenheit mit dem PCF untersucht. Die PCF bieten eine Niedrigenergiestrategie bei gleichzeitiger Erfüllung der thermischen Komfortanforderungen in warmen Räumen. Die Wirkung der Luftbewegung, die entsprechenden physiologischen Reaktionen und die psychologische Anpassung durch persönliche Kontrolle sind wesentliche Eigenschaften der PCF zur Verbesserung des thermischen Komforts. Die thermische Wahrnehmung hängt eng mit den Erwartungen zusammen und verringert den thermischen Komfort, wenn diese nicht übereinstimmen. Kognitive psychologische Konstrukte charakterisieren die Behaglichkeitserwartungen, die hauptsächlich durch warme Innentemperaturen und bekannte Umgebungen beeinflusst werden. Die Nutzererwartungen können mit der Einführung von PCF in Einklang gebracht werden, indem normative Motivationen durch maßgeschneiderte Informationen gefördert werden.

Zusammenfassend können Nutzer über die Bewertung von sozialpsychologischen Faktoren anhand ihrer individuellen Erwartungen identifiziert werden. Eine Anpassung der Komforterwartung, z. B. durch normative Nachrichten und persönliche Kontrolle, könnte dazu führen, dass Nutzer widerstandsfähiger werden und Niedrigenergiesteuerungsstrategien übernehmen. Die Einführung von Lüftung-PECS könnte damit den thermischen Komfort und die Energieeffizienz in Gebäuden verbessern.

Impact Statement

This thesis contributes to the knowledge of thermal comfort and personal environmental control systems (PECS) aimed at increasing occupant thermal satisfaction and the adoption of low-energy adaptive strategies. The key theoretical, methodological, and practical contributions of this thesis are:

- The main theoretical contribution relates to enhancing the current understanding of thermal comfort by expanding on the definition of comfort expectations in the built environment. A theoretical framework was developed to characterize comfort expectations, expanding the understanding of thermal comfort beyond the traditional engineering perspective to incorporate insights from psychology and behavioral theories. By identifying socio-psychological constructs, the assessment of thermal comfort in buildings was enhanced to encompass the dimension of comfort expectations.
- A significant methodological contribution lies in the assessment of comfort expectations. The questionnaire designed to collect information about thermal and behavioral expectations enabled the establishment of a proxy to measure comfort expectations in office environments. This method could be further expanded to investigate comfort expectations across various environments and cultural and climatic contexts.
- Significant methodological and practical contributions relate to the proposed framework for the cost-benefit assessment for the embedded personal ceiling fan (PCF). The methodological approach for the cost-benefit analysis combines well-established models to assess employees' work performance and thermal comfort, and a method to transfer productivity losses into costs. The proposed framework could be used for assessing other types of PECS in buildings.
- This research represents a pivotal contribution to informing constructors, designers, and building owners. Findings from the comprehensive performance assessment of the embedded PCF could guide its further implementation in buildings as an effective building solution, especially in renovation projects. Additionally, the exploration of socio-psychological influences on thermal comfort and fan satisfaction offers insights for designing strategies for the implementation of PECS. This includes the potential for developing behavioral interventions or feedback focused on the identified cognitive constructs, thereby enhancing occupants' thermal satisfaction.

List of Appended Papers

PAPER I - Romina Rissetto et al. (2021). “Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort”. In: *Energy and Buildings* 235.11, p. 110721. ISSN: 03787788. DOI: `10.1016/j.enbuild.2021.110721`

PAPER II - Romina Rissetto et al. (2022a). “The effect and influence of personalised ceiling fans on occupants’ comfort and physiological response”. In: *Proceedings of the 3rd Comfort at the Extremes Conference.* Ed. by Ecohouse Initative Ltd. London: Ecohouse Initative Ltd., pp. 358–367. ISBN: 978-1-9161876-4-1

PAPER III - Mattis Knudsen et al. (2023). “Comfort and Economic Viability of Personal Ceiling Fans Assisted by Night Ventilation in a Renovated Office Building”. In: *Buildings* 13.3, p. 589. DOI: `10.3390/buildings13030589`

PAPER IV - Marcel Schweiker et al. (2020b). “Thermal expectation: Influencing factors and its effect on thermal perception”. In: *Energy & Buildings* 210. DOI: `10.1016/j.enbuild.2019.109729`

PAPER V - Romina Rissetto et al. (2020). “The effects of occupants’ expectations on thermal comfort under summer conditions”. In: *Proceedings of 11th Windsor Conference.* Ed. by Ecohouse Initative Ltd. London: Ecohouse Initative Ltd., pp. 252–268. ISBN: 978-1-9161876-3-4

PAPER VI - Romina Rissetto et al. (2022b). “Assessing comfort in the workplace: A unified theory of behavioral and thermal expectations”. In: *Building and Environment* 216, p. 109015. ISSN: 03601323. DOI: `10.1016/j.buildenv.2022.109015`

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Laura Arpan et al. (2022). "The hopeful expect to be comfortable: Exploring emotion and personal norms related to sustainable buildings in the United States". In: *Energy Research & Social Science* 93, p. 102846. ISSN: 22146296. DOI: `10.1016/j.erss.2022.102846`

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1 Introduction

In the face of global warming and rising global surface temperatures (IPCC 2023), maximum indoor temperatures are expected to increase linearly with the increase of outdoor temperatures (Coley and Kershaw 2010). Rising complaints of overheating during the summer together with the anticipated economic growth (Santamouris 2016), will lead to an increased use of air conditioners. In air-conditioned buildings, a decrease in the cooling setpoint can be expected (Cian and Sue Wing 2019). Such improvement of the building's indoor environmental quality (IEQ) will lead to higher energy demand and negative ecological impact in a scenario where the building sector accounted for 30% of the global final energy consumption and 26% of the global energy-related emissions in 2022 (IEA 2023). Besides, maintaining uniform and narrow indoor temperature ranges and ignoring real-world natural variable conditions would raise occupant expectations of how thermal conditions should be. Shifting the trend towards this comfort criterion together with the building design and operation is an imminent challenge so that buildings remain comfortable for occupants without becoming cold capsules detached from the outside world.

Given that the main objective of cooling indoor spaces is to enhance occupants' thermal comfort and performance, an extensive body of literature has been focused on reducing the comfort-related energy demand of buildings by better understanding how humans perceive and adapt to the thermal built environment. Several efforts have been made in the last fifty years to understand occupants' thermal preferences, carrying out experiments in climate chambers and field surveys, to develop indices and to establish thermal comfort standards and evaluation methods. The most important findings are the basis of standards, such as ISO 7730 2005, which define temperature ranges that predict thermal satisfaction for at least 80% of occupants in a space. These standards are mostly based on the Predicted Mean Vote (PMV) index (Fanger 1970), one of the most well-established theories. This model is based on the assumption that comfortable conditions are perceived when there is a balance between the heat generated by metabolism and the heat lost or gained through convection, radiation, and evaporation. The PMV comfort model originates from laboratory studies conducted in a controlled climate chamber, where participants had almost no interaction with the environment. Based on the hypothesis that regardless of demographics and cultural differences occupants feel comfortable in a defined and narrow range of thermal conditions (Djongyang et al. 2010), its application in actual buildings, especially in warm environments, has many limitations, leading to differences in predicted and observed thermal sensation.

An alternative to the PMV approach is the adaptive thermal comfort model (Dear and Brager 1998b; Humphreys and Nicol 1998), which is based on the idea that outdoor climate influences thermal comfort because humans can adapt to different temperatures throughout the year. Against unusual or uncomfortable thermal experiences, occupants may utilize different adaptive approaches to restore their comfort, namely physiological, psychological, and behavioral (Dear and Brager 1998a). Various attempts have tried to capture those adaptations to close the gap between predicted comfort temperatures and those observed in field studies (Gao et al. 2015; Yao et al. 2009; Fanger and Toftum 2002; Schweiker and Wagner 2015). Still, comfort temperatures have been found to notably vary among locations (Nicol et al. 2020), and thermal sensation can differ among people in the same environment (Kalmár 2016).

Occupants' understanding of comfort is a complex cultural construct, and numerous factors influencing individual thermal perception are responsible for diversity in comfort temperatures. It is common agreement that psychological adaptation processes must still be better defined in the literature (Schweiker et al. 2018). According to Dear et al. 2020, the lack of empirical evidence for the psychological dimension of *expectation* may be the missing piece for understanding more accurately human thermal perception. Expectation refers to an attitude of anticipation. In the context of thermal comfort, this expectation, or feeling of anticipating a certain level of comfort, affects people's attitude towards achieving thermal comfort. Thus, the expectation of specific thermal conditions certainly is a major aspect of subjective assessment and satisfaction (Höppe 2002; Keeling et al. 2016). Luo et al. 2016 studied the effect of long-thermal experiences on thermal comfort expectations by analyzing changes in thermal satisfaction between groups exposed to air-conditioned and non-air-conditioned buildings in two climate zones in China. They suggested that it may be easier and quicker to enhance one's thermal expectations but harder to lower them. Thus, occupants in air-conditioned buildings are more likely to complain whenever the indoor temperature slightly deviates from the usual setpoint because they have come to expect thermal constancy (Dear 2007).

Relaxing comfort expectations may be an alternative path for promoting resilience in buildings. Shifted expectations could, to some extent, increase human adaptability without compromising health and productivity. When occupants' comfort temperature follows the variations in indoor climate, and after long-term climatic changes, they might be able to lower their expectations of those conditions (Fountain et al.

1996). A strategy to transform expectations could be achieved by widening occupants' thermal acceptability through adaptive behaviors, especially in free-running and green buildings (Deuble and Dear 2012a; Leaman and Bordass 2007). Implementing effective adaptive strategies in buildings is strongly related to adding control strategies possibilities (Kwok and Rajkovich 2010). Results from a field study in Australia (Deuble and Dear 2012b) suggested that expectations have a greater influence on the perception of comfort when the subject controls the indoor environment than when the users are passive. Luo et al. 2016 proposed moving air for comfort, mixed-mode buildings, and personal control systems as alternative comfort strategies to enhance adaptive capacity in buildings.

Personal environmental control systems (PECS) can provide individual thermal comfort and improve energy performance (He et al. 2017; Heidarinejad et al. 2018). PECS support the notion of adaptive thermal comfort by enabling the occupants to adjust their indoor environment to their individual comfort perception (Rawal et al. 2020) and increase thermal satisfaction by addressing intra- and interpersonal differences among occupants (Wang et al. 2018). Additionally, PECS work as "stimulation" to the thermoregulation system by aiming at body segments, which may also benefit health (Luo et al. 2022). Another advantage of PECS is that they target the direct thermal environment of occupants by conditioning their personal space in contrast to the entire building. This allows a broader range of comfortable indoor ambient temperatures, reflecting occupants' individual differences. By expanding the temperature setpoints in either the hot or cold direction, the total annual HVAC energy could be reduced at a rate between 9 and 20% per degree Celsius, depending on the climate conditions (Hoyt et al. 2015). In a review paper, Zhang et al. 2015 showed that when using PECS, an estimated potential HVAC energy savings greater than 30% can be achieved without loss of comfort. Certain PECS are suitable solutions to provide comfort in existing buildings due to their increased flexibility to adapt to the existing architecture and reduced installation efforts compared to other heating and cooling solutions. Considering that around 85% of the building stock in Europe was built before 2000, from which 75% have a poor energy performance (European Commission 2024), building refurbishment is a crucial initiative to drive energy efficiency in the sector.

Current indoor temperature design narrows the boundaries of comfort zones and minimizes the thermoregulatory efforts of occupants, jeopardizing their thermal resilience. Adaptive opportunities, such as PECS, can offer occupants the means to tailor their environment to their personal preferences. Because thermal comfort is a cultural construct shaped by society over time (Brager and Dear 2003), it may be possible to capitalize on the existing diversity of human expectations and variations in the built environment by redefining the types of conditions to which people become accustomed (Chappells and Shove 2005). Advocating for greater flexibility in comfort strategies and lowering expectations can bring thermal adaptation to non-neutral indoor climate conditions. Recognizing that future expectations are partly shaped by current experiences, shaping more resilient occupants seems to be an alternative way to redefine comfort in the face of climate change and to improve indoor control strategies towards healthier, more comfortable, and more energy-efficient buildings.

1.1 Problem statement

To get back on track with the climate goals, more than 80% of buildings are expected to be net zero carbon by 2050. Thus, using low carbon technologies and the active involvement or engagement of citizens and consumers is required to achieve 55% of the emissions reductions (IEA 2021). Implementing PECS in buildings might help reduce energy consumption while considering occupants' individual comfort preferences. Advocating for passive and hybrid cooling solutions may increase human resilience in the long term. Still, peoples' understanding of comfort will need to evolve to accept building solutions suited to the conditions of the future. As an occupant-centric building solution, PECS might help to move towards a change in comfort expectations. However, implementing PECS may require a comprehensive investigation of their performance, a better understanding of what lies behind occupants' expectations, and an investigation of how expectations might impact the adoption of PECS technologies.

1.1.1 PECS performance

PECS have actively been researched in the recent while. Based on the nature of conditioning, PECS can be categorized as heating, ventilation, cooling, or combination modes (e.g., heating and ventilation). In a review paper, Rawal et al. 2020 showed that most studies on PECS have focused on investigating ventilation PECS. A widely used type of ventilation PECS to improve thermal comfort is personal fans, such as desk or standing fans. By increasing the air movement around the human body, ventilation-based PECS reduce a person's skin temperature and facilitate increased evaporation of sweat. This heat removal produces a cool sensation without using any compressor-based cooling. A large body of literature has analyzed the effect of ventilation PECS on thermal comfort under warm indoor temperatures (e.g., Huang et al. 2013; Lipczynska et al. 2015; Zhai et al. 2015) and energy efficiency (e.g. Bauman et al. 1994; Sekhar et al. 2005; Schiavon et al. 2010; Schiavon and Melikov 2008). Some studies (Luo et al. 2022; Luo et al. 2018a; Mishra et al. 2016) have addressed human physiological adaptation when PECS is aimed at body extremities and its impact on occupants' thermal comfort. Recent studies on personal comfort models (Bogatu et al. 2022; Luo et al. 2023; Warthmann et al. 2019) have explored the possibilities of measuring physiological indicators to supplement occupant feedback when using PECS. Linking the costs of installation, operation, and maintenance with the metrics of user productivity and satisfaction might provide a wider perspective on the utility of PECS. However, very few studies included cost considerations in their analyses, and most considered only one cost aspect. A combined assessment that relates human adaptation (physiological and psychological) and energy performance may help establish the prominence of PECS over conventional air conditioning methods. Although several efforts have been made in the past decades to gain knowledge about the capabilities of PECS, the implementation of PECS in buildings is still limited. A first gap in the literature has been identified:

- There is still a lack of studies that provide a comprehensive assessment of the overall impact of PECS on occupants' human adaptation, energy savings, and cost-benefit ratio for one type of PECS.

1.1.2 Comfort expectations

In general, thermal comfort occurs when the body's temperature is within narrow ranges, the skin moisture is low, and the thermoregulation effort is minimal. However, thermal sensations are different among people even in the same environment, issuing very different opinions on thermal comfort. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2017) defined thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". As such, judgment of comfort is a cognitive process involving many inputs influenced by physiological, psychological, and behavioral adaptations. So "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol et al. 2012). Engineers and physiologists have developed our current knowledge of human thermal comfort (Rupp et al. 2015), leading to a somewhat functional definition. People's psychological characteristics can mentally affect their comfort, such as expectations or the ability to acclimate and adapt. Thus, there is more to comfort than temperature, but where expectations lie along this range is largely a matter of culture and convention (Chappells and Shove 2005).

Occupants' expectations may vary according to contextual factors such as building type, control opportunities, and climatic zones. Previous studies analyzed the effect of expectations on thermal satisfaction with the indoor environment, mainly in relation to perceived control (Zhou et al. 2014; Luo et al. 2016; Deuble and Dear 2012a), thermal experience and exposure (Luo et al. 2018b; Chun et al. 2008; Candido et al. 2010; Kim and Dear 2012), and thermal memory (Rajkovich and Kwok 2003). Although there is general agreement on the effect of expectations on occupant thermal and overall satisfaction (Dear and Brager 1998a; McIntyre 1981), it remains unclear how and to what extent expectations influence occupant comfort perception. As a first attempt, Auliciems 1981 proposed a comprehensive psycho-physiological framework of thermal perception, suggesting that expectations are influenced by past thermal experiences and behavioral and techno-cultural adaptations. However, the interdependence between expectations and behavioral adaptation has not been empirically tested. Despite the efforts to include comfort expectations in the thermal comfort assessment, there is no common agreement on how expectations in the built environment are formed and how they relate to occupants' thermal comfort. A second gap is defined as follows:

- There is a lack of a theory-based definition of comfort expectation and practical evidence on how comfort expectations influence psychological and behavioral adaptation in buildings.

1.1.3 Changing expectations toward technology acceptance

Occupant behavior significantly impacts building systems' operations and might help reduce building energy consumption (Hong and Lin 2012). To avoid impacting occupant comfort, energy reduction strategies should be occupant-centric, i.e., by considering factors such as personal preferences and expectations, personal (moral) and social norms, economic motivations, and cultural norms (Keskin and Mengüç 2018). Understanding the underlying drivers of occupant behaviors from the lens of behavioral sciences (psychological, sociological, and economic) could be associated with occupants' use and control of building systems (Heydarian et al. 2020).

Cognitive-psychological theories and factors have been widely used to test the effect of feedback on energy conservation (Karlin et al. 2015). For instance, Fischer 2008 used a heuristic model of environmentally relevant behavior to analyze the positive effects of energy-related feedback on behavior; Carrico and Riemer 2011 analyzed a mediation effect of descriptive and injunctive norms on the direct effect of interventions on energy consumption and conservation behavior. The effect of information dissemination on behaviors has been studied. Schweiker and Shukuya 2011; Day and Gunderson 2015; Brown and Cole 2009 examined the positive effect of effective training and knowledge of building systems on occupant satisfaction and energy-saving behaviors.

Many studies link the potential of targeted information and pro-environmental occupant behavior. However, occupants are more likely to adopt so-called energy-efficient behaviors when the action equals the benefits in comfort and health (McMakin et al. 2002). The increasing studies on PECS to reduce energy consumption in buildings require matching occupants' thermal comfort preferences with a non-fully-conditioned environment. Occupants' comfort preferences may be reflected in their expectations of building systems and their behaviors (Banham 1969). For instance, Li et al. 2019 used social normative messages to investigate whether energy feedback affects occupant subjective thermal evaluation of an environment and their intended personal fan usage. Results from this study showed that when messaging was delivered participants' reported thermal comfort and intention to turn on the fan at higher temperatures increased. In a recent study, Arpan et al. 2022 found that more positive expectations of IEQ were reported by participants asked to envision working in a sustainable building than by participants asked to imagine working in a conventional one. Through a qualitative study, Rissetto and Huebner 2023 found that aligning occupants' expectations of cooling strategies with PECS features, particularly the provision of personal control, could increase their thermal satisfaction. Thus, it might be meaningful to understand the interaction between targeted information to motivate the use and acceptance of PECS and occupants' expectations of IEQ. A third gap can be identified as follows:

- There is a lack of studies that examine how tailored information may influence occupants' perception and acceptance of PECS based on their comfort expectations.

Based on the identified gaps, there is a clear need for further research to enhance the current understanding of thermal comfort, taking into account occupants' expectations of indoor environmental conditions. Such research endeavors are essential for advancing the design and implementation of PECS that prioritize occupants' thermal comfort and energy savings.

1.2 Objectives and research questions

The importance of this research lies in the necessity to reduce the gap between predicted and actual comfort and expand the current knowledge on the use of energy-efficient building technologies that address individual comfort needs in an increasingly warming world. Therefore, this work aims to extend the thermal comfort criteria to be used for the implementation of ventilation PECS in buildings in line with the expectations of the occupants. In response to the need for research and the lack of evidence for comfort expectations and the interaction with PECS, this research investigates the role of occupant comfort expectations and their impact on the acceptance and evaluation of ventilation PECS. This thesis formulates three specific research objectives:

- To explore human adaptation to ventilation PECS as an occupant-centric building technology.
- To evaluate the ability of a type of ventilation PECS to provide thermal satisfaction with the minimum cost-benefit ratio.
- To provide empirical evidence of the effect of comfort expectations on reported thermal comfort.
- To develop a theory-based framework to define comfort expectations in the built environment, accounting for the factors influencing them.
- To investigate the effect of tailored information influence on the interactions between PECS and occupants' comfort expectations.

Based on the aspects above mentioned, the research questions are defined as follows:

Research Question 1: *How do occupants respond psychologically and physiologically when using a type of ventilation PECS?*

Research Question 2: *What is the cost-benefit relationship of ventilation PECS compared to other building solutions?*

Research Question 3: *To what extent do occupants' expectations of the indoor environment and building controls influence their thermal satisfaction and behavior?*

Research Question 4: *How can comfort expectations be characterized in the context of the built environment?*

Research Question 5: *To what extent can shifting comfort expectations through normative motivation improve occupants' satisfaction with ventilation PECS?*

1.3 Research scope and workflow

The scope of this research entails assessing comfort expectations in buildings in relation to the use and evaluation of PECS. Research on thermal comfort and PECS has expanded in the last decades. However, there is a lack of understanding of how comfort expectations of the indoor environment and towards building technologies, such as PECS, might shift the prediction of comfort votes and occupants' satisfaction. Thus, this thesis aims to reduce the gap between predicted and actual comfort and expand the current knowledge on the use of PECS to address the diversity of comfort needs without compromising energy consumption. For this purpose, the proposed research combines a series of experimental studies and building simulation analysis to test the performance of one type of PECS, and uses results from laboratory and field studies and theory-driven surveys to define expectations in the built environment. Figure 1.1 illustrates the overarching research workflow, encompassing the research questions and associated publications.

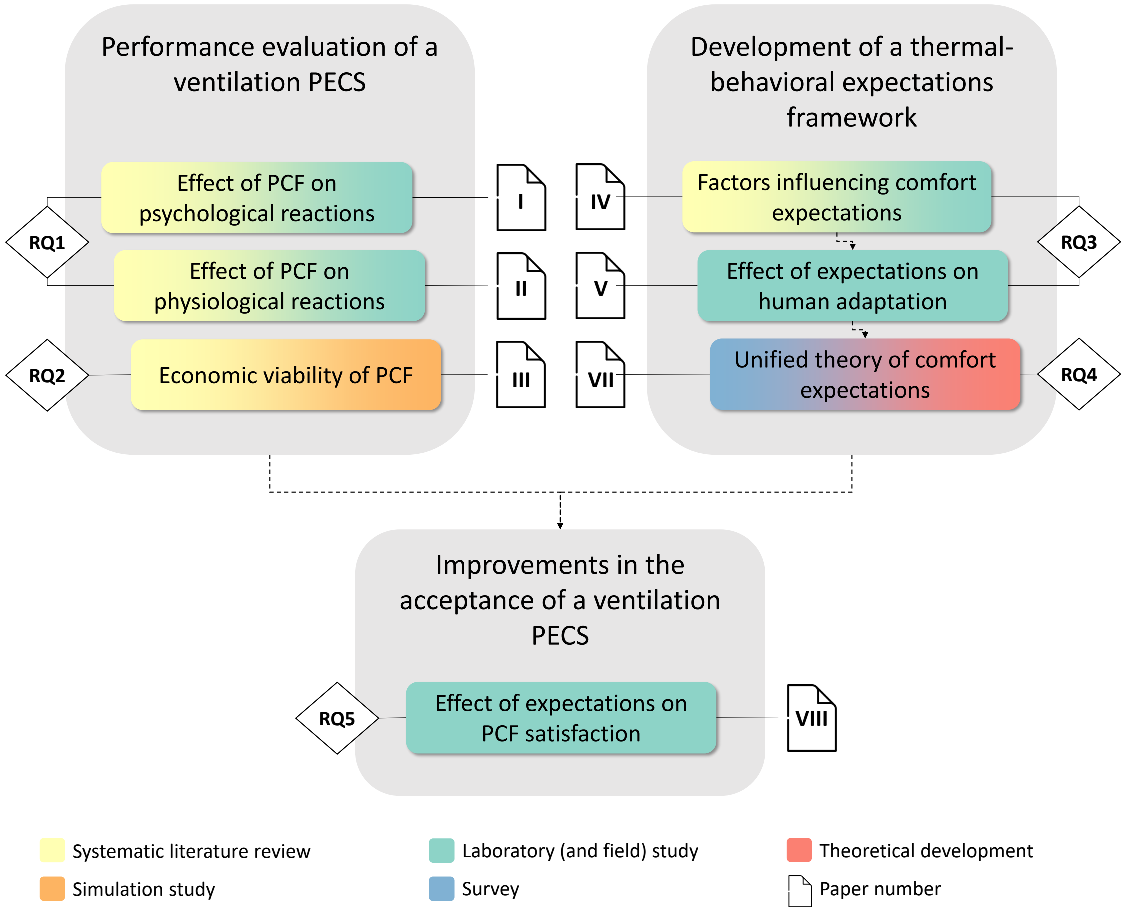
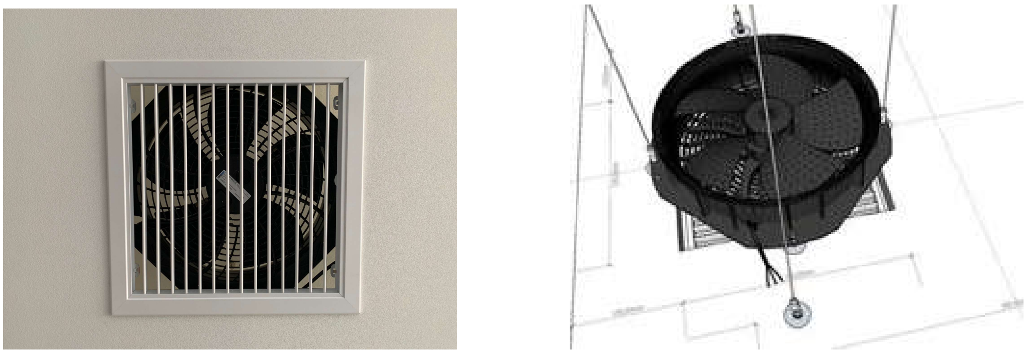


Figure 1.1: Overview of the research workflow. RQ: research question. PCF: Embedded personal ceiling fan.

The grey boxes delineate the principal phases of the thesis, while the colored boxes denote the specific studies and methods employed within each phase. Arrows indicate the interdependence between the phases and, where applicable, between individual studies, elucidating the interconnected nature of the research process.

The first phase of the research focuses on assessing the effectiveness of PECS in addressing individual comfort requirements. Specifically, this thesis examines the performance of an embedded personal ceiling fan (PCF) as a form of ventilation PECS within an office setting. The innovative PCF was developed as part of the BMWK project "Deck-In-Vent" (03ET1563). The main objective of the project was to design and deploy the PCF as an integral part of the refurbishment of the district office building in Dillingen, Germany. The district office is a 4-story office building built in 1966 with a typical final energy requirement of 206 kWh/m^{2}a (DIN EN 18599 2018-09). The difficulty of reducing the number of hours in summer with room temperatures above the comfortable range is typologically significant for existing buildings and is of great importance in the context of the increasing summer heat load due to climate change. Therefore, the incorporation of the embedded PCF, as a energy-efficient cooling strategy, together with the inclusion of night ventilation aimed to enhance occupants' thermal satisfaction during the summer months.

Figure 1.2 shows the developed solution, which is a small-diameter ceiling fan incorporated into an acoustic panel hanging below the ceiling. Below each ceiling fan, a removable grille with blades fixed at one point allows adjustable angles to manipulate different air directions to the head of the participants. The PCF is an individualized cooling solution, as each workplace has its PCF that the employees can control according to their preferences.



(a) View from below: mounted grille with an angle of 90°

(b) 3D representation from above: fan mounted above hanging panel.

Figure 1.2: Details of the integrated ceiling fan.

After conducting a systematic literature review of PECS, an experimental study was developed to assess the PCF's ability to meet occupants' thermal comfort needs in warm indoor conditions. The study targeted a sample of German adults within a simulated office context. In addition to analyzing participants' selection of fan air speed and psychological responses, the study investigated their physiological reactions while using the device. The final phase of the assessment involved conducting a cost-benefit analysis of this technology, which was performed through a simulation study validated with results from a monitoring campaign.

The second phase focuses on developing a thermal-behavioral expectations framework. A first analysis delved into studies and theories from various fields to explore human expectations. An initial assessment of comfort expectations was proposed through a combination of laboratory and field studies, with a primary focus on identifying factors influencing occupant expectations. These outcomes laid the groundwork for designing a subsequent laboratory study to examine the effect of expectations on thermal perception and behavioral adaptation under controlled conditions.

Drawing from findings in the experimental studies and existing psychological and behavioral theories, a theoretical framework was proposed to represent expectations in the built environment, which was empirically tested using data collected through a nationwide survey.

The third phase aims to enhance acceptance and satisfaction with the PCF. Leveraging results from the performance evaluation of PCF in the first phase, a laboratory study was designed. Building upon the expectation framework developed in the second phase, this study investigates the influence of comfort expectations and normative motivations on participants' evaluation of the PCF and their reported thermal comfort.

1.4 Overview of the thesis

The structure of the thesis comprises five chapters (Figure 1.3). Within each chapter, summaries of the methods and results from individual papers are provided, accompanied by discussions on the respective research questions[1]. Chapter 2 focuses on papers I, II and III, which delve into the performance evaluation of the embedded PCF. Chapter 3 describes papers IV, V and VI, which investigate comfort expectations. Chapter 4 discusses paper VII, exploring the impact of comfort expectations on the acceptance and evaluation of the embedded PCF. More comprehensive details on the studies can be found in the associated publications appended to the thesis. Additionally, certain chapters contain "remarks", highlighting significant findings pertinent to the design of subsequent studies within this thesis. A conclusion of the work is presented in chapter 5, where the main contributions to the field are delineated alongside the limitations of the studies, its practical implications, and recommendations for future research.

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[1] The use of "we" in describing the papers is intended to encompass the corresponding co-authors.

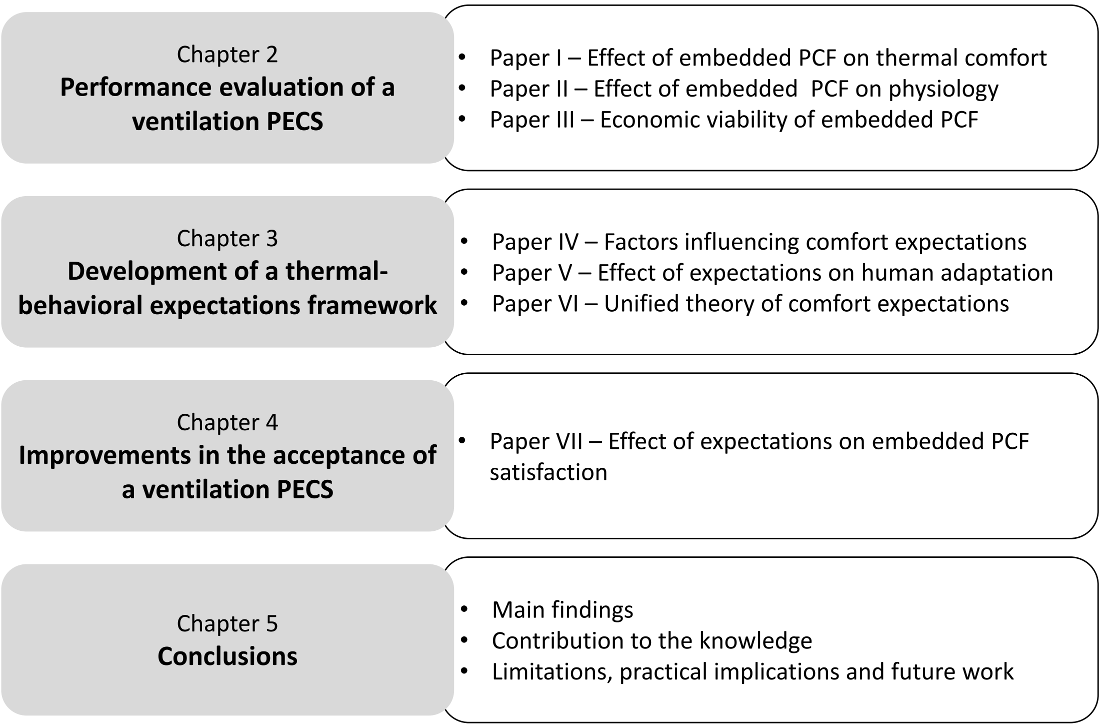

Figure 1.3: Overview of the thesis structure.

2 Performance evaluation of a ventilation PECS

This section aims to address RQ1 and RQ2 by summarizing the findings of papers I, II and III.

2.1 Effect of an embedded personal ceiling fan on occupants' thermal comfort

Paper I - Romina Rissetto et al. (2021). "Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort". In: *Energy and Buildings* 235.11, p. 110721. ISSN: 03787788. DOI: `10.1016/j.enbuild.2021.110721`

This study aimed to examine the performance of an embedded personal ceiling fan to enhance thermal comfort at moderately high indoor temperatures. We tested the effects of temperature conditions, the direction of supplied air, and the possibility of personal control at different activity levels.

2.1.1 Methods

We conducted a repeated measures experimental design in a laboratory setting. We performed the study in a climate chamber in Germany (Schweiker et al. 2014), testing the embedded personal fan presented in section 1.3. A total of 45 German-speaking participants (42% female and 58% male), divided into two age groups (42% between 18 – 34 years old and 58% between 50 – 70 years old) participated in the experimental test.

After a 30-minute acclimation phase, where no fan use was allowed, participants were exposed to six different fan configurations (20 minutes each) in sitting or standing positions. The fan configurations related to the airflow direction and distance to the participant's head. In each configuration, participants were first exposed to a constant air velocity coming from an embedded personal ceiling fan and, afterward, were allowed to modify the fan air speed via remote control. The rooms were set to a room temperature of 28 °C (slightly warm) in the first session and 31 °C (hot) in the second session, and a constant relative humidity ($\sim$ 50%). We summarized the experimental conditions in Table 2.1.

Table 2.1: Experimental conditions from the study in 2018.

	Description
Study duration	15 working days
Session duration	3.5 hours
Control possibilities [a]	Turn on the fan and adjust air velocity
Distance to fan (m) [b] and direction of airflow (positions)	0.0 (above), 0.5 (side), 0.5 (side, standing), 0.75 (front), 0.75 (back), 1.15 (side)
Thermal conditions	28 – 31 °C (50% RH)
Fan air speed	constant – adjustable
Participants in each room	1
Metabolic rate (met)	1.1 – 1.3 (standing)
Sessions per participant	2
Daytime	morning – afternoon
Clothing level (clo)	0.4 + 0.1 from chair

[a] It refers to the given possibilities to adapt to or change the indoor environmental conditions in the room. [b] The distance was measured from the center of the fan to the participant's head.

The participants answered several questionnaires during the acclimation phase and at different times during the experimental phase (for each experienced position). The questions focused mainly on the participants' perception of the indoor thermal conditions and indoor air quality (IAQ), the airflow coming from the fan, and their experience with the fan. We collected indoor and outdoor parameters and the interactions with the remote control through the building management system (BMS) and AHLBORN comfort meters. Besides, we collected physiological data, such as heart rate, electrodermal activity, and skin temperature. The analysis of the latter is presented in section 2.2.

Forty-two datasets remained for analysis. We analyzed differences in air velocity, thermal perception, and airflow perception between the six positions, personal control, daytime, demographics (age, sex, body mass index (BMI)), length of the test, and air temperature. Additionally, we investigated participants' perception of air velocity at individual body parts, air humidity, and eye dryness, and the influence of previous fan experiences on the reported thermal comfort.

2.1.2 Results

The main findings are as follows:

- At higher indoor temperatures, participants selected higher fan air speeds. Although there was a preference for higher air velocity in the warmer setting (31 °C), participants did not set the fan air speed to the maximum possible level, and the measured air velocity did not differ significantly between thermal conditions. Besides, most participants perceived the air velocity as acceptable.

- Half of the participants perceived the temperature (28 °C – 31 °C) and the air velocity acceptable at fan air speeds between 0.2 and 0.4 m/s. This might indicate a positive effect of the airflow direction to specific body parts on thermal acceptability.

- At higher outdoor temperatures exposed before entering the chamber, higher fan air speeds were selected, and a significantly lower thermal satisfaction was observed despite having an acclimation phase of thirty minutes afterward.

- The fan air speed selection was independent of the airflow direction (positions), and there was no difference in participants' thermal acceptance during the experimental phase. Additionally, the fan air speed selection was independent of the length of the experiment. We observed a possible effect of fatigue, as the later the vote in the sequence, the less acceptable participants rated the air velocity.

- During the standing position and fixed fan speed condition (no control over the fan air speed), participants perceived the temperature to be significantly warmer. However, during the adjustable fan speed condition, participants' thermal comfort increased, even though the fixed fan air speed did not differ significantly from the average fan air speed selected by participants. Thus, one can conclude that the personal control improved participants' thermal satisfaction.

- Participants evaluated the air humidity at the end of the session as significantly more comfortable than at the beginning (acclimation phase) despite the constant relative humidity during the whole test. As participants' thermal comfort increased once provided with personal cooling, this could indicate a relationship between an increase in thermal perception and, thus, in the perception of air humidity.

- Most participants who had previous experience with fans evaluated the tested embedded ceiling fans as better or much more better than the ones used before the experiment. Furthermore, participants' evaluation correlated with their previous experience with fans: participants who had previously a better experience with fans were more prompt to evaluate the embedded ceiling fan more positively.

2.2 Effect of an embedded personal ceiling fan on human physiological response

Paper II - Romina Rissetto et al. (2022a). "The effect and influence of personalised ceiling fans on occupants' comfort and physiological response". In: *Proceedings of the 3rd Comfort at the Extremes Conference.* Ed. by Ecohouse Initative Ltd. London: Ecohouse Initative Ltd., pp. 358–367. ISBN: 978-1-9161876-4-1

This work explored significant differences between participants' psychological and physiological responses when using an embedded personal ceiling fan. The study focuses on the effect of fan use on skin temperature and heart rate, and assesses differences due to personal, contextual characteristics, and thermal sensation votes at moderately warm indoor environmental conditions.

2.2.1 Methods

We collected the data from the experimental study described in the previous section (2.1). We analyzed heart rate and skin temperature data (proximal and distal temperature), chosen fan air speed, and thermal comfort/sensation votes from the forty-five participants. For the data analysis, we considered the measurements from the whole experimental phase of the session together, excluding the acclimation phase. Through statistical analysis, we tested differences in heart rate and skin temperature between the following groups: sex (female – male), age (young – elderly), BMI (overweight – average weight), daytime (morning – afternoon), air temperature (28 °C – 31 °C) and thermal sensation votes (neutral – non-neutral).

2.2.2 Results

The results can be summarized as follows:

- Overweight participants showed a significantly lower proximal skin temperature than average-weight participants, but no differences in thermal perception were found.

- Heart rate results yielded statistically significant differences between age groups. Younger participants showed higher values than the elderly group and considered the thermal conditions more comfortable.
- Although female participants perceived the thermal conditions as less comfortable, no differences in skin temperature or heart rate were found between sex groups.
- Participants showed significantly higher values of distal skin temperature when the indoor temperature was 31 °C, regardless of the air speed level. Still, no significant difference in proximal skin temperature values was found between thermal conditions.
- Participants who voted neutral thermal conditions showed significantly lower distal and proximal skin temperature compared to participants voting feeling warmer (non-neutral). With increasing air speed (higher than 0.8m/s), the difference in distal skin temperature between the neutral and non-neutral groups was greater than when the air speed was lower than 0.4m/s.

2.3 Comfort and economic viability of personal ceiling fans

Paper III - Mattis Knudsen et al. (2023). "Comfort and Economic Viability of Personal Ceiling Fans Assisted by Night Ventilation in a Renovated Office Building". In: *Buildings* 13.3, p. 589. DOI: `10.3390/buildings13030589`

In this study, we investigated the effort and benefits of embedded personal ceiling fans regarding energy demand, cost, and thermal comfort compared to alternative active and passive cooling solutions, assessing different climatic scenarios.

2.3.1 Methods

We carried out a simulation study using the office building in Dillingen (see section 1.3) as a base case study to model and simulate different cooling concepts and cost calculations. We evaluated the following concepts: no cooling solution, night ventilation, embedded personal ceiling fans combined with night ventilation (this corresponds to the implemented solution in the building), and a decentralized air-conditioning system (AC).

Figure 2.1 presents the workflow of this study. We developed a building energy model in Energy Plus using existing building data. With the measured data from a monitoring campaign conducted in the office building, we calibrated and validated the building model and developed an occupant behavior model. We used the building energy model to simulate the temperature distribution and resulting fan and air-conditioning usage. This allowed the simulation of the building cooling energy demand for all cooling concepts — except the concept with night ventilation and embedded ceiling fan, from which monitoring and project data were available. We used the energy consumption to calculate the electricity costs. We used the Adaptive Thermal Heat Balance Model (ATHB) and the Maximal Adaptability Model (MAM) for the thermal comfort and productivity assessments. Indoor temperatures and fan usage were inputs for the comfort models to obtain occupants' discomfort hours and productivity losses. Discomfort hours were calculated using the predicted mean vote (PMV) and the standard effective temperature (SET), and expressed in PMV and predicted thermal sensation (PTS) for active and passive cooling strategies, respectively. We translated the results from the productivity model into cost values. Based on building data and the available literature, we estimated the different cooling strategies' investment, installation, operation, and maintenance costs.

We compared the cooling solutions regarding discomfort hours, productivity losses, energy consumption, and costs. Using present climate data, we conducted a comprehensive economic assessment (base case). We used the delta net present value (ΔNPV) as an investment efficiency indicator, taking the no cooling solution as the baseline case to compare the costs between concepts. To assess the potential of the personal cooling solution, we compared the base case with future scenarios with warmer temperatures by using the predicted test reference year (TRY 2035) for different locations in Germany.

2.3.2 Results

The results can be summarized as follows:

- When implementing the solution of the embedded ceiling fan with night ventilation, the indoor temperatures did not exceed 29 °C. The effect of the fan air movement reduced the SET, which decreased the discomfort hours by 50% compared to the solution with no cooling strategy. In future climate scenarios (TRY 2035), the concept with the embedded ceiling fan reduced discomfort hours by approximately 75%.

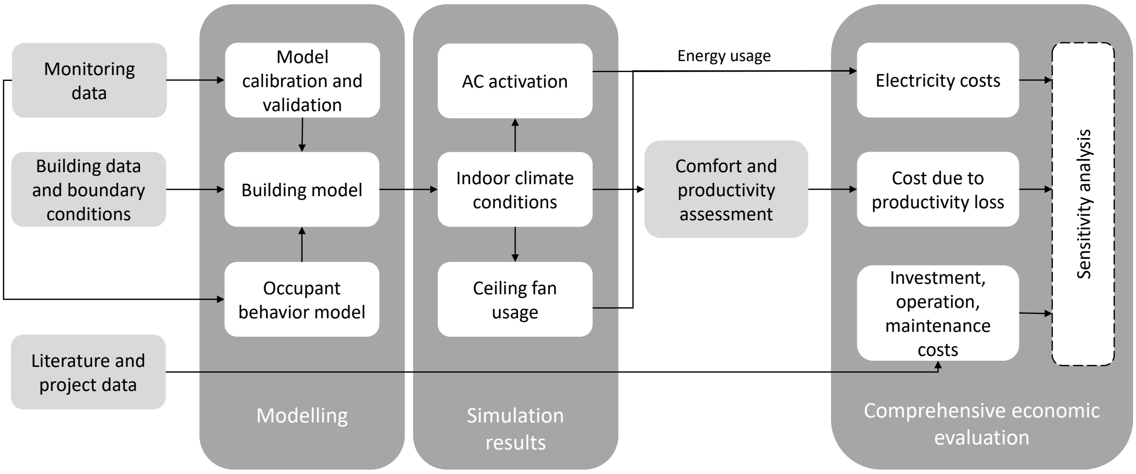

Figure 2.1: Methodology flowchart for the economic viability assessment of the embedded personal ceiling fans. AC: air-conditioning system.

- The solution of the embedded ceiling fan with night ventilation consumed ten times less energy than the AC solution, resulting in proportionally higher electricity costs. The investment, operational, and maintenance costs of an AC system were around two times higher than the embedded ceiling fan and night ventilation concept.
- The ΔNPV in the base case was positive only for night ventilation, as savings in productivity losses did not compensate for the initial investment in the case of the embedded ceiling fan and the AC system. The embedded ceiling fan became profitable in future climate scenarios with higher outdoor temperatures (TRY 2035) but remained behind night ventilation. Thus, a technology cost reduction might help compensate economically for the investment costs in the embedded ceiling fan and the additional productivity losses.

2.4 Discussion

PECS systems are designed to provide IEQ comfort for occupants while maintaining energy consumption at the minimum level possible. Personal ventilation systems are an important part of PECS within the context of increasing cooling energy demand. In addition, promoting passive and low-energy strategies helps to reduce the negative environmental impact of active air-conditioning. Within this thesis, we investigated an innovative cooling solution that integrates a small-diameter-personal ceiling fan within a hanging acoustic panel. We evaluated the performance of the embedded personal ceiling fan regarding its effect on occupants' psychological and physiological reactions with minimal energy consumption and environmental impact. The research questions 1 and 2 are answered as follows:

Research Question 1: *How do occupants respond psychologically and physiologically when using a type of ventilation PECS?*

Results from the presented studies showed that the embedded personal ceiling fan fulfilled participants' thermal comfort at moderately warm indoor temperatures (28 °C – 31 °C). Directing the airflow to the upper body parts and avoiding high air velocity in the face area reduced participants' perception of eye dryness. Additionally, the design of the embedded personal ceiling fan allowed the flexibility to direct the supplied air at a horizontal distance of up to one meter (between the fan and the participant), achieving participants' comfort independent of the direction of the air coming from above. By repositioning the participants' workstations and adjusting the fan's grille, higher air velocities compared to the ones measured in the experimental study could be eventually achieved. This is particularly important to counterbalance the effect of outdoor temperatures on indoor thermal perception. We observed significantly lower thermal satisfaction when participants were exposed to higher outdoor temperatures before entering the test chamber even though the indoor temperature did not vary during the session. This may indicate that the acclimation period was not long enough for participants to physiologically adapt to the given indoor conditions, or that participants' previous thermal exposure may have increased their thermal expectations when experiencing higher outdoor temperatures.

The increasing warm-to-hot indoor conditions encountered in non-air-conditioned buildings may impact directly on occupants' comfort. At higher indoor temperature conditions, participants from our study expressed a decrease in thermal satisfaction. Air movement the fan provided helped restore thermal comfort through physiological adaptations. A reduction of the skin temperature was achieved by the cooling effect of the air movement in the participant's proximity. By providing air movement even lower than 0.4 m/s at the upper part of the human body, participants' subjective evaluations of the thermal environment were within the comfortable range. Additionally, the observed air velocities were, on average, lower than in previous studies with traditional fans. This indicates the positive effect of directing the airflow at specific body parts to achieve participants' thermal satisfaction. Together with physiological reactions due to thermal conditions (high indoor temperature), participants' characteristics played an essential role in the body's thermoregulation. Findings suggested that differences in body composition and aging affect the physiological reactions of the human body, which consequently affect occupants' thermal perception.

To address individual differences and requirements of occupants, PECS can influence psychological reactions by providing occupants with personal control. In our studies, the possibility of controlling the fan air speed increased thermal comfort for participants with a slightly higher metabolic rate, even though the fan air speed did not rise. Furthermore, the discomfort of air humidity perception was reduced by the end of the test. Due to the positive relationship between increased thermal comfort and humidity satisfaction, it can be assumed that the perception of stuffy air was reduced when personal cooling to increase thermal satisfaction was provided. However, the satisfaction with the perception of the fan air speed decreased by the end of the session despite not being set by participants at its maximum level possible. A fatigue effect could have occurred, likely associated with the length of the session, and a habituation effect in the selection of fan air speed (i.e., remained unchanged).

Research Question 2: *What is the cost-benefit relationship of ventilation PECS compared to other building solutions?*

Targeting occupants' micro-environment can have significant impacts on reducing energy consumption. Simulations showed that the embedded personal ceiling fans consumed ten times less than an ideally-modelled decentralized air-conditioning system. To minimize the slightly warm sensation occupants may perceive in future climate scenarios, this low-energy consuming technology could be combined with additional passive solutions, such as night ventilation. This combined solution could represent a viable strategy for building refurbishment, as a significant part of the existing building stock in Germany corresponds to naturally ventilated buildings. Besides, this system allows flexibility in terms of desk position and office arrangement, which may have implications on the design of existing workspaces (e.g., existing luminaires, furniture, etc.) and new working trends (e.g., hot desking). Due to the reduced installation and maintenance efforts and costs compared to active cooling solutions, embedded personal ceiling fans could be an economically viable solution for building refurbishment in the future.

3 Development of a thermal-behavioral expectations framework

This section addresses RQ3 and RQ4 by summarizing the findings of papers IV, V and VI.

3.1 Thermal expectations in the built environment

Paper IV - Marcel Schweiker et al. (2020b). "Thermal expectation: Influencing factors and its effect on thermal perception". In: *Energy & Buildings* 210. DOI: `10.1016/j.enbuild.2019.109729`

In this study, we investigated people's expectations in the built environment and their impact on thermal comfort and sensation by directly assessing the congruence between people's expectations and experience. Besides, we analyzed factors influencing people's thermal expectations.

3.1.1 Methods

We analyzed data from a sample of 47 participants between 18 and 30 years old, obtained from a combination of laboratory and field studies. In the experimental study, participants attended one-day sessions in the climate chamber described in section 2.1 for three non-consecutive times. Adaptive behaviors available to the participants were opening or tilting the windows, adjusting their clothing insulation, and using a ceiling fan. As part of the field study, participants were asked to monitor temperature and humidity levels in their workplaces with a provided temperature sensor (HOBO Data logger) over three non-consecutive days. During the six tested days (laboratory and field), participants were asked directly through questionnaires about their thermal expectations and current thermal perception. Table 3.1 shows the questions asked to measure participants' thermal expectancy votes.

Thermal sensation and comfort votes and the level of expectancy were analyzed. Besides, the indoor thermal conditions using the SET (laboratory data) and indoor temperature (field data) were used for the analysis. A series of ordinal regression models were tested to evaluate the effect of expectations on thermal comfort and thermal sensation. The thermal sensation and comfort votes predicted by the statistical models were compared to the observed votes by means of the true positive

Table 3.1: Items, questions and scale.

Item	Question	Scale
Expectancy	When you left home/entered the office, was the outdoor/indoor temperature as expected?	yes/no
Level of expectancy	If not as expected, how did you perceive the outdoor/indoor temperature?	much cooler – much warmer than expected

Note: Expectations of outdoor and indoor conditions were assessed in separate questions.

rate (TPR). In addition, differences between demographics, the number of sessions, and indoor-outdoor conditions were assessed.

3.1.2 Results

The results can be described as follows:

- Questions about expectations have not been previously employed in the built environment context. The questions used to inquire about participants' expectations in this study represent a straightforward approach.
- This study only assessed the "intensity" of agreement ("yes") or disagreement ("no") of expected thermal sensation votes, but not of the *affective* evaluation of the conditions (expected thermal comfort). This could suggest that even if conditions were warmer/cooler than expected, participants may have expected more/less comfortable conditions.
- Regression analysis showed a significant influence of the level of expectancy on thermal sensation votes for the field and laboratory study. The effect of a different perception (cooler/warmer than expected) is around one vote on the thermal sensation scale (slightly cool/slightly warm). Furthermore, we observed a significant influence of the level of expectancy on thermal comfort votes. When conditions are not as expected, there is a higher probability of experiencing a decrease in thermal comfort when SET is higher (∼29 °C) compared to lower SET values (∼20 °C).
- Overall, the tested models to predict thermal sensation and comfort votes, including expectation as an independent variable, showed good predictive performance. The TPRs obtained in this study (between 50% and 60%) are comparable to previous studies, and even higher for thermal comfort (∼70%).

- Moreover, results showed that indoor temperature (SET) and the location (laboratory vs. field) significantly influenced the prediction of thermal expectations. Thus, for the field dataset, expectation follows indoor thermal conditions. Contrarily, the effects of outdoor temperature, indoor-outdoor difference, and sex were not significant in the model.
- During each laboratory session, the number of "unexpected" votes increased when experiencing an increase in temperature of around 0.5 K/hr over the day. Still, the SET also increased over the day, which does not permit conclusions on whether the increase in unexpected votes is due to the (unnatural) increase in indoor thermal conditions or other factors.

3.2 Effects of occupants' expectations on thermal perception

Paper V - Romina Rissetto et al. (2020). "The effects of occupants' expectations on thermal comfort under summer conditions". In: *Proceedings of 11th Windsor Conference.* Ed. by Ecohouse Initative Ltd. London: Ecohouse Initative Ltd., pp. 252–268. ISBN: 978-1-9161876-3-4

This study expanded the analysis of occupants' expectations of IEQ and examined the influence of expectations of behavioral adaptations. Influences of different warm thermal conditions and the effect of tailored information on expectations were included in the analysis.

3.2.1 Methods

A repeated-measures experimental design was conducted during 12 working days in the LOBSTER climate chamber, with test conditions similar to those described in section 2.1. In this study, each test room accommodated two participants, who were seated one meter away from their own embedded PCF. They had control over adjusting the air velocity of the fan, consuming beverages, and tilting windows. The 18 recruited participants experienced a constant temperature of 28 °C throughout the session. They repeated the session on a second non-consecutive day, with temperatures set at either 28°C or 31°C, to investigate potential changes in expectations over the course of the day (see results in section 3.1). To assess the influence of tailored information on performance expectations of the embedded PCF, participants were divided into control and experimental groups in the first session. The experimental group received a pamphlet detailing the characteristics and benefits of the embedded PCF, while the control group received instructions on fan operation without additional information. For the second session, participants were equally distributed and balanced across control and experimental groups.

Throughout the session, participants completed various questionnaires, as depicted in Figure 3.1, with corresponding numbers indicating the questions asked during different phases of the session. Upon entering the unconditioned corridor of the chamber, participants were asked about their thermal expectations (question 1) and expected thermal preference (question 2). Subsequently, in the conditioned room and during the acclimation phase, participants reported their actual thermal/air quality perception (question 3), expectancy (question 4), and level of expectancy (question 5). Additionally, participants provided insights into their anticipated fan effectiveness (question 6) and general attitudes toward fans. After implementing adaptive measures in the experimental phase, participants revisited the same questions. To capture possible shifts in expectations, participants completed the questionnaire 30 minutes after the beginning of the experimental phase and at the end of the session. Finally, participants were asked to compare the fan's effectiveness with their initial expectations (question 7). Building on insights gained in the previous study (see results in section 3.1), expectations were assessed both before and after participants experienced the environment, utilizing a two-dimensional approach to evaluate expectations based on sensation and comfort.

Differences in the perception of thermal conditions and air quality were tested for the same participants under the two thermal conditions and between the experimental and control groups and the session phases. Thermal and air quality expectations votes between those groups were analyzed. A series of correlations tested possible relationships between expectations and attitudes toward ceiling fans before and after using the embedded personal ceiling fan.

3.2.2 Results

The following conclusions arose:

- For unmet thermal expectations in the first session, participants who had anticipated more comfortable indoor thermal conditions reported a higher thermal sensation vote (towards warm) compared to participants who expected less

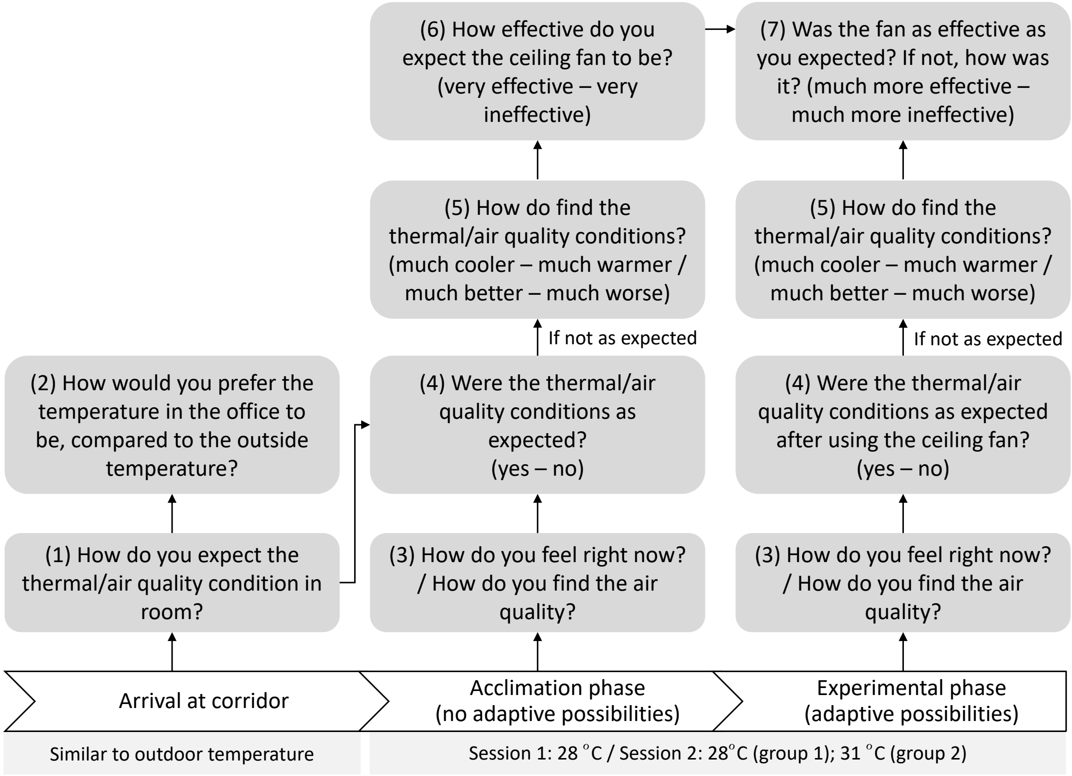

Figure 3.1: Questions asked during the different phases in the climate chamber for one session. Schema adapted from the original paper.

comfortable conditions.

- The expectations set in the first session impacted differently the expectations for the second session: the group anticipating more comfortable indoor thermal conditions in the first session expected significantly less comfortable thermal conditions in the second session compared to the group initially expecting less comfortable conditions, regardless of the room temperature.
- We found no significant differences in the "expected" votes throughout the day, neither in the first nor the second session. This indicates that stable thermal conditions did not influence expectations, even at high temperatures ranging from 28°C to 31°C.
- Participants' expectations of IAQ significantly varied between the first and the second sessions. In the first session, participants perceived the air quality to be slightly worse and less comfortable than expected. Despite a temperature increase of approximately ∼3 K compared to the first session, participants found the conditions to be "as expected" in the second session. This could

suggest that temperature settings may not influence expectations of IAQ in a familiar environment.

- No significant differences were observed between the control and experimental groups in thermal and air quality perception during both the acclimation and experimental phases, as well as in their performance expectations of the embedded PCF in the first session. This suggests that the information provided may not have significantly impacted participants' expectations.
- Positive expectations of using traditional ceiling fans and positive attitudes towards them were found to be positively correlated with the expectations of the embedded PCF after participants had used it.

3.3 A unified theory of behavioral and thermal expectations

Paper VI - Romina Rissetto et al. (2022b). "Assessing comfort in the workplace: A unified theory of behavioral and thermal expectations". In: *Building and Environment* 216, p. 109015. ISSN: 03601323. DOI: `10.1016/j.buildenv.2022.109015`

Findings from the last two studies suggested to investigate possible influencing factors, such as thermal history and attitudes, on occupants' thermal and behavioral expectations. This study proposed an integrated framework of expectations that integrates constructs from existing comfort and behavior theories to define expectations under a psycho-physiological model of comfort and behavior.

3.3.1 Methods

Based on the psycho-physiological perception model of Auliciems 1981, we proposed a framework that integrates constructs from the Theory of Planned Behavior (TPB) (Ajzen 1991), the Norm-Activation-Model (NAM) (Schwartz 1977) and the Self-efficacy theory (Bandura 1986). The framework defined measurable dimensions of expectations and their effect on reported comfort and behavior (Figure 3.2).

To test the proposed framework, we conducted a nationwide Internet-based survey. The survey focused on a representative sample of the German population concerning gender, age, and office employees. Besides screening and measurement of control variables, the questionnaire focused on the primary measures of this study: (1) thermal expectations and behavioral expectation measures, (2) self-efficacy, perceived control, personal norms, thermal history and attitudes, (3) reported comfort and behavior, (4) previous experience with the different building system. As the study was conducted during the COVID-19 pandemic, participants were asked to envision working in an office environment. They had to imagine that they had personal control over an energy-efficient fan and that the office had other building systems that could be accessed to modify the indoor environment (windows, blinds, air conditioning system). A total of 430 responses were retained for the analysis.

We conducted a principal component analysis (PCA) to reduce the number of observed variables. We tested the proposed framework using the structural equation model technique (SEM). We presented a case study using a model to test interactions with a fan.

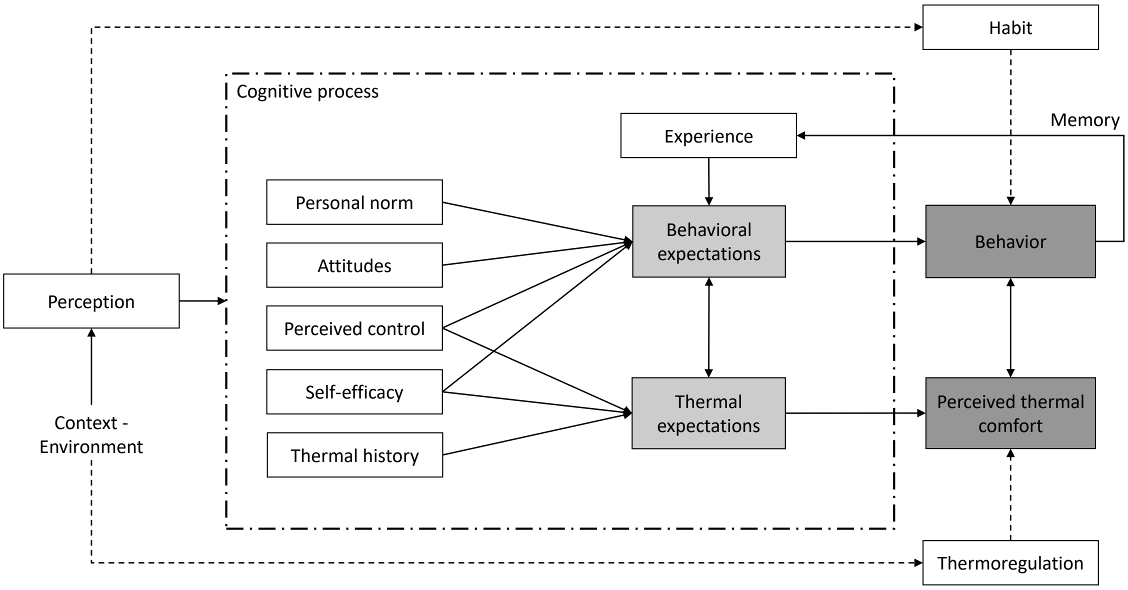

Figure 3.2: Overview of the integrated expectation framework. Schema adapted from the original paper.

3.3.2 Results

Results from this study can be summarized as follows:

- A distinction between thermal and behavioral expectations was proposed. Thermal expectations refer to the thermal experience predicted by occupants; behavioral expectations refer to the probability of performing a specific adaptive behavior to enhance comfort in the workplace.
- The measurement model indicated that thermal expectations were explained

by perceived control, thermal history, and self-efficacy, whereas personal norms, attitudes, perceived control, and self-efficacy explained behavioral expectations.

- A direct effect of thermal expectations on thermal comfort and fan expectations on fan usage was observed, as occupants' expectations positively influenced thermal comfort and fan use.
- A mediation effect of thermal memory was included in the model, as the relationship between the expected interaction with a fan to modify the indoor environment and the current occupant behavior was positively mediated by occupants' previous experiences with fans.

3.4 Discussion

Understanding occupant perception of the indoor environment and their comfort-related behaviors is relevant to the building design and operation, namely to reduce energy consumption and provide a comfortable indoor environment for occupants. However, a performance gap between intentions and actual occupant behavior has been frequently reported. Besides, a disparity between intended comfort conditions and occupants' perception of indoor environments has been assigned to differences in comfort expectations. The potential of interdisciplinary theory-based studies has been identified to understand better the driving factors in occupant behavior and occupants' expectations. The studies presented in this chapter aimed to understand the interaction between thermal and behavioral expectations and the effects on occupant comfort-related behavior and thermal perception, with the ultimate goal of characterizing expectations in the built environment. The research questions 3 and 4 are answered as follows:

Research Question 3: *To what extent do occupants' expectations of the indoor environment and building controls influence their thermal satisfaction and behavior?*

By directly asking participants about their expected sensation and comfort and comparing their expectations, the presented laboratory studies confirmed that people have a wide range of expectations about indoor conditions, which are positively related to their reported thermal perception. When expectations about indoor thermal conditions are unmet, thermal comfort decreases. The greater the discrepancy between expected and experienced conditions, the greater the dissatisfaction of occupants, as participants who expected more comfortable indoor thermal conditions reported higher thermal sensation votes under the same warm indoor conditions. These findings suggest that shifting occupants' comfort expectations may be essential for ensuring thermal comfort in naturally ventilated buildings, where more temperature variations are expected.

To support design strategies tailored to building occupants, it may be helpful to understand what factors influence expectations. Indoor conditions have the most significant influence on thermal expectations in naturally ventilated buildings. In the first laboratory study, the number of "expected" votes (i.e., when expectations match actual thermal sensation) did not increase when experiencing an increase in temperature over the day. In the second study, expected votes increased for different but constant temperature settings over the day. These results suggest that participants expected stable thermal conditions, even moderately warm indoor conditions. As participants reported their expectations for the indoor environment regardless of the outdoor conditions or the indoor/outdoor temperature difference, this could negatively impact their acceptance of a higher variance in indoor thermal conditions.

Although significant changes in indoor temperatures are the most sensitive parameter influencing expectations, occupants might lower their expectations of indoor conditions if it is a known environment. We concluded that participants' previous thermal experience (i.e., thermal history) significantly impacted their acceptability of indoor thermal conditions. After becoming familiar with an environment, participants from the second study expected the same thermal and air quality conditions in the second session as they had experienced in the first session. As the percentage of "expected" votes increased in the final days of the first experiment, it suggests that participants seemed to adjust their expected thermal and air quality sensation very quickly based on a few experiences with such a new environment. Participants' thermal comfort reported in previous experiences also influenced their expectations. Thus, the group that expected more comfortable indoor thermal conditions in the first session expected significantly more uncomfortable conditions in the second session than the group that expected more uncomfortable conditions in the first. This suggests that setting higher expectations of a thermal environment may increase expectations of thermal conditions in future experiences.

Results from the laboratory study suggested that positive expectations and attitudes towards using traditional ceiling fans were positively correlated to the compared expectations when using the embedded PCF. Additionally, results showed that although participants perceived the thermal conditions as warm, they expected to be comfortable on the second experimental day, suggesting that the adaptive actions performed during the first day effectively achieved comfortable conditions. Thus, participants set their expectations for the second day by adjusting their memory concerning previous experiences and expectations, thereby minimizing thermal discomfort.

Research Question 4: *How can comfort expectations be characterized in the context of the built environment?*

Through the proposed integrated expectations model, we concluded that expectations are important drivers of comfort and behavior. Consistent with the adaptive principle, we observed a negative correlation between fan and thermal expectations, suggesting that adaptive behavior is expected when the thermal conditions are not as expected. Furthermore, the relationship between the expected interaction with a fan and the actual behavior was mediated by occupants' previous experience with fans. This was observed in the laboratory study, where the fulfilled expectations when using the embedded PCF could be related to the effectiveness and improvement of indoor conditions. In the theoretical framework, comfort expectations result from the interaction of thermal and behavioral expectations, which, in turn, are explained by psychological constructs. For instance, the model suggested that perceived control and self-efficacy shape thermal and behavioral expectations. In the laboratory study, participants' perceived control and self-efficacy could have been activated to increase their expectations when providing information on how to operate the fan. Attitudes and personal norms were related to behavioral expectations in the integrated expectations model. The effect of personal norms could not be tested through the provided information in the experimental study. Attitudes, however, may have set performance expectations in the experimental study. Results showed that participants' attitudes toward the embedded PCF were positively correlated with their performance expectations after using it. The findings suggest that it may be helpful to address occupant expectations of building systems and operations by increasing occupants' positive experiences, knowledge, and control over these adaptive opportunities in the building. The framework suggested that thermal history explained thermal expectations. This effect was observed in the results from the experimental studies that suggested an influence of previous thermal experiences on future occupants' expectations in a known environment. Findings indicate that psychological constructs can help address comfort expectations. Results from the integrated framework may have policy implications in the building design and operation phase, for instance, by focusing on the identified constructs for the design of behavioral interventions and adaptive possibilities in the building.

4 Improvements in the acceptance of a ventilation PECS

This section aims to address RQ5 by summarizing the findings of paper VII.

4.1 Effect of information and comfort expectations on the use of an embedded personal ceiling fan

Paper VII - Romina Rissetto and Marcel Schweiker (2024). “Exploring Information and Comfort Expectations Related to the Use of a Personal Ceiling Fan”. In: *Buildings* 14.1, p. 262. DOI: `10.3390/buildings14010262`

This study examined the influence of tailored information and occupant comfort expectations on their thermal perceptions and satisfaction with an embedded personal ceiling fan.

4.1.1 Methods

We conducted an independent measures experimental design in the climate chamber LOBSTER. The experimental conditions and daily schedule were similar to the study presented in Section 2.1. In this study, 76 participants completed an online questionnaire (pre-test) and participated in one LOBSTER session (post-test). The lessons learned from the previous study (see results in section 3.2) suggest that occupant behavior and reported comfort might vary depending on the way the information is delivered (e.g., Schweiker and Shukuya 2011). Therefore, a new manipulation technique based on the Goal-framing theory (Lindenberg and Steg 2007) was used during the stay in the chamber to test the effect of expectancy groups on thermal satisfaction and satisfaction with PECS, tailored by normative motivations (personal norms). The study was conducted as follows.

One week before the session in the climate chamber, participants completed a questionnaire to represent their expectations about IEQ and PECS based on the expectations framework presented in Section 3.3. An expectancy value was obtained for each participant based on a score for thermal expectations and a score for behavioral expectations. Using a support vector machine (SVM) method, the resulting scores were classified into three expectancy groups (Figure 4.1): participants with negative thermal expectations but positive fan expectations (cluster 1); participants with positive thermal and fan expectations (cluster 2); participants with negative fan expectations and near-neutral thermal expectations (cluster 3).

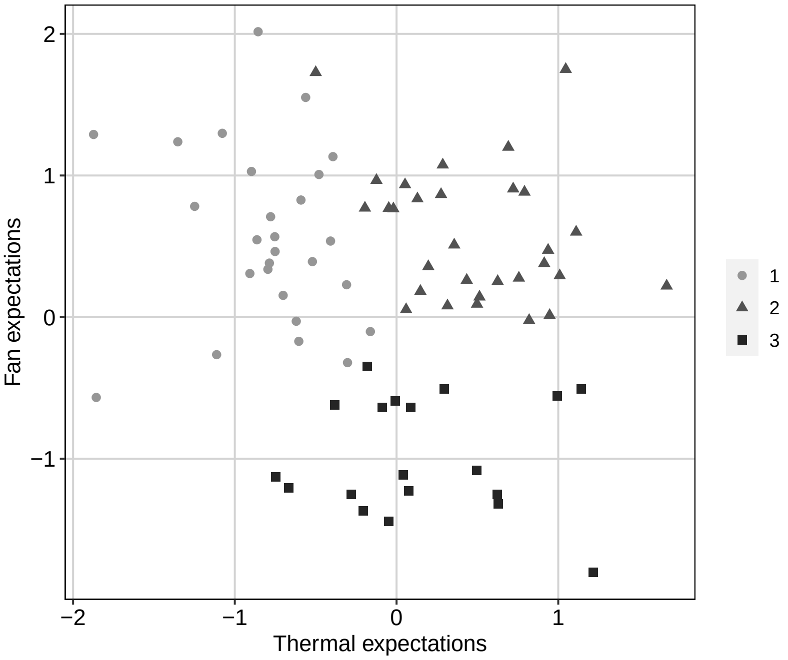

Figure 4.1: Classification groups for thermal and behavioral expectations.

During the session in the LOBSTER, each participant worked alone in one of the test rooms with an air temperature of 30 °C. Participants were divided into control and experimental groups and were similarly distributed according to their group of expectations (cluster). At the beginning of the session, participants from the control group watched a video (*short video*) with information about sustainability, climate change, and political energy targets in Germany. An extended video (*long video*) was created for the experimental group, which included additional information about benefits and scientific explanations of how ceiling fans work. After the acclimation phase, participants could turn on the embedded personal ceiling fan, tilt the windows, or drink a beverage to adjust to climatic conditions. Participants completed various questionnaires to collect information mainly on their perception of and satisfaction with the IEQ and the embedded personal ceiling fan.

Before testing the hypotheses, we verified the equivalence of participant groups in the expectation groups (clusters) according to demographics and personal characteristics (e.g., age, gender, BMI, previous experience with fans and office work), experimental conditions (office number, daytime, video short vs long), current mood, video rating and fan use (air velocity and duration of fan turned on). We conducted a regression analysis to test the hypothesis that groups of occupants with different types of thermal and behavioral expectations will express different thermal satisfaction. We performed a series of conditional process analyses of moderation to test the effect of information on thermal satisfaction and satisfaction with a type of PECS.

4.1.2 Results

From this study, it can be concluded that:

- Participants with more positive thermal and behavioral expectations were significantly more comfortable with the thermal conditions than participants with negative thermal expectations.
- The activation of personal norms on the experimental group was found to significantly moderate expectancy's influence on reported thermal comfort. Greater variance in thermal comfort was explained by the moderation model that included the activation of personal norms compared to that explained by the total effect model, which isolated the effect of comfort expectations.
- There was no moderation effect of personal norms on the influence of expectancy on the change in fan evaluation. However, expectancy had a significant impact on the change in fan evaluation. After participating in the session, participants with negative thermal expectations showed a more positive change in fan evaluation than those with positive thermal expectations.

4.2 Discussion

By giving occupants the responsibility of managing certain aspects of the building, more information needs to be provided related to building control to help occupants pursue an energy-efficient approach and reduce the gap between how designers expect occupants to use a building and how they actually do. However, occupants' comfort preferences may be reflected in their expectations of building systems. Assuming underlying comfort drivers influence expectations of the building performance, then it may be helpful to examine the extent to which comfort expectations can be challenged to tailor the acceptance of new energy-efficient technologies within a changing and dynamic climate scenario. This chapter analyzed whether information and knowledge can manipulate occupants with different comfort expectations toward higher satisfaction with an embedded PCF and the IEQ. The research question 5 is answered as follows.

Research Question 5: *How can knowledge of comfort expectations improve occupants' acceptance and satisfaction with ventilation PECS?*

The study results indicate that participants had a wide range of expectations about indoor climatic conditions and behavioral opportunities. Moreover, it was possible to distinguish and group participants according to their comfort expectations to study the extent to which different expectations could influence participants' perception and satisfaction with the built environment. Results showed that reported thermal comfort was greater among those participants with more positive thermal and behavioral expectations and significantly differed from participants with negative thermal expectations. These results support the previously presented studies, reflecting the assimilation effect (i.e., any discrepancy will be minimized), given by the coherence between expected and experienced indoor conditions that lead to greater thermal satisfaction.

The higher influence of thermal expectations in predicting comfort compared to the effect of behavioral expectations could be associated with the modest expectations of occupants towards building controls in naturally ventilated buildings, who do not expect their comfort to change due to the building performance but through their actions. These results emphasized the importance of motivating occupants to use adaptive opportunities in non-air-conditioned buildings to increase their thermal satisfaction. Results from the study showed that the positive association between expectancy and thermal comfort could be largely explained by the activation of personal norms elicited among participants with more positive expectations. Findings suggest that investigating the potential influence of social-psychological factors on perceptions of IEQ, such as focusing on personal norms to save energy or responses to sustainable buildings, could help identify which types of occupants are likely to feel more comfortable based on their personal characteristics and shape their comfort expectations.

Accounting for different comfort expectations could allow for an assessment of the suitability of PECS for the variety of occupant experiences and requirements. The present study indicated that individually controlling the fan to increase thermal comfort may have effectively induced a change toward a more positive fan evaluation, especially in participants with lower comfort expectations. These results indicate that providing occupants with personal environmental control could align their comfort expectations with their thermal experience, increasing their satisfaction with the indoor environmental conditions and building controls.

5 Conclusions and outlook

This work aims to advance the understanding of thermal comfort, particularly in alignment with occupant's comfort expectations, to support the implementation of ventilation PECS in buildings. Advocating for the adoption of these personal devices could contribute to reducing energy consumption while accommodating individual comfort preferences. However, evolving people's understanding of comfort is essential for adapting to future building conditions. As an occupant-centric building solution, ventilation PECS might help to move towards a shift in comfort expectations. In response to the need for research and the lack of evidence for comfort expectations and the interaction with a ventilation PECS, this research provides a comprehensive performance assessment of this building technology, enhances understanding of occupants' expectations and thermal comfort, and investigates the impact of expectations on the adoption of an embedded PCF.

To address the lack of studies that comprehensively evaluate ventilation PECS, human adaptation and the ability of the PCF to provide thermal satisfaction in office environments with the minimum cost-benefit ratio were investigated. Findings demonstrated that the embedded PCF effectively meets occupant comfort requirements in moderately warm indoor environments typical of naturally ventilated buildings. Key features included targeted air movement to upper body parts, reducing skin temperature and enhancing thermal comfort. Additionally, PCFs offer personalized comfort irrespective of occupants' demographics and body characteristics, as body composition and age variations influence occupants' physiological responses. The adaptable positioning of PCFs within room layouts ensured comfort regardless of airflow direction, making them particularly relevant for building refurbishment efforts by addressing architectural constraints and enhancing occupant comfort in existing spaces.

A comprehensive PECS assessment framework was implemented, encompassing thermal comfort, productivity, energy consumption, and cost analysis, to evaluate the cost-benefit ratio of the embedded PCF. Results indicated a tenfold reduction in energy consumption and lower investment, operational, and maintenance costs compared to conventional AC solutions. Sensitivity analysis using future climate scenarios emphasized the embedded PCF's profitability, especially in regions with elevated outdoor temperatures. These findings underscore the significance of promoting low-energy technologies to sustain comfortable building conditions amidst climate change challenges.

Providing empirical evidence of the impact of comfort expectations on reported thermal comfort might help bridge the gap between predicted and actual comfort perceptions. Findings from experimental and field studies revealed a strong correlation between thermal perception and expectations, indicating a decrease in occupants' thermal comfort when experiences diverged from expectations. The results emphasize the importance of aligning occupants' comfort expectations, especially in naturally ventilated buildings susceptible to temperature fluctuations. Indoor conditions emerged as the most influential factor shaping thermal expectations, with participants expecting stable thermal conditions despite daily temperature variations. Moreover, participants demonstrated a rapid adjustment of their expectations of IEQ and adaptive actions based on their prior experiences, highlighting the dynamic nature of comfort expectations.

Given the significant impact of expectations on thermal perception, establishing a theory-based definition of comfort expectation was crucial to elucidate the cognitive mechanisms underlying occupants' comfort expectations. This study introduced a novel theoretical framework to delineate comfort expectations in the built environment. Results revealed the pivotal role of expectations as drivers of comfort and behavior. Comfort expectations resulted from the interaction between expectations of the IEQ and adaptive actions, which were influenced by psychological constructs. These findings underscore the importance of understanding occupants' expectations through a psychological perspective for enhancing occupant satisfaction.

Addressing occupants' comfort expectations has the potential to shape their comfort preferences, facilitating the use of ventilation PECS. This work evaluated how targeted information influenced the interaction between comfort expectations and occupants' evaluation of the embedded PCF. The results indicated that occupants could be categorized based on their comfort expectations, and activating personal norms increased thermal comfort for those with positive IEQ expectations. Conversely, participants with negative expectations showed a more positive change in their fan evaluation. In summary, leveraging social-psychological factors and providing personal control holds promise to shape occupants' comfort expectations and improve satisfaction with indoor environmental conditions.

5.1 Contribution to the knowledge

The work in this thesis provides a further understanding of thermal comfort and the use of ventilation PECS in office environments. The key theoretical, methodological, and practical contributions of this thesis are:

- The main theoretical contribution relates to enhancing the current understanding of thermal comfort by expanding on the definition of comfort expectations in the built environment. A theoretical framework to characterize comfort expectations was developed. The understanding of thermal comfort from the engineering perspective was expanded through the lens of psychology and behavioral theories. By identifying socio-psychological constructs, the dimension of comfort expectations was accounted for in the assessment of thermal comfort in buildings.
- A significant methodological contribution lies in the assessment of comfort expectations. Directly asking occupants about their expectations provided a straightforward approach to establishing congruence between occupants' thermal requirements and their perception of the indoor environment. Furthermore, the questionnaire designed to collect information about thermal and behavioral expectations enabled the establishment of a proxy to measure comfort expectations in office environments within a German context. This method could be further expanded to investigate comfort expectations across various environments and cultural and climatic contexts.
- Significant methodological and practical contributions relate to the proposed framework for the cost-benefit assessment and the performance evaluation of the embedded PCF. On the one hand, the methodological approach for the cost-benefit analysis combines well-established models to assess employees' work performance and thermal comfort, and a method to transfer productivity losses into costs. The proposed framework could be used for assessing other types of PECS in buildings, and the modified MAM using SET to consider the effect of fan air movement on thermal comfort could be implemented for the productivity assessment of different types of personal fans. On the other hand, the resulting fan operation model derived from monitoring data could be used as a reference for further research.
- Finally, this research work represents a pivotal contribution to informing constructors, designers, and building owners. The knowledge acquired from the comprehensive performance assessment of embedded PCF could serve as a reference for its further implementation in buildings as an effective building solution, particularly in building renovation projects. Additionally, the exploration of socio-psychological influences on thermal comfort and satisfaction

with the embedded PCF offers valuable insights for the development of design strategies for the implementation of PECS in buildings. This includes the potential for developing behavioral interventions or feedback messaging focused on the identified cognitive constructs, thereby enhancing occupants' thermal comfort and satisfaction.

5.2 Limitations

The thesis is limited to the analysis of occupants' expectations in naturally ventilated office buildings and the use of a ventilation PECS, in this case, an embedded personal ceiling fan. The limitations of the thesis can be described as follows.

The integrated expectations framework was developed based on a dataset derived from a German sample focused on office employees. Similarly, the climate chamber studies were conducted with a sample of German participants during the summer months. These context-related limitations may have implications for the characterization of comfort expectations, as cultural aspects and habituation to a particular climate type may influence occupants' psychological and physiological adaptation, thereby affecting their thermal preferences and requirements. Applying the expectations framework developed in this thesis in a different context may yield varying effects of influencing factors on comfort expectations. Additionally, the attitudes of the average German population towards climate change may have influenced the effect of tailored information on comfort expectations and satisfaction with the IEQ. To validate the results presented in this work, a diverse sample should be tested, including variations in location, season, climate zone, building type and cooling strategy.

The evaluation of ventilation PECS is also subject to cultural and contextual limitations. On the one hand, participants' behavioral adaptation might have been influenced by cultural factors, such as the use of specific adaptive strategies. It is worth noting that the use of fans in office buildings is less common in Germany compared to other European countries, potentially affecting occupants' expectations of certain adaptive strategies for restoring comfort. Thus, occupants' satisfaction with the embedded PCF and reported effectiveness may differ in other cultural settings. On the other hand, the cost-benefit analysis of the embedded PCF was conducted within a German context, affecting assumptions in the calculations, including interest rates, device price, and labor cost. Performing cost analyses of the embedded PCF in different countries may yield divergent results.

The studies conducted in this thesis focused on the assessment of thermal expectations, i.e., primarily indoor temperature and relative humidity. Although the results of one of the climate chamber studies showed that expectations of the evaluation of indoor air quality of the participants did not differ, differences in occupants' indoor air quality expectations should not be ignored. The fact that participants knew that they were participating in an experimental study could have implicitly suggested to them that the room was a controlled environment. This may refer to the actual occupied buildings that may have different types of ventilation systems or strategies to control indoor air. Conducting field studies may result in different expectations and perceptions of IAQ. In addition, the effects of thermal expectations were analyzed in isolation, and the interaction with other comfort dimensions, such as auditory or visual effects, were overlooked. Besides, the analyzed fan was embedded in an acoustic absorber, which also gave the system an appearance that is not just that of a personal desk fan or a classic ceiling fan. A possible improvement in the room acoustics and the buildings' aesthetics and integration may have influenced the participants' expectations and, therefore, their satisfaction with the indoor conditions. Further research could focus on different IEQ parameters and other comfort dimensions and consider cross-effects and interactions between these variables.

Another limitation is that comfort expectations and the reported comfort (thermal comfort and sensation) are collected at a single point in time. The dynamics of future thermal experiences, changes in comfort expectations, and changes in outdoor climate are beyond the scope of this work. Additionally, satisfaction with a PECS after multiple uses may change expectations of the device and satisfaction with the indoor environment, which was not assessed in this study.

This thesis focused on the evaluation of one type of ventilation PECS, an embedded personal ceiling fan. The evaluation focused on the effect of air movement on thermal comfort and physiological responses and the effect of PECS features, such as personal control, on thermal satisfaction. Evaluating other types of PECS, such as ventilation, heating, or other cooling devices, may require different approaches and evaluation methods. This may also affect the analysis of the effect of expectations on PECS and the type of tailored information provided to change occupant expectations.

Finally, the methods used in this thesis to evaluate PECS were mainly experimental and simulation-based. Although part of the evaluation of the embedded personal ceiling fans was derived from their implementation in a real case study, the inclusion of a post-occupancy evaluation could support the presented findings. A longitudinal field study could evaluate the same group of occupants to assess their interactions with PECS over time, its relationship to personal expectations, and the effect of information on changes in IEQ expectations.

5.3 Practical implications

This thesis explores the topic of comfort expectations and ventilation PECS, rethinking standard definitions of comfort and current approaches to room conditioning. The introduction of an embedded PCF, as a passive, energy-efficient PECS, assumes significant importance against the backdrop of climate change. With the impracticality of relying on energy-intensive solutions like HVAC systems to achieve building sufficiency, there arises a pressing need for a paradigm shift in adaptive room conditioning approaches. Such a transition necessitates a relaxation of comfort expectations, entailing acceptance of a wider variance of indoor thermal conditions. The findings of this work suggest that certain occupants have adapted to the narrow temperature range provided by current building standards in today's climatic context. This insight bears implications for the design of indoor conditions expected to remain stable, even in unfamiliar settings. If relaxed comfort expectations can be fostered through tailored information, occupant-centric building systems design could account for occupants' potential tolerance to a broader range of indoor conditions.

Better characterizing occupants' needs and expectations for the indoor environment could also support the building operation phase. This could be achieved by providing information and guidelines detailing available adaptive options for indoor climatic conditions, building systems operation, and the consequences of occupants' actions on thermal comfort, energy consumption, and health. Targeting occupants' expectations makes it possible to directly impact energy consumption reduction by aligning expected behavior with actual behavior. Moreover, increasing performance expectations of energy-efficient technologies could increase the acceptance and effective use of PECS. Shifting comfort expectations towards greater resilience and promoting behavioral changes to embrace low-energy solutions could serve as effective mitigation measures against climate change while positively impacting health and productivity.

5.4 Future work

This thesis involved interdisciplinary work, combining the fields of building science, architecture and psychology to understand building systems and occupants in-depth, which motivates future work to take a similar approach.

In addition to addressing the aforementioned limitations due to a specific cultural background and climatic conditions, future work could focus on validating and extending the notion of expectations in other indoor environments, cultural background and climate contexts. Contextualized categorization of comfort needs could support the operation and development of automated controls for PECS in addition to manual interaction of occupants with control devices. Automated systems could increase the productivity of individuals by reducing distractions (Warthmann et al. 2019) and achieve higher energy efficiency by targeting operating hours. However, the integration of PECS into the building management system is a complex task and still limited (André et al. 2020). The presented work focused on evaluating a type of ventilation PECS in terms of comfort requirements and energy consumption under controlled conditions to minimize other confounding factors. A further step to promote its implementation in buildings could include field studies focusing on the building integration of the embedded PCF within the architectural design and building systems concept and gathering information on occupant acceptance and thermal satisfaction. This approach could be extended to other types of PECS. Future work to promote the use of the embedded PCF could expand on measuring the effect of the acoustic panel on the overall room acoustics.

Future work could deepen the knowledge of whether providing information and feedback impacts the actual use of PECS. Future studies could examine the extent to which different appropriately designed messages or more information about the features of PECS influence occupants' adaptive behavior in the field. At the same time, these types of intervention field studies could evaluate how occupants' comfort expectations may influence real-time perceptions of IEQ. To address the complexity of influencing factors in human perception in buildings, this work could be extended to other dimensions of thermal perception beyond thermal sensation and comfort by considering combined effects in indoor environmental perception and behavior. Investigating other comfort domains' expectations could help reduce the knowledge gap of multi-domain environmental effects, as only a few studies have addressed this topic (Schweiker et al. 2020a). Furthermore, further research could expand on how thermal fluctuations and the use of ventilation PECS may result in significant health benefits in times of climate change (van Marken Lichtenbelt et al. 2022). Considering future planning and building design trends, a better understanding of thermal comfort and shaping occupants' expectations could broaden the field towards more resilient buildings and cities with higher adaptive capacity to climate change.

Nomenclature

Abbreviations

ΔNPV	Delta net present value
AC	Air conditioning
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
ASV	Actual sensation votes
ATHB	Adaptive thermal heat balance indices
BMI	Body mass index
BMS	Building management system
BMWK	Bundesministerium für Wirtschaft und Klimaschutz
clo	Clothing value
HVAC	Heating, ventilation and air conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
LOBSTER	Laboratory of occupant behavior, satisfaction, thermal comfort and environmental research
MAM	Maximal adaptability model
met	Metabolic rate
NAM	Norm activation model
NPV	Net present value
NV	Naturally ventilated
PECS	Personal environmental control system
PCA	Principal component analysis
PCF	Personal ceiling fan
PD	Percentage dissatisfied
PMV	Predicted mean votes
PTS	Predicted thermal sensation calculated based on SET
RH	Relative humidity
SEM	Structural equation model
SET	Standard effective temperature
SVM	Support vector machines
TPB	Theory of planned behavior
TPR	True positive rate
TRY	Test reference year

Glossary

Attitude	An individual's belief about likely positive and negative consequences of performing a particular behavior.
Expectation	An anticipated outcome, what a person believes will happen.
IEQ	A general indicator of the quality of conditions that affect the human life inside a building. It is a domain that encompasses diverse sub-domains, such as indoor air quality (IAQ), lighting, thermal comfort, acoustics, ergonomics, and many other factors.
NPV	The difference between the present value of cash inflows and the present value of cash outflows over a period of time.
Personal norms	Feelings of personal obligation, and strong motivations to take action to protect the environment, and are generally correlated with the performance of pro-environmental behaviors.
Perceived control	An individual's belief about their ability to enact the behavior (capacity) and whether or not their actions are completely under their control (autonomy).
PMV	An index that predicts the mean value of thermal votes of a group of subjects exposed to the same steady-state environment according to the ASHRAE seven-point thermal sensation scale (cold to hot).
PPD	Defines the percentage of people predicted to be dissatisfied due to uncomfortably warm or cold conditions.
Self-efficacy	An individual's belief in their capacity to act in the ways necessary to reach specific goals.
SET	The temperature of an imaginary environment at 50% relative humidity, less than 0.1 m/s air speed, and the mean radiant temperature equals the air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level.

Sufficiency	In the built environment, a set of policy measures and daily practices which avoid the demand for energy, materials, land, water, and other natural resources, while delivering well-being for all within planetary boundaries.
Relaxation	Likened to the notion of habituation in psychophysics, where repeated exposure to a stimulus diminishes the magnitude of the evoked response.
TPR	The proportion of actual positive cases that were correctly identified or classified as positive by the model.
TRY	A single year of hourly data (8760 hours), selected to represent the range of weather patterns that would typically be found in a multi-year dataset.

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Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort

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ABSTRACT

Research related to personal comfort systems is growing due to their potential to increase an individual's satisfaction with indoor environmental conditions and energy efficiency. At moderately high indoor temperatures, the use of ceiling fans can be a low-energy cooling strategy to enhance comfort in a working environment. This paper studies the performance of a personal ceiling fan and its influence on occupants' satisfaction with the indoor environment, focusing on the effects of personal control, previous experience with fans, variations on participants' activity level and air coming from different directions. In a laboratory study, 41 participants from two age groups were exposed to six different ceiling fan configurations either in sitting or standing positions, with and without control over the ceiling fan speed, and under two thermal conditions (balanced order of in total 24 conditions). Results showed that participants' thermal comfort at indoor temperatures of 28 °C and 31 °C was fulfilled when they used the personal ceiling fan, independent of the direction of the supplied air coming from above. The possibility to control the fan speed showed a significant influence on the thermal perception of participants at a slightly higher activity level compared to fully sedentary. The influence of previous experiences with fans had a positive effect on the rating of the analyzed ceiling fan and thermal comfort. The positive acceptance of personal ceiling fans encourages its use in retrofitted office buildings to increase thermal comfort and motivate energy savings.

1. Introduction

In the face of climate change, energy retrofit in the built environment represents a fundamental strategy to increase energy efficiency. However, building refurbishments may lead to negative implications. For example, renovation of European buildings often cause overheating problems which may lower occupant satisfaction [1]. Tightening the building envelope and better thermal insulation may reduce infiltration – and thus the air exchange rates – and increase indoor temperatures in the summer season. Földváry et al. [2] showed that the indoor air temperature was significantly lower in non-refurbished buildings than in renovated ones; encountering 12% of the latter overheating problems. Therefore, the application of ceiling fans may be a potential solution to enhance thermal comfort in the context of a moderate outdoor climate. Additionally, this low-energy cooling strategy allows more flexibility in the design and implementation in existing buildings, as they eliminate the need for ducts and reduce the number of diffusers in comparison to other cooling solutions [3].

In order to react to individual differences between occupants, recent studies have analyzed the impact of personal comfort systems (PCS) on thermal comfort and energy efficiency, as described in a review by Rawal et al. [4]. Wang et al. [5] proposed a paradigm shift from centralized to personalized air conditioning, where only a relatively small space around the user is conditioned. Zhang et al. [6] introduced the concept of corrective power as a measure of the cooling effect capacity of a PCS. The corrective power of ceiling fans is greater than that of front air jets, providing comfort up to 33 °C room temperature. Concerning energy efficiency, the use of PCS enables the possibility of relaxing ambient temperatures, i.e. allows higher room temperature set points in a cooling dominated environment. According to He et al. [7], personal fans can achieve higher energy efficiency in comparison to other personal cooling systems and Schiavon and Melikov [8] found that cooling energy between 17% and 48% can be saved when using fans at elevated ambient temperatures.

Several studies have revealed the positive impact of the use of fans on thermal comfort, as described in the review by He at al. [9]. In the case of mechanically ventilated buildings, the incorporation of a ceiling fan helps to distribute the air more uniformly in

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the room [10,11] and increase thermal satisfaction [12]. By increasing air velocity, indoor temperatures above 28 °C were found to be still acceptable [13]. According to Huang et al. [14], the airflow generated by desk fans could be used as an effective cooling method to maintain a comfortable environment at 28–32 °C. Zhang et al. [15] found that most occupants turned on the fan at indoor temperatures between 28 °C and 31 °C and that the main motivation for fan use is based on the thermal aspect to "cool the body", rather than for improving IAQ.

There has been a large body of studies addressing the effect of air velocities on thermal comfort under different thermal conditions. According to Cândido et al. [16], the minimum required air velocity for acceptable conditions in naturally ventilated buildings in a hot humid climate is between 0.41 and 0.8 m/s for an indoor temperature range of 27–29 °C, while Lipczynska et al. [12] have shown that on average 0.6 m/s was the most desired air velocity at temperatures above 28 °C in an office building in Singapore. According to Voss et al. [17], above an indoor temperature of 28 °C heat transfer between the human and the environment is dominated by the evaporation rate, and ceiling fans operated at air velocities between 0.8 and 1.2 m/s have shown to be effective in maintaining comfort in those warm conditions. A summary of previous studies with ceiling fans in controlled climate chambers is shown in Table 1. These studies evaluated the perception of thermal conditions with seated participants at ambient temperature ranges from 28 °C to 31 °C for different humidity levels. At higher temperatures and higher relative humidity, a higher air velocity was desired. Overall, these studies have been done in the US and China, showing a lack of chamber studies with ceiling fans in the European context. Table 2.

As mentioned by Huang et al. [14], the type of air supply device – e.g. ceiling fan, desk fan or wind box – and consequently the body parts affected by the airflow may be a possible reason for differences in the desired air velocities in chamber experiments despite the same room temperature. Luo et al. [23] found that thermal sensitivity varies widely between individual body parts. Pasut et al. [18] analyzed the effect of different directions of the supplied airflow to the participants' head on thermal comfort and thermal sensation. Participants were positioned in front, at the side and beneath the ceiling-mounted fan. They found a significant difference in thermal comfort and sensation between the no-fan baseline case and the different fan configurations, but no analysis was performed to test statistical differences between those fan configurations.

When suitable fan speeds were imposed by experimenters, occupants' thermal comfort may not differ much from fan speeds selected by users [19]. However, Huang et al. [14] found that personally controlled air velocity could improve thermal comfort in thermal conditions as high as 34 °C room temperature, in comparison to conditions with given air velocities, i.e. without control possibilities.

Studies described so far looked at near-sedentary physical activities, with a metabolic rate of 1.0 met. At the same time, the use of movable tables and application of standing working positions [25] increases and leads to higher activity levels, characterized by metabolic rates from 1.2 to 1.4 met [26]. Zhai et al. [19] investigated the effect of a slight increase in activity level in warm temperatures on thermal comfort and sensation. They suggested that a slightly high metabolic rate (1.4) caused an increase in participants' thermal sensation, but no significant difference was found in the air velocities participants chose for the sedentary activity. They found that personal control over air movement had no significant effect on thermal comfort at different activity levels. Additionally, Zhai et al. [27,28] investigated the effect of increased air movement at high metabolic conditions. For elevated activity levels between 2 and 6 met, which corresponds to moderate exercise, air movement provided by either a pedestal fan or a personal controlled ceiling fan can relax cooling requirements, indicating that exercising humans do not necessarily want neutral thermal conditions but rather warm sensations.

Despite the benefits of ceiling fans in terms of comfort conditioning, energy use reduction, perceived air movement and air quality and the possibility of personal control, its implementation in commercial buildings that have mechanical ventilation is still a relatively uncommon practice [3]. The lack of a systematic assessment of the effects of personal control in combination with different thermal conditions and targeted body parts, the understanding of possible influences of previous experience with ceiling fans and the desirable fan speeds under different activity levels motivates the investigation of this personal and low-energy cooling strategy at moderately high indoor conditions. Besides, there is a lack of European studies about ceiling fans in an office context. The present work is developed within the framework of a retrofitted office building in Dillingen a.d. Donau, Germany. This study focuses on the evaluation of a personalized ceiling fan to enhance thermal comfort within an office setting. The main objectives of this paper are the following:

- analyze the impact of the ceiling fan on the user's thermal comfort as a function of different directions of supplied air concerning the occupant position,
- analyze the influence of a slight increase in activity levels, temperature settings and personal control on the participants' assessment of comfort,
- analyze the influence of activity level and temperature setting on the chosen fan speed and related air velocity,
- assess the effect of previous experiences with ceiling fans on the participants' thermal comfort and evaluation of the device efficiency.

2. Methodology

In order to address the above-stated objectives, a repeated measure experimental design in a laboratory setting was chosen.

Table 1
Comparison of experimental conditions and results from previous studies with ceiling fans in controlled climate chambers.

Study	Location	Temperature [°C]	RH [%]	Comfort air velocity [m/s]
[18]	US	28	50	0.68–0.88
[19]	US/China	28	40–60	1.0–1.2
		30	40–60	1.2–1.4
[20]	US	28	50	0.80
[21]	US	29.5	50	1.00
[13]	US/China	30	60	1.2–1.6
		30	80	1.2–1.8
[22]	US	28.3	73	1.02
		31.1	50	1.02

Table 2
Gender, age group and the number of participants for both thermal settings. Mean and standard deviation (SD) of the participant's height while sitting and standing at eye level. Mean and standard deviation (SD) of the participant's age.

Gender	Day 1 (28 °C)		Day 2 (31 °C)		Total		Eyes' height [cm]		Age (SD)
	Number	%	Number	%	Number	%	Sitting (SD)	Standing (SD)	
Male	21	40.38	7	13.46	28	53.85			Older
Older	13	25.00	4	7.69	17	32.69	126.82 (2.48)	165.81 (6.13)	65 (4.04)
Younger	8	15.38	3	5.77	11	21.15	121.57 (3.89)	154.85 (6.64)	
Female	20	38.46	4	7.69	24	46.15			Young
Older	12	23.08	2	3.85	14	26.92	118.80 (6.47)	156.00 (7.45)	29 (6.45)
Young	8	15.38	2	3.85	10	19.23	124.72 (5.46)	163.63 (7.26)	
Total	41	78.85	11	21.15	52	100	122.98	160.07	

2.1. Facility and experimental conditions

The experiment was conducted during three consecutive weeks (working days) between August and September 2018 in the test facility LOBSTER [29] in Karlsruhe, Germany. The facility consists of two office rooms (each 4 m width by 6 m depth by 3 m height) with one façade each. The façade appears as a common post and beam structure with the middle and upper part being transparent glazing. Each room was equipped with a ceiling fan, which is integrated into an acoustical ceiling panel with dimensions of 1200 × 1200 × 40 mm and a weight of approximately 6 kg. The composition of the ceiling fan and panel was a prototype developed for this study based on existing components (Fig. 1).

The axial fan is characterized by its small rotating area (300 mm diameter), its small installation depth (92 mm), low noise level and excellent efficiency. The fan has a nominal fan speed of 600 rpm, which corresponds to a mass flow rate of 600 m^3/h (the relationship between fan speed and the mass flow rate is linear). The hanging panel has a hole and the fan is positioned on top of the acoustic panel facing its hole (Fig. 2). The suspended acoustic panel is hanging 20 cm below the ceiling. Below each ceiling fan, a custom fabricated 350 × 350 mm grille is positioned. This grille can be mounted below the ceiling panel and is removable. The grille has 14 blades (15 mm thickness), which are only fixed at one point allowing adjustable angles to manipulate different air directions. To change the blades' angle a comb was designed for each angle.

To determine the distances between the ceiling fan and the workstation and consequently, the grille angle, frequent configurations of the office rooms in the existing building in Dillingen were analyzed. Fig. 3 shows the possible panels' positions depending on the position of the luminaires and the workstation, and the correspondent distance to the participants' head. In all positions, participants are seated except in position B, in which the person works in a standing position. For the determination of the angles, an average of a German man and woman size [30] was calculated for both sitting and standing configurations (see Fig. 4 below). A detailed description of the selected positions is explained below.

The ceiling panel with the fan was suspended at a distance of 2.5 m from the floor. Fig. 4 shows the positions of the participant in each office room and the distances of the participant's head to the center of the fan, which corresponds to the positions shown in Fig. 3. In order to adjust positions efficiently, a movable workstation was used. Each position was assigned a letter. Five sitting positions were evaluated: beneath the ceiling fan (A), 50 cm away from the center of the fan and the airflow was directed to the side of the participant (C), 75 cm away with the airflow directed to the backside (E) and front side (F) of the participant and 115 cm away and the airflow directed to the side of the participant (D). One standing

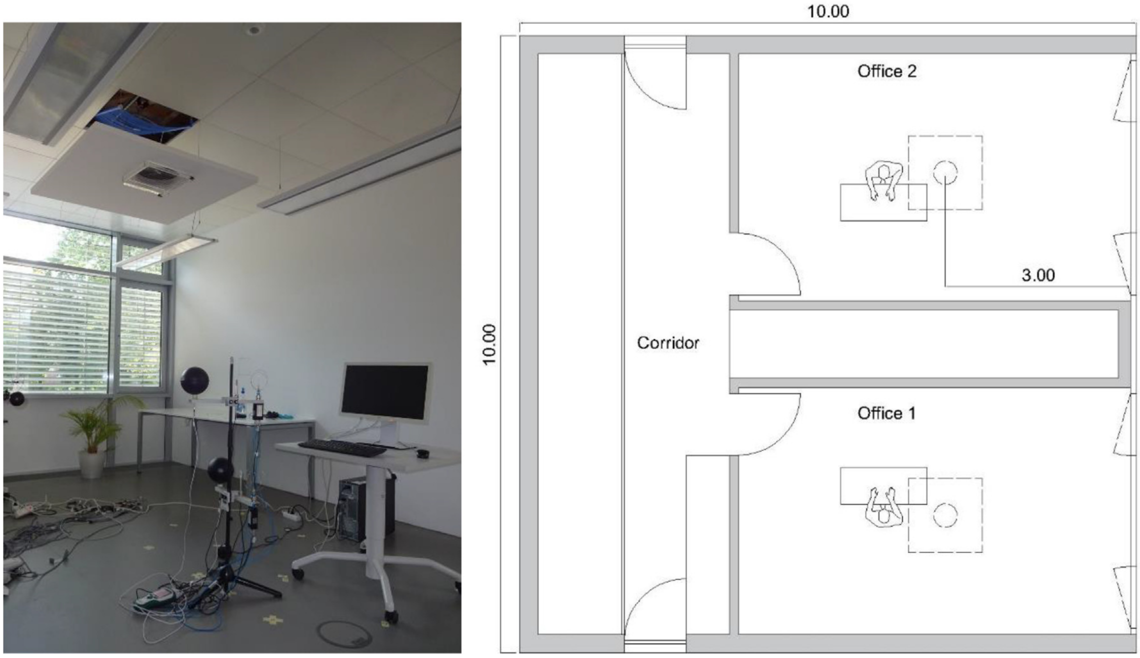

Fig. 1. Chamber set up and integrated ceiling fan prototype in one of the rooms (left). Floor plan of the chamber and position of the participants and ceiling fans in each room (right). All values are in meters.

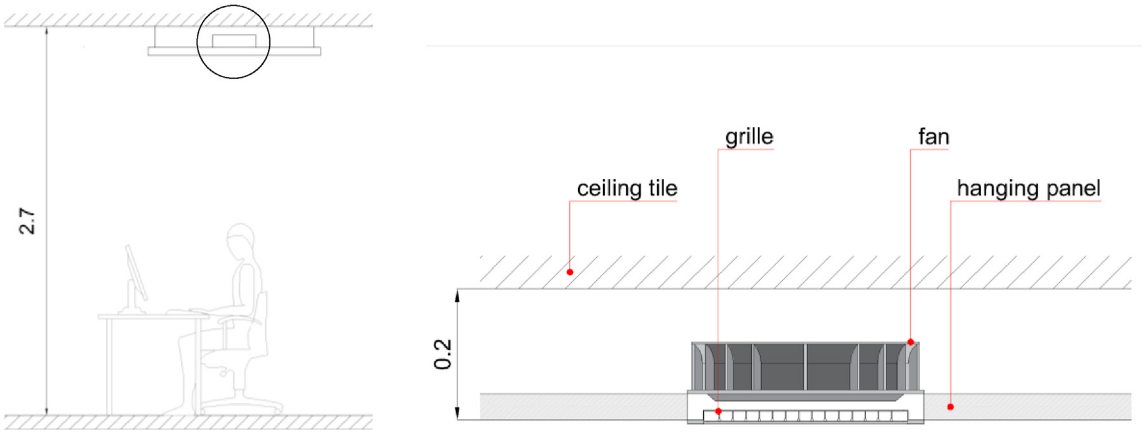

Fig. 2. Section (left) and detail (right) of the arrangement of the hanging panel and fan. All values are in meters.

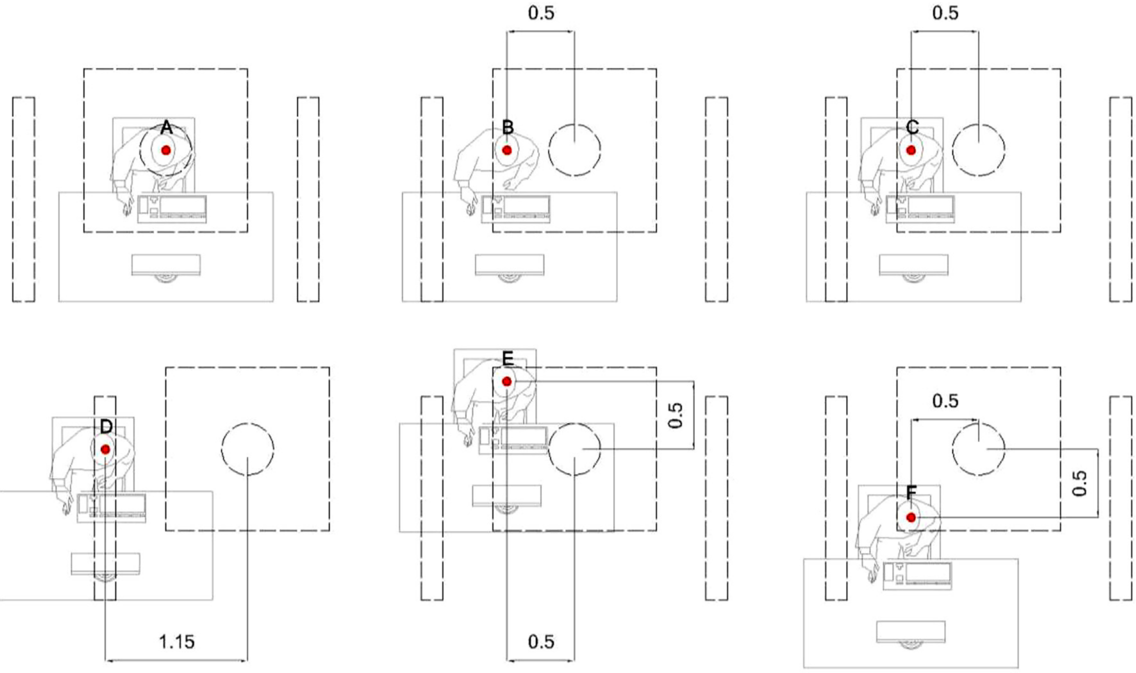

Fig. 3. Most frequent panels' positions in the existing building. Dashed lines represent a) fan integrated into the acoustic panel and b) luminaires. Red dots represent the occupant's head. All values are in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

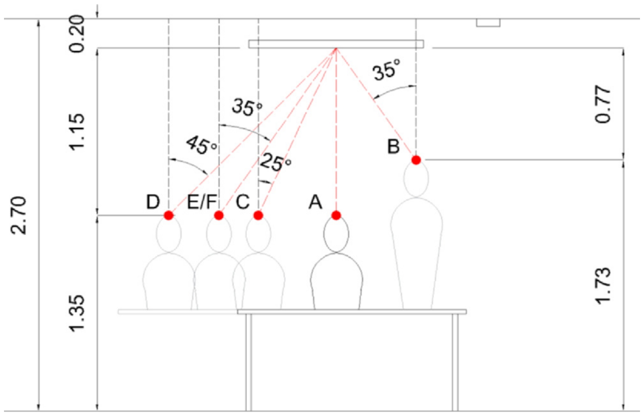

Fig. 4. Scheme of the subjects' positions, angles and distances to the fan in the LOBSTER. All values are in meters.

position was evaluated 50 cm away from the fan (B). For each position, the grille was adjusted correspondingly so that the air was directed towards the participant. However, the different positions required different fan speeds to achieve the same air velocity at the participant's location. Measured air velocities at different speeds for each position are presented in the results section. These positions were crossed with two thermal settings: the first thermal setting was with a room temperature of 28 °C/50% RH and the second one with 31 °C/50% RH.

2.2. Experimental procedure

One session for each participant lasted 3 h 30 min. Fig. 5 describes the schedule for one session. In the first 10 min, the experiment was explained. During the following 30 min, the participant adapted to the given conditions in the room. After this acclimatization phase, each participant experienced the six above mentioned positions for 20 min each, in which a constant fan speed

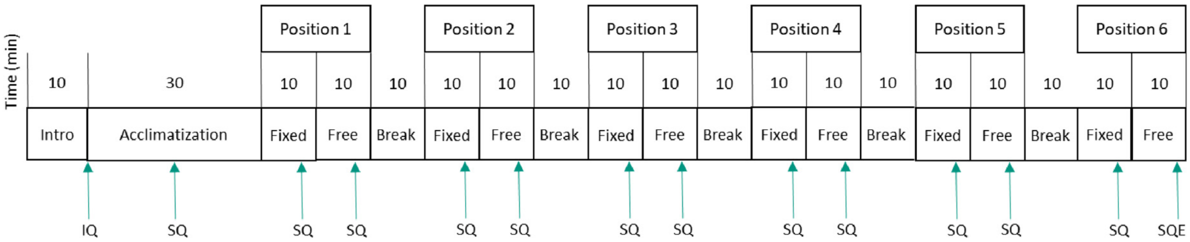

Fig. 5. 5 Timeline of surveys and experimental conditions. IQ: initial questionnaire; SQ: status questionnaire; SQE: status end questionnaire. The main content of the questionnaires is explained in Table 3.

was set during the first 10 min (fixed). Pre-tests were conducted in order to define the fan speed for each position during the fixed condition, which lead to an air velocity of 0.4 m/s at the position of the participants' head in that position. Fan speeds for each position was A: 38%, B: 25%, C: 38%, D: 45% and E/F: 40%. In the second 10 min, participants could control the fan speed via a remote controller in a range of 0–10 V (free). The remote controllers had a reference level from 0 to 100% with a 10 points-interval displayed, but the fan speeds could be set also in between these points continuously. The order in which each participant experienced the six positions was randomized (Fig. 6). In between each position, the participants had a break of 10 min in which they stayed seated without using the ceiling fan to be thermophysiologically restored to the state before the fan use. During the experiment, the participants were allowed to read the literature provided on the computer. Participants were exposed during the half-day session, either during the morning or during the afternoon, to the two thermal settings explained before: the first thermal setting took place during the first thirteen days and the second thermal setting during the last three days of the whole experiment.

Indoor and outdoor parameters were collected in a 1-minute interval from sensors through the building management system (BMS). Besides, air temperature, globe temperature, relative humidity, and air velocity were collected with AHLBORN comfort meters, which were positioned at a height of 1.1 m and 0.25 m away from the participant's head. The corresponding resolutions are 0.01 °C, 0.01 °C, 0.1%, and 0.001 m/s; the accuracies are ±0.2 K, ±(0.30 K + 0.005 × T), ±2.0% and ±(3% measured value + 0.01) respectively. Participants' interactions to modify the fan speed were also collected through the BMS to which the remote controller was connected. Physiological data were also collected, including heart rate, electrodermal activity and skin temperature measurements. The resulting analysis of the latter was not included in the present paper.

2.3. Participants

Forty-one male and female participants between 18 and 34 and 50–70 years old took part in a half-day experiment for the first thermal setting. After the session at 28 °C, the recruited participants were invited to second participation on a different day. Of those 41 participants, only 11 repeated the experiment in the second setting condition. Participants had to be German or show proficiency level of the German language, and be non-smokers. The following table summarizes their basic characteristics and distribution.

Participants were asked to wear long trousers, a T-shirt and closed shoes. Clothing data was collected in the initial questionnaire and the clothing level was estimated, based on self-reported clothing items in the questionnaire and transfer to clo-

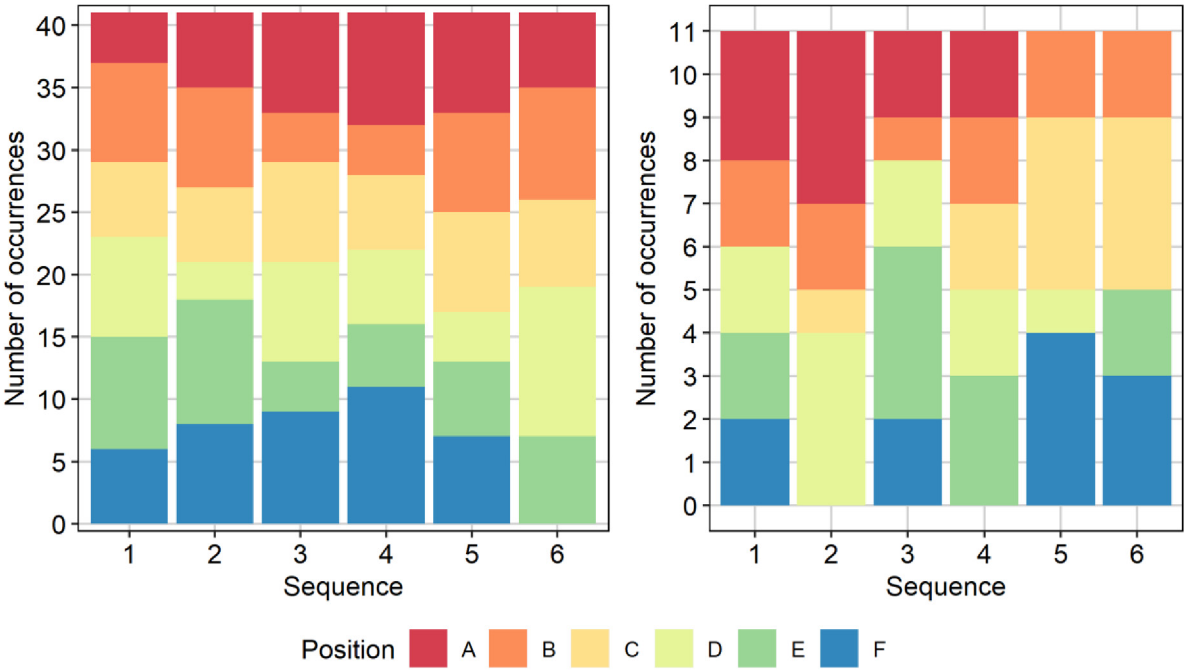

Fig. 6. Number of exposures at specific positions in sessions 28 °C (left) and 31 °C (right) according to the number of the sequence.

values based on ISO 7730 [31]. An average value of 0.44 clo (SD = 0.12) was calculated. Subjects were not allowed to change or adjust their clothing throughout the test. For the sitting positions, an additional value of 0.1 clo was added to the ensemble to add the insulation provided by the desk chair [26].

2.4. Materials, data collection and data analysis

The participants answered several questionnaires, which were provided through a web interface based on pre-set schedules (Fig. 5). The questionnaires were divided into three blocks: an initial questionnaire at the beginning of the acclimatization phase (first 30 min of the experiment), an intermediate questionnaire during each position (asked at the rather end of each condition) and a final questionnaire at the end of the experiment. Table 3 synthesizes the information gathered on the questionnaires relevant to this paper. Besides, it should be noted, that answer options to these questions were not done on a continuous scale, but a categorical scale, where participants could not choose a position in between labels. The data of the status questionnaire (SQ) obtained during the acclimatization phase are referred to as the 'no fan' condition and the intermediate ones are referred to according to the six different positions (A, B, C, D, E, F). The conditions where participants could control the fan speed individually are referred to as "adjustable" and the conditions where the fan speed was given (no personal control) are referred to as "fixed".

All data preparation and analysis were conducted within the software environment R Version 3.6.3 [32] and SPSS [33]. Due to incomplete data, one data set was excluded from the analysis (N = 40). All calculations of effect sizes were conducted via Psychometrica [34]. The single answer choices for the measurement of sensation, comfort, preference and acceptability of temperature and air velocity cannot be assumed to be equidistant but have to be considered as ordered-categorical data. Differences in these categories are therefore assessed with the Mann-Whitney *U* tests for independent group scores and the Wilcoxon signed-rank test for related samples and repeated measurements. A Bonferroni adjustment was applied to the results from the Wilcoxon signed-rank tests for the comparison of comfort, sensation, preference and acceptability between positions, to compensate for the increase in the likelihood of type I errors due to multiple comparisons. The Bonferroni adjustment applied to the significance level of 0.05 initially used resulted in a new significance level of 0.004. Other Willcoxon signed-rank tests were calculated with a significance level of 0.05. Correlations were measured using Kendall's rank correlation coefficient *Tau*. Based on benchmarks suggested by Cohen [35], effect sizes are interpreted as small (d = 0.14), medium (d = 0.35), and large (d = 0.57). For non-parametric tests, *z* values are used instead of *t* values [36].

Table 3
Main information obtained by the questionnaires. IQ: initial questionnaire; SQ: status questionnaire; SQE: status end questionnaire.

Category	Scale (all in integer values)	When?
Experience with fans	Yes–No	IQ
Thermal comfort votes	5-point (comfortable ←→ extremely uncomfortable)	SQ
Thermal sensation votes	7-point (cold ←→ hot)	SQ
Thermal acceptability	4-point (clearly acceptable ←→ clearly not acceptable)	SQ
Thermal preference	7-point (much cooler ←→ much warmer)	SQ
Air velocity comfort	5-point (comfortable ←→ extremely uncomfortable)	SQ
Air velocity sensation	7-point (very strong ←→ very weak)	SQ
Air velocity acceptability	4-point (clearly acceptable to clearly not acceptable)	SQ
Air velocity preference	7-point (much stronger ←→ much weaker)	SQ
Air humidity sensation	7-point (very high ←→ very low)	IQ/SQE
Air humidity evaluation	5-point (comfortable ←→ extremely uncomfortable)	IQ/SQE
Eyes' dryness perception	Yes – No	IQ/SQE
Eyes' dryness acceptability	5-point (comfortable ←→ extremely uncomfortable)	IQ/SQE
Air perception at body parts	Yes–No	SQ
Air comfort at body parts	5-point (comfortable ←→ extremely uncomfortable)	SQ
Evaluation of ceiling fan	7-point (very effective ←→ very ineffective)	IQ/SQE

2.5. Measured outdoor temperature

Fig. 7 shows the mean values of the outdoor temperature measured one hour before the participants' arrival for the fifteen days of the experiment for the morning and the afternoon sessions, respectively. Outdoor temperatures measured during the morning ranged from 16 °C to 20.5 °C, while during the afternoon they varied between 17.5 °C and 30 °C. Further analysis regarding morning and afternoon differences is shown in the results section.

3. Results

3.1. Air velocity and fan speed

Fig. 8 shows the relationship between air velocity and fan speed – which is linearly related to the rotation speed of the fan – for each position at a room temperature of 28 °C and 50% RH. Results measured at a room temperature of 31 °C are comparable with the ones presented in the figure. Except from the position situated under the ceiling fan (A), which shows the highest air velocity values – between 0.9 and 1.15 m/s –, most positions showed values ranging from 0.2 to 0.6 m/s. At lower fan speeds (30%), the air velocity values are similar between positions, but at a high fan speed (100%) mean air velocities differentiate from each other. Nonetheless, the maximum air velocities measured at positions B, C, D, E and F presented in Fig. 8 do not coincide with the maximum possible air velocities delivered by the fan. This was a consequence of the arrangement of the positions concerning the ceiling fan and the grille angle, which correspond to the working positions in the existing office building (see Methodology).

Fig. 9 shows the measured air velocities for both fixed (median) and adjustable (median, maximum and minimum) fan speed conditions at each position and temperature setting. We can observe that for an indoor temperature of 28 °C there is a slight decrease in the measured air velocity in most positions when participants were given the possibility to change the fan speed. An exception is the standing position (B), where an increase in air velocity can be observed both for the 28 °C and 31 °C setting. However, changes in fan speed are not quite evident. Further analysis of participants' interactions with the remote controller is shown below.

In order to analyze the user interaction with the ceiling fan, the fan speeds selected by the participants were analyzed. Fig. 10 shows the boxplots of the chosen fan speed during the experiment according to positions and temperature settings. The crosses represent the fan speed given in the fixed condition Compared to the resulting air velocities in Fig. 9, the given fan speed for position "A" resulted in an air velocity higher than 0.4 m/s (originally intended in the pre-test).

A Wilcoxon test for continuous and non-parametric data shows that the selected fan speeds during the 28 °C sessions (Mdn = 34)

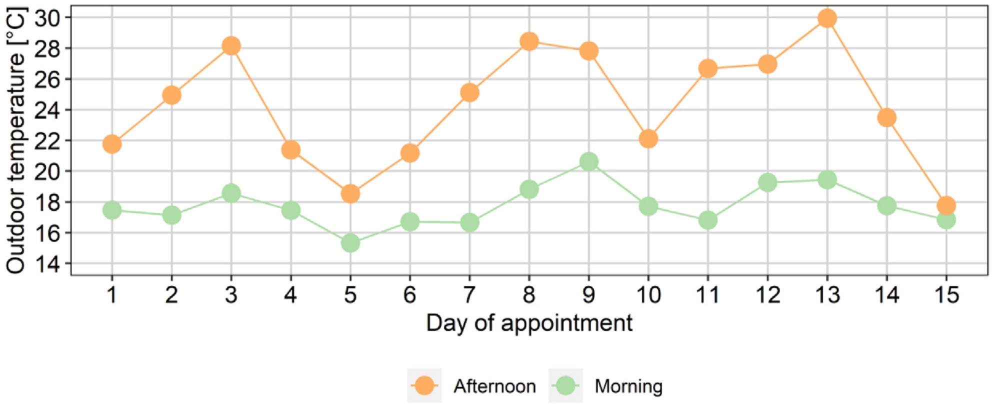

Fig. 7. Mean outdoor temperature values measured one hour before the participants' arrival for the morning and afternoon sessions.

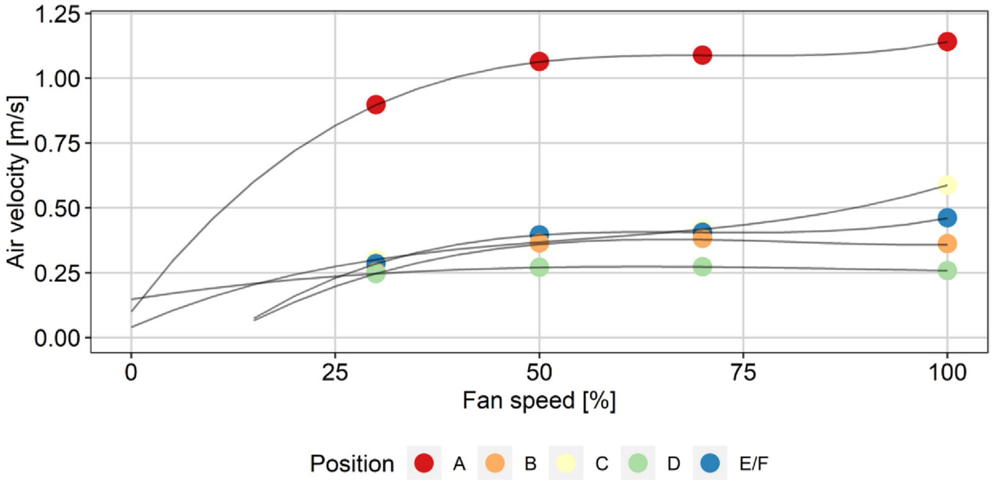

Fig. 8. Fitted lines (cubic polynomial) for measured air velocities and recorded fan speeds for each position.

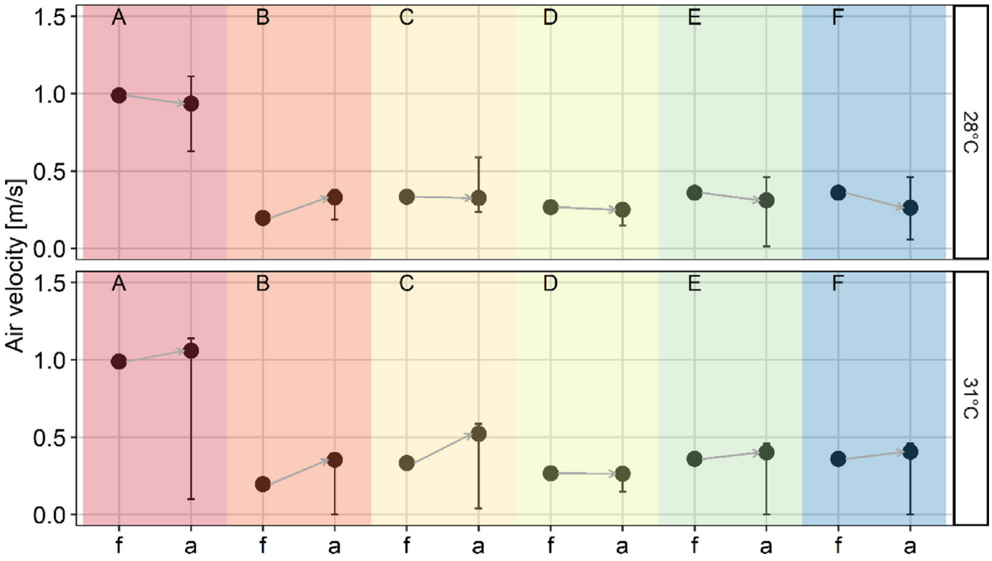

Fig. 9. Median of air velocity for the fixed condition (f) and median, maximum and minimum values for the adjustable condition (a) for each position and temperature setting. Arrows indicate the change – no change, decrease, increase – in air velocity between conditions.

differ significantly from the ones in the 31 °C sessions (Mdn = 59, W = 1504.5, p = .002, r = −0.67). The Kruskal–Wallis test applied to the difference in selected fan speed between positions for each temperature setting shows that the selected fan speed did not differ significantly between positions for 28 °C (H(5) = 2.10, p = .83) and 31 °C (H(5) = 4.47, p = .48). These last results are unexpected

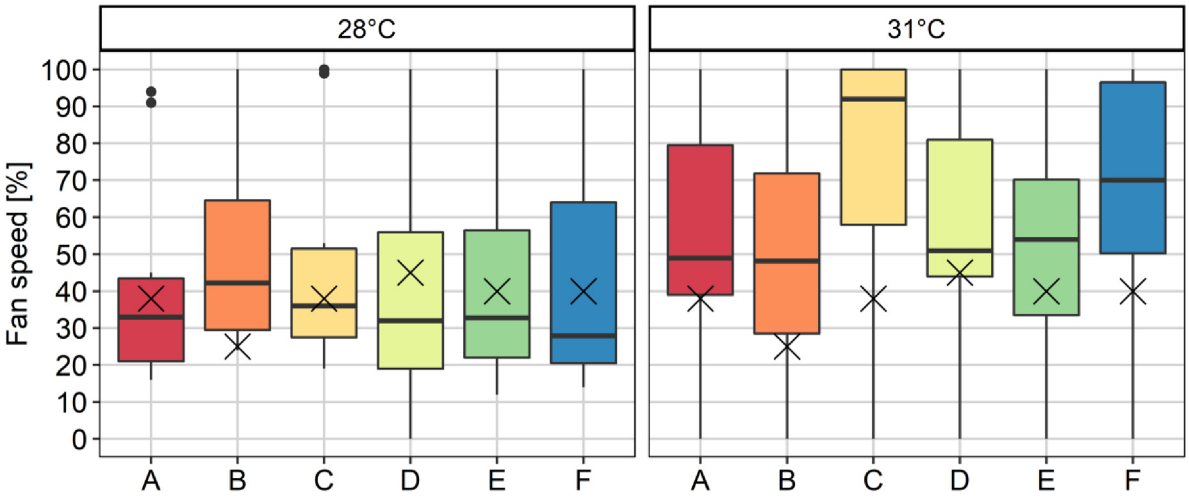

Fig. 10. Boxplot of chosen fan speed according to position and temperature sessions for participants in both sessions. Crosses represent the fan speed for the fixed condition for each position.

if we compare them to the measured air velocities in Fig. 8, as the velocity in position A is much higher than in the rest of the positions. Therefore, we could expect that the participants would have chosen a lower fan speed. Similarly, the chosen fan speed for positions C and F were higher than position E and D, which have similar or even lower air velocities, respectively. One possible explanation could be that the higher observed fan speeds in C and F are a result of them being more frequent towards the end of the session (Fig. 6) when participants' thermal capacity might have been rather at the warm end. An analysis of chosen fan speeds in each sequence is shown below.

3.2. Sequence effects on chosen fan speeds

Fig. 11 shows the boxplot for chosen fan speeds ordered by sequence – the point in time at which each condition took place during the session – according to the temperature setting. A Kruskal–Wallis test was conducted to assess significant differences between the number in the sequence for each temperature setting. The selected fan speeds did not differ significantly between numbers of the sequence either for 28 °C (H(5) = 3.07, p = .51) and 31 °C (H(5) = 7.47, p = .19). However, we can observe an increasing tendency of selected fan speed for the 31 °C setting. This could explain the higher selected fan speeds in Fig. 10 for positions C and F.

3.3. Thermal and air velocity evaluation

Figs. 12 and 13 show the thermal sensations and comfort votes, respectively, for all positions according to the control possibility. All positions were rated between "neutral"-"slightly warm" (50%) and "comfortable"-"slightly uncomfortable" (50–75%), but the majority of votes in the standing position (B) were warmer and more uncomfortable in comparison to the other positions. The condition with no fan was rated as "slightly warm"-"warm" and "slightly uncomfortable"-"uncomfortable" (65%). Participants rated the no fan condition slightly different for the two thermal settings, half of the participants characterized the temperature at 28° as "slightly warm"-"warm" and at 31 °C as "warm", but "slightly comfortable"-"uncomfortable" for both settings. Results of a Friedman test showed a significant effect of the different positions on thermal sensation ($\chi^2(11) = 130.67$, $p < .001$) and thermal comfort ($\chi^2(12) = 85.65$, $p < .001$).

Post hoc Wilcoxon signed-rank tests indicated that the temperature was perceived as significantly warmer and less comfortable during the no fan condition compared to all other conditions

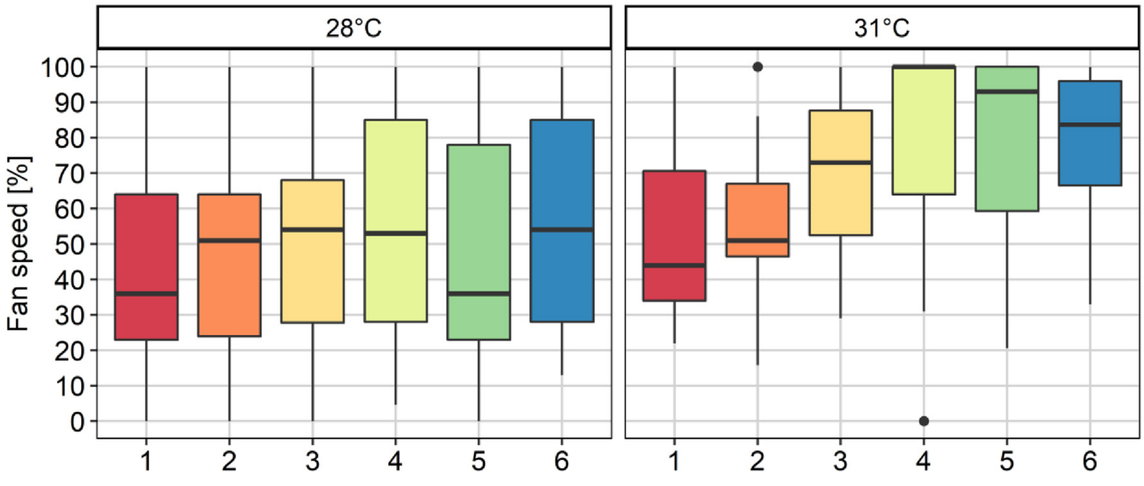

Fig. 11. Boxplot of chosen fan speed in each sequence according to temperature settings.

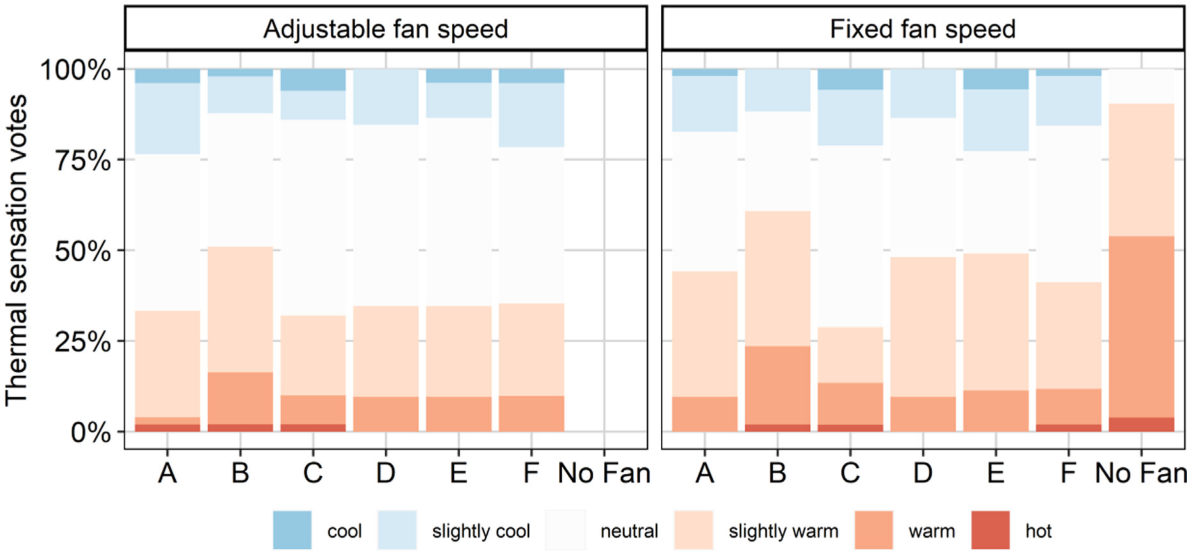

Fig. 12. Percentage of thermal sensation votes in the acclimatization phase (No Fan) and all six position according to the control possibility.

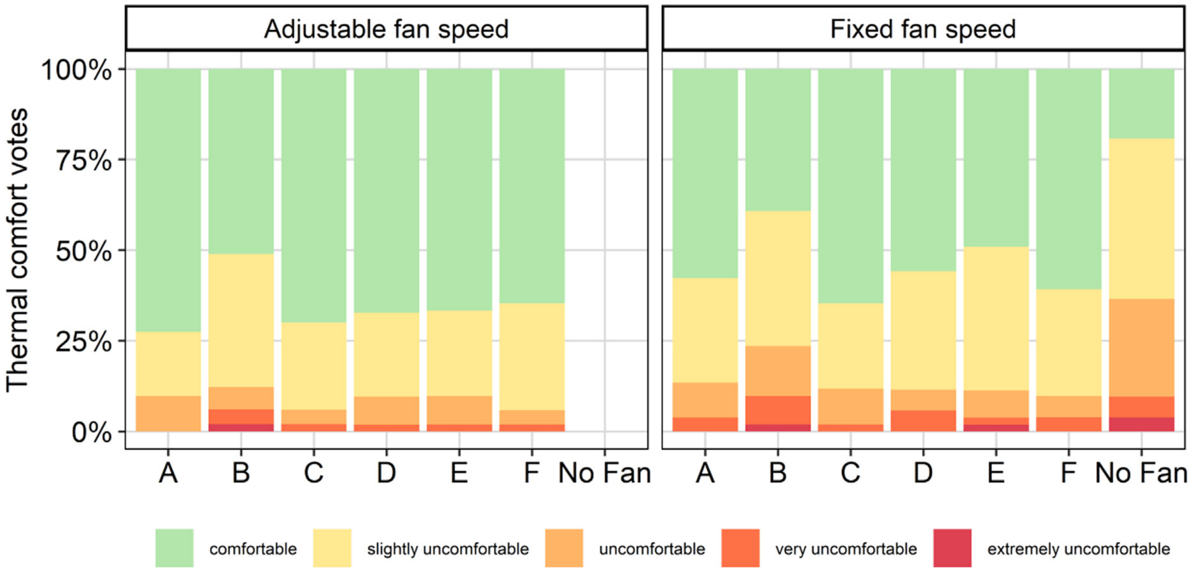

Fig. 13. Percentage of thermal comfort votes in the acclimatization phase (No Fan) and all six position according to the control possibility.

(p < .001), except in the thermal comfort vote for the standing position (B) with fixed fan speed. However, other conditions generally did not differ significantly from each other at the p = .004 level regarding the thermal comfort. The exceptions being B (standing) with fixed fan speed that differed significantly from most other positions – evaluated as warmer and less comfortable –, and position A (beneath the fan) with adjustable fan speed which also differed significantly from position B with adjustable fan speed concerning thermal sensation votes. Except for position B with fixed fan speed, for none of the different positions we saw a significant difference between control and no control conditions (fixed vs adjustable). Results in detail are shown in Table A.1 in Appendix A.

Fig. 14 shows the distributions of thermal preference and acceptability votes for all positions. Around 50–60% of the participants preferred no change in almost all positions, while 30–40% preferred “slightly cooler”-“cooler” thermal conditions. Similar to the thermal evaluation and comfort votes, the standing position differed from the other positions, as 65% of the participants preferred cooler thermal conditions. While most positions were rated as acceptable (between 88 and 94%), the standing position showed slightly lower acceptability rates (87%). Results of a Friedman test showed a significant effect of the different positions on thermal preference ($\chi^2(12) = 80.27$, $p < .001$) and thermal comfort ($\chi^2(12) = 78.24$, $p < .001$).

In line with the results from thermal comfort and sensation votes, post hoc Wilcoxon tests indicated generally higher acceptability for all positions compared to the no fan condition (p < .001, B adjustable p = .003) and a general preference for a significantly cooler temperature during the no fan condition (p < .001, B adjustable p = .003), except for the standing position (B) with fixed fan speed. Results in detail are shown in Table A.2 in Appendix A.

A series of Friedman tests were conducted to compare the effect of the positions on the evaluation of the air velocity. A significant effect can be observed in all four airflow domains: sensation

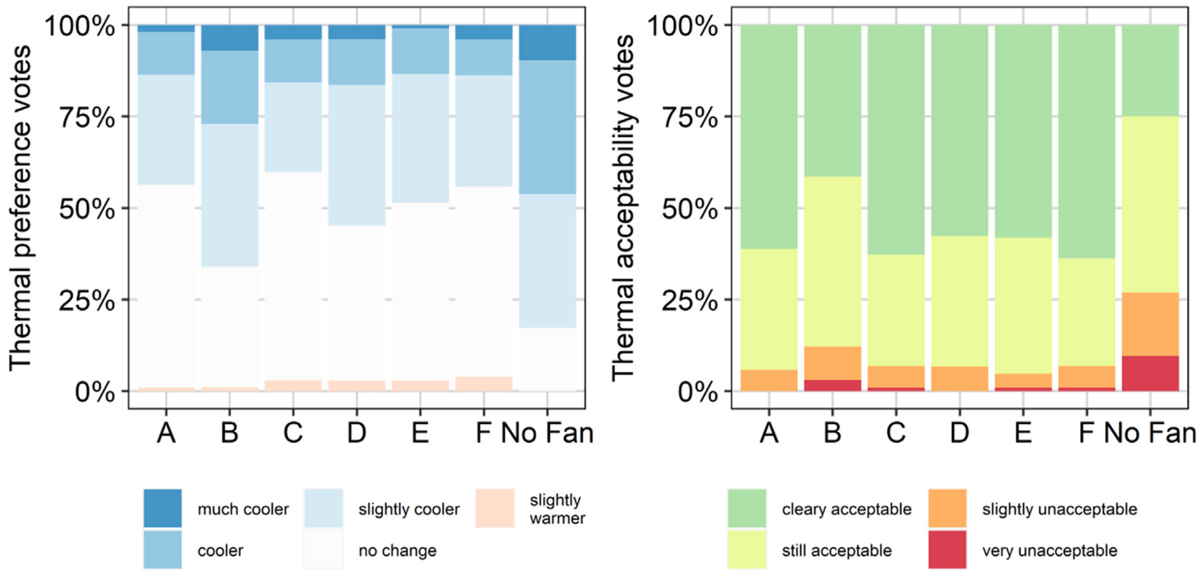

Fig. 14. Percentage of thermal preference and acceptability votes in the acclimatization phase (No Fan) and all six position.

($\chi^2(12) = 128.91$, $p < .001$), comfort ($\chi^2(12) = 91.17$, $p < .001$), preference ($\chi^2(12) = 77.84$, $p < .001$) and acceptability ($\chi^2(12) = 73.6$, $p < .001$). Post hoc Wilcoxon tests indicated a stronger air velocity sensation ($p < .001$) and higher comfort concerning air velocity (generally $p < .001$, position B fixed $p = .002$) in all conditions compared to the no fan condition, in which a preference for higher air velocity ($p < .001$) and less acceptability was observed. Furthermore, Wilcoxon signed-rank tests also showed that participants perceived a significantly stronger air velocity in the condition with airflow coming from above the participants' head (A) with adjustable fan speed compared to the standing position (B) with fixed fan speed ($p < .001$). We observed only at the standing position a significant difference between adjustable and fixed fan speed for all airflow domains (results in detail are shown in Table A.3 and Table A.4 in Appendix A). These results are reflected in the selected fan speeds: at the standing position (B) higher fan speeds were selected in comparison to the fixed condition. The fixed fan speed is almost the same value as the selected minimum for this position (Fig. 10).

We tested the relationship between participants' thermal and air velocity evaluation. Table 4 shows the results of a series of Wilcoxon tests to compare the means of temperature and air velocity, which showed a significant difference for all evaluation categories. A series of Kendall's rank correlations for all evaluation categories were conducted. A positive correlation was found between thermal and air velocity comfort. As on average participants rated the air velocity as more comfortable than the temperature, the relationship between perception of temperature and preference of air velocity was tested to gain more insights. The latter showed a significant negative correlation, meaning that on average participants that rated the temperature as warmer did express a preference for stronger air velocity. The tests for the correlation between the preference of temperature and air velocity and between acceptability of both groups showed a significant positive correlation. Participants that opted for a cooler temperature also opted for stronger air velocity. On average, participants rated the air velocity as more acceptable than the temperature.

Furthermore, we tested whether the length of the experiment had a negative effect on the acceptability of the temperature and air velocity. The correlation was measured with all experimental conditions aggregated. Results from a Kendall's rank correlation showed that no linear correlation was found between the thermal acceptability votes and the number of the sequence ($\tau = 0.08$, $p = .51$). There was, however, a positive correlation between the acceptability of air velocity and the timing of the scoring ($\tau = 0.248$, $p = .048$) indicating that the later during the sequence the score was taken, the less acceptable participants rated the air velocity. Half of the participants expressed a preference for a change in the air velocity in the last sequences, preferring 66% a higher air velocity. This means that the lower acceptability at the end of the experiment is mostly due to too low air velocity, rather than too strong. Note, that for all positions – except A – the average air velocity was less than 0.5 m/s at the last two sequences of the experiment.

Fig. 15 shows the number of thermal and air velocity acceptability votes binned according to air velocity measured for the adjustable conditions. Most thermal and air velocity votes are within the acceptable range, where 46% (both for thermal and air velocity votes) of participants selected the air velocity in a range of 0.2–0.4 m/s, 22–23% (thermal and air velocity, respectively) in a range of 0.4–0.6 m/s and 15% (both thermal and air velocity votes) higher than 0.6 m/s. In both evaluation categories, the unacceptable votes were due to too warm and too weak air velocity sensations, as the fan speed chosen by the participants for those

Table 4
Mean, median and standard deviation for all four evaluation categories for temperature and air velocity. Wilcoxon test p-values and effect sizes. Kendall's rank correlation coefficient (Tau) and p-values. Significant differences and correlations are marked with bold characters.

Evaluation categories	Temperature	Air velocity	Wilcoxon test	Kendall's rank correlation coefficient
Comfort	Mdn = 1, M = 1.61, SD = 0.84	Mdn = 1, M = 1.44, SD = 0.75	z = −5.83, p < .001, d = −0.48	**τ = 0.47, p < .01**
Preference	Mdn = 3, M = 3.27, SD = 0.89	Mdn = 4, M = 3.65, SD = 0.95	z = −10.93, p < .001, d = −0.94	**τ = 0.52, p < .01**
Acceptability	Mdn = 1, M = 1.55, SD = 0.7	Mdn = 1, M = 1.47, SD = 0.65	z = −3.38, p = .001, d = −0.27	**τ = 0.56, p < .01**
Sensation-Preference	Mdn = 4, M = 4.43, SD = 1.01	Mdn = 4, M = 3.65, SD = 0.95	z = −10.91, p < .001, d = 0.94	**τ = −0.37, p < .01**

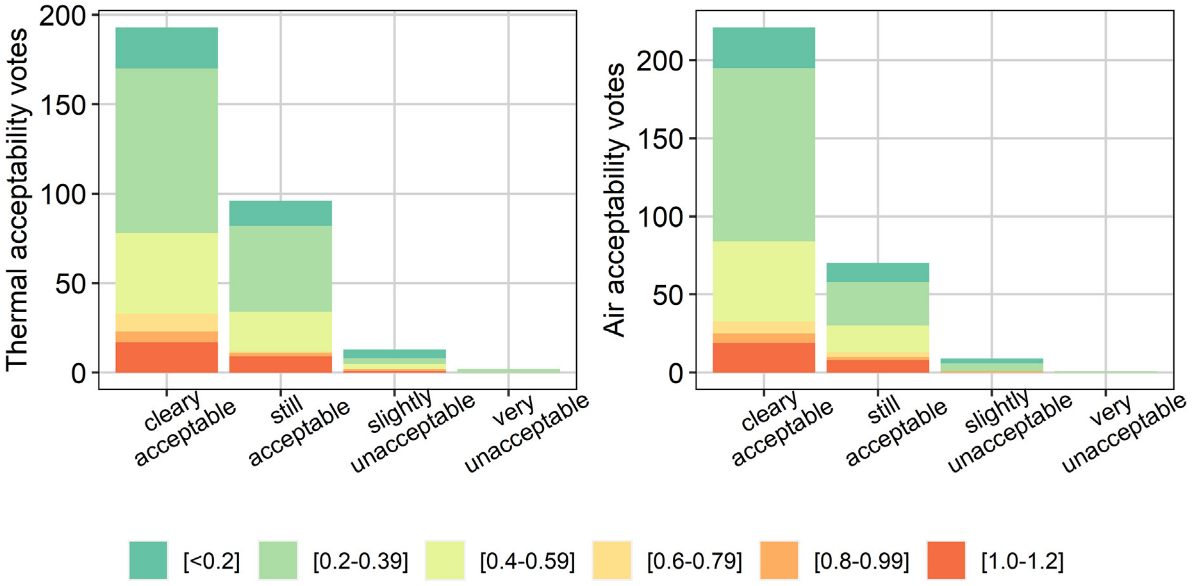

Fig. 15. Thermal and air velocity acceptability votes binned according to air velocity.

votes was on average between 80 and 100%. This means that only in 5% (thermal) and 3% (air velocity) of the votes, the air velocity delivered by the fan was not enough to enhance the acceptability of those participants.

3.4. Differences in extrinsic factors: temperature settings and time of the day

To compare the two temperature settings of the experiment, the sub-sample of the 11 participants who took part in both thermal settings (28 °C and 31 °C) was analyzed. A series of Mann-Whitney U tests were conducted to compare all domains at both temperature conditions (Table A.5 in Appendix A). The results showed that participants characterized the temperature at 31 °C as significantly warmer and less comfortable. Additionally, they expressed a preference for a cooler temperature and stronger air velocity and found temperature and air velocity significantly less acceptable. As far as the perception of air velocity was concerned, participants considered the air velocity sensation as not significantly different between the two temperature conditions.

A series of Mann-Whitney U tests were conducted to compare the evaluation of temperature and air velocity between the morning and the afternoon participants (Table A.5 in Appendix A). We found statistically significant differences in scores between the morning and the afternoon participants. Afternoon participants perceived the temperature as higher and the air velocity as weaker. Afternoon participants also evaluated the temperature and air velocity as less comfortable and expressed a preference for stronger air velocity and their acceptability for the air velocity was lower. Nonetheless, effect sizes were around 0.2 and therefore rather small.

Results from the Wilcoxon test showed that the time of the day significantly affected the selected fan speed: the selected fan speed during morning sessions (Mdn = 40) differed significantly from afternoon sessions (Mdn = 57), W = 14862, $p < .001$, $r = -0.76$. These results correspond to the differences observed in the measured outside temperature before arrival (Fig. 7) between morning and afternoon sessions, while indoor thermal conditions were comparable. Besides, other differences, e.g. in the level of nutrition could have affected such results. Additionally, we check the interference of other potential differences between groups. No significant differences between morning and afternoon sessions were found between sex ($\chi^2(1) = 0.9$, p = .764), age ($\chi^2(1) = 1.41$, p = .235) and normal weight and overweight participants (BMI $\geq$ 25 kg/m^2) according to the classification from WHO [37] ($\chi^2(1) = 0.28$, p = .598).

3.5. Differences in demographics: sex and age group

A series of Mann-Whitney U tests were conducted to compare all domains of thermal perception for different groups: sex, age and BMI groups (Table A.6 in Appendix A). For the sex analysis, the results showed that female participants characterized the temperature as significantly hotter and less comfortable. Females also expressed a wish for a cooler temperature and found the temperature less acceptable than males. Nonetheless, the effect sizes were rather small for comfort, acceptability and preference ($d < 0.33$), except for the sensation ($d = -0.41$). As far as air velocity was concerned females preferred a significantly stronger air velocity than males. There was no statistically significant difference in the sensation, comfort and acceptability of the air velocity between the sexes.

Moreover, the results showed that although there was no significant difference in the thermal sensation between younger and older participants (Table A.6 in Appendix A), younger participants characterized the temperature as significantly less comfortable, expressed a preference for a cooler temperature and found the temperature less acceptable than older participants. However, there was no significant difference in the comfort, preference and acceptability of the air velocity between the age groups. The only significant difference for air velocity was found in the perception of the strength of the air velocity (sensation), where older participants perceived the air velocity as significantly stronger than younger participants. All statistically different scores had small to very small effect sizes (between 0.18 and 0.25).

3.6. Perception of air velocity at individual body parts

Participants were asked to rate the air velocity at individual body parts. Fig. 16 shows the frequency of votes where the air velocity was perceived at the mentioned body parts at each thermal setting. Both thermal settings show similar patterns of votes.

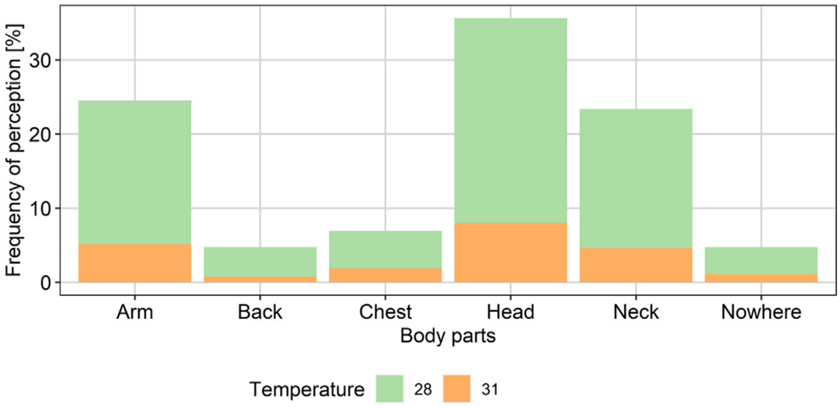

Fig. 16. Frequency of votes when the air velocity was perceived at each body part for each thermal setting.

Most participants perceived the influence of the air velocity at their head (~35%), followed by the arms and neck (~24%). Chest and back were mentioned less often (~4–7%). Around 4% of the participants voted no perception of the air velocity at any part of their body. The air velocity was perceived as comfortable at the arm, back and chest for almost all participants, while for the head and neck it was perceived on average as comfortable for half of the participants and between slightly uncomfortable and uncomfortable for 25% of the participants.

3.7. Eye dryness and humidity

Participants were asked about their perception and evaluation of the humidity of the air and the dryness of their eyes at the beginning and end of the sessions. Although the perception of the humidity of the air did not differ significantly statistically (Wilcoxon test for repeated measures, Mdn Start = 4, Mdn End = 4, z = -0.16, p = .876), participants evaluated the humidity at the end of the session as significantly more comfortable than at the beginning (z = −2.18, p = .029, d = −0.64). As far as the dryness of the eyes is concerned, there was a statistically significant change in perception (z = −2.53, p = .011, d = −0.76) at the beginning and end of the session in both thermal settings (28 °C and 31 °C). Whereas in the beginning 48 votes (47%) were recorded for not experiencing dryness, this number decreased to 39 at the end (38%). However, this did not result in a significant change in the acceptability of the dryness of the eyes (z = −1.63, p = .102).

3.8. Experience with ceiling fans

In order to compare the assessment of the fans used during the experiment with previously used fans, participants were asked specific questions at the beginning and the end of the session. During the acclimatization phase, participants were asked if they have used fans before (N("Yes") = 28, N("No") = 12) and if they were used to use ceiling fans at the workplace and home. Only one participant claimed to have used a ceiling fan at home. Additionally, they were asked to rate the comfort achieved by fans used in the past (*"Wie wirksam sind Ventilatoren Ihrer Erfahrung nach? Dadurch wird bei hohen Raumtemperaturen im Allgemeinen die Behaglichkeit verbessert"*/ Translation: *"How effective are fans in your experience? In order to improve comfort at high room temperatures"*). Besides, participants had to rate the comfort achieved by the fans used during the experiment (*"Wie wirksam waren die Ventilatoren heute Ihrer Erfahrung nach? Dadurch wird bei hohen Raumtemperaturen im Allgemeinen die Behaglichkeit verbessert"*/ Translation: *"In your experience, how effective were the fans today? In order to improve comfort at high room temperatures"*). Fig. 17 shows the distribution of votes.

Results from a Wilcoxon test showed no significant difference between the assessment of previously used fans (Mdn = 2, M = 2.08, SD = 0.67) and fans used during the experiment (Mdn = 2, M = 1.84, SD = 0.73, z = −1.44, p = .15). Besides, participants were asked to directly compare the fans used during the experiment with past fan experience (*"Wie wirksam waren die hier eingesetzten Ventilatoren im Vergleich zu den von Ihnen bisher verwendeten Ventilatoren, die Sie am Anfang bewertet haben?"*/Translation: *"How effective were the fans used here compared to the fans you have used so far, which you evaluated at the beginning?"*). Participants who had previous experience with fans generally scored the tested ceiling fans as better or even much better than the ones experienced previously (N = 40, Mdn = 2, M = 2.07, SD = 0.72). A fifth of participants noted no change and two considered the ceiling fans as worse. As far as the correlation between previous experiences and the assessment on the day of the experiment is concerned, correlation results showed no statistically significant correlation between previous experience and the evaluation on the day (τ = 0.3). There was however a significant positive correlation between the evaluation of ceiling fans used during the experiment and the scores awarded for the ceiling fans used during the experiment compared to ceiling fans previously experienced (τ = 0.38, p < .01).

4. Discussion

4.1. Selected fan speed and perceived comfort

From the results, it can be concluded that the indoor temperature and the time of the day have shown influences on the selection of the fan speed. Results regarding indoor temperature are in line with a previous study with a desk fan [14], where at higher indoor temperature, higher fan speeds were selected. Even though participants increased the fan speed, thermal and air velocity comfort were rated differently for both temperature conditions, indicating a well-developed capacity of perceiving temperature changes. Similarly, the results of an experimental study by Zhai et al. [13] showed that even though the sensation votes were close to neutral when increasing the air velocity at 31 °C, ceiling fans could not fully eliminate warm sensation. In this study, the air velocity was not differently perceived between the two temperature settings, which means that the air velocity sensation coincides with the actual air velocity. Although there was a preference for stronger air velocity in the warmer setting, the fan speed was not set to the maximum level possible. This finding confirms find-

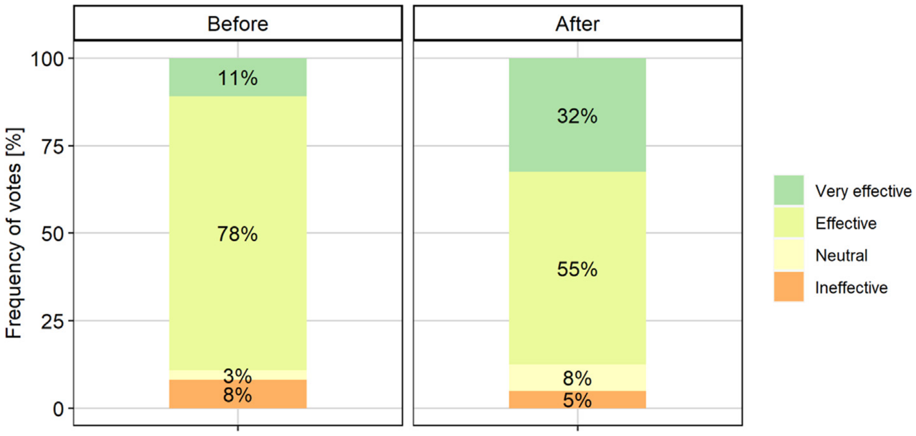

Fig. 17. Frequency of votes of the effectiveness of fans before and after the experiment.

ings by Zhai et al. [38], who found that only 10% of the participants who wanted more air movement used the full power of their fan.

Regarding the time of the day, at higher outdoor temperatures exposed before entering the chamber, higher fan speeds were selected. Besides, although the participants were exposed to a half-an-hour acclimatization phase, differences between morning and afternoon sessions were noted both on thermal and air velocity satisfaction. Wagner et al. [39] found differences in thermal sensation votes between people working in the morning and the afternoon, indicating a possible influence of either a previous exposure with the outdoor environment or leaving the office half an hour before the afternoon survey. In a more recent study, Ji et al. [40] found that past short-term thermal experiences affected the current perception of the environment. Results of that study showed that participants who experienced a thermal setting of 20 °C and then changing to a setting of 30 °C did not feel very hot and their thermal sensation vote improved. In contrast, participants who changed from a thermal setting of 28 °C to one of 30 °C expressed a higher thermal sensation vote. These results are comparable with the present study, where participants in the morning were exposed to outdoor temperatures between 15 °C and 20 °C and expressed comfortable conditions during the experiment with thermal conditions of 28 °C and 31 °C. Similarly to the results from Ji et al., participants in the afternoon sessions, who were exposed to outdoor temperatures as high as 30 °C, expressed higher thermal sensation votes and lower comfort votes – in comparison to morning results –, showing that the lack of contrast between thermal conditions, could not improve their comfort.

Furthermore, the fan speed selection was independent of the airflow direction (positions) and length of the experiment, although there was a tendency of increasing the fan level during the 31 °C setting. During the duration of the experiment, there was no difference in participant's thermal acceptance. Similar results were obtained in the study of Zhai et al. [38], where participants were thermally comfortable during the experiment, except at the acclimatization period where no air movement was provided. Moreover, the 10-minute breaks without airflow in this study seemed not to influence the ratings during the session, confirming the findings of Zhai et al. [38] that when exposed to air movement after breaks with no airflow – and even increased activity level –, thermal comfort was improved immediately and restored within 5 min. However, the later the vote in the sequence, the less acceptable participants rated the air velocity. Results seem to indicate that the dissatisfaction was perceived as a need for increased air velocity but not as a thermal discomfort caused by the length of the experiment.

Even though there was a significant influence of the temperature setting on the selected fan speed, the measured air velocity did not differ significantly for both thermal conditions. Results suggest that acceptability with both thermal and air velocity conditions was achieved for half the participants with air velocities between 0.2 and 0.4 m/s for both thermal conditions. Fig. 18 shows the boxplot of measured air velocities at times of neutral sensation votes (neutral air velocities) for both temperatures analyzed separately (28 °C and 31 °C), compared to neutral air velocities from other studies (adapted from [41]). The results from our lower temperature conditions at 28 °C differ from previous studies performed before 1997 [20,42,43], which evaluate a front fan with a uniform airflow [42,43] and a ceiling fan with a vertical airflow on the whole body [20]. However, our results are in line with more recent studies [6,13,41], which evaluate the cooling power with air jets [6], piston flow [41] and ceiling fan [13].

According to previous studies [6,14], air velocities lower than 0.5 m/s were within the comfortable range for an ambient temperature of 28 °C. For a room temperature of 28 °C, providing air velocity appears as an effective way to enhance heat loss and consequently reduce skin temperature. When temperatures are between 30 °C and 32 °C the elevated air velocity is unable to offset the increase of skin temperature, but airflow can enable heat loss via evaporation [41].

At the same time, our results for a room temperature of 31 °C differ in terms of neutral air velocities from previous studies, which evaluated indoor temperatures between 30 °C and 32 °C. One possible explanation might be the fact that the airflow was directed to specific body parts, which may modify the skin temperature and activate spatial alliesthesia to enhance the whole-body comfort [44]. According to Yang et al. [45], the effect of personalized ventilation on the overall thermal sensation is stronger than the room air temperature. In our study, the airflow was mostly perceived at the head, arms and neck. These results are similar to the study by Luo et al. [23], who found that the face and back part of the neck have higher sensibility in comparison to the whole-body average. While arms, back and chest were perceived as the most comfortable body part by most participants, the head and the neck were perceived as slightly uncomfortable by half of them. These results differ from the study by He et al. [46], where participants thermal comfort was improved when they felt air movement towards their head, chest and back, supplied by a desk fan. A possible explanation may lie in cultural differences.

The cultural background of participants may be a potential influence when analyzing the evaluation of air movement. In the present study, participants were not used to ceiling fans in the

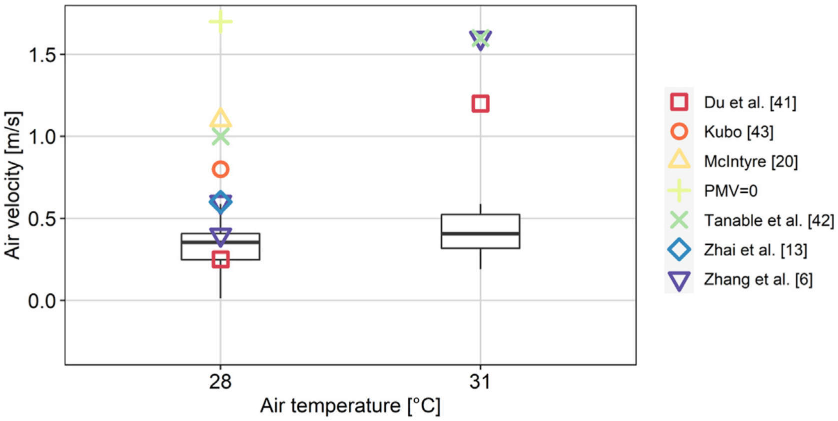

Fig. 18. Boxplot of air velocities measured for neutral sensation votes from the present study compared to results from other studies.

workspace, which indicates they were not accustomed to the air movement from a ceiling fan while working. This may differ from the previously mentioned study by He et al. [46]. Huang et al. [14] stated that the majority of people in China have a high demand for air velocity in the warm season, while in the study from Zhai et al. [19], students from the US needed higher air velocities in comparison to Chinese to offset their larger thermal sensation deviation from neutral, highlighting the impact of cultural differences on the preferred air velocities.

4.2. Airflow direction and personal control

With respect to the airflow direction, we found no differences in thermal comfort and air velocity evaluation for the different positions. These results confirm the findings of Pasut et al. [18], who found no differences in thermal comfort for an airflow direction between the fan and the participant from the front, side and right above the head in comparison to the no-fan configuration. An exception was the standing position, where the perception of a significantly higher temperature could be attributed to the slightly higher activity rate in a standing position combined with the lack of control, confirming previous findings by Arens et al. [47]. Moreover, personal control showed no influence on the perception and evaluation of positions. Findings differ from the studies from Zhai et al. [38], where they found higher thermal comfort when perceived control was given. However, this can be explained as in our study the selected fan speeds did not differ significantly from the fixed conditions, being in line with results from Zhai et al. [19]. The standing position however was the exception, where even though the fixed fan speed did not differ significantly with the average fan speed selected by participants (Fig. 9), the personal control – showing a slight increase in chosen fan speed – improved the thermal perception, evaluation, preference and acceptability in comparison to the condition with given air velocity. These findings could be compared to the analysis from Luo [48], who reported that personal control has a higher effect under severe conditions, which in our study could be due to a slightly higher metabolic rate.

Our results showed that the preferences concerning air velocity are close to the "no change" vote and that most of the votes regarding air velocity are within the acceptable range. This finding indicates that participants are quite satisfied with the air velocity. Therefore, the assumption of a wish for a stronger air velocity as mentioned for the correlation between perception of temperature and preference of air velocity might not hold. A possible explanation could be due to the slightly cool, and thus slightly uncomfortable, local thermal sensation at the specific body part – mostly perceived around the head area in our study –, which may correspond to an almost thermally neutral whole-body thermal sensation and consequently a preference for no air movement change [45]. Furthermore, the results suggest that the use of Likert type answers could make scores of the different aspects comparable on a parametric level and a factor analysis could be conducted to investigate further correlations.

4.3. Eye dryness and humidity

Results showed that longer exposure to airflow may lead to increased perception with dryness of eyes, but acceptability may not be changed. However, a causal relation cannot be taken for granted, as there may be other factors influencing the slight increase in perception of dry eyes, such as being working in front of a computer for three hours. The sensation of humidity was not altered by time, but results may suggest that the personal control along the session might reduce discomfort about humidity. These results are in line with findings from He et al. [7], who found that providing participants with personal cooling reduced their complaints about air humidity, but increased reported eye dryness. Contrarily to the findings from Zhai et al. [13], which indicated that increased air velocity reduces humidity sensation, our study suggests that sensation may not change but comfort with humidity may be increased by higher air velocity.

4.4. Demographics

When we analyzed the differences in votes for different demographic groups, we found differences between sex and age for most categories of the thermal assessment. The results regarding sex seem to go against the findings from Humphreys and Rupp [49–51], who found no significant difference between sexes concerning thermal comfort. However, in a review by Wang et al. [51], contradictory results were found. They concluded that females are more critical and sensitive about the indoor thermal environment, supporting our findings, where female participants tended to be more dissatisfied in comparison to males, confirming their higher sensitivity to changes in temperature. The ambiguity of results might lie in a difference in width and location of thermal comfort zones between age and sex groups explained by Schweiker et al. [52]. Regarding age groups, results seem to coincide with Bischof et al. [53] who stated that younger participants have higher thermal expectations, being in our study thermally more dissatisfied in comparison to older participants. Concerning the air velocity evaluation, in general, no differences were found between both analyzed groups. These findings may be explained by the fact that the fan speed could be adjusted individually, achieving satisfaction with the air velocity in both groups.

4.5. Experience and effectiveness of the ceiling fan

Results from this study showed that ceiling fans were in general positively rated after and before the experiment. According to He et al. [7], the effectiveness of a cooling system is one of the most important factors for the adoption of a personal cooling device. Additionally, results may indicate that the actual rating of fans may be in line with previous attitudes towards them, although ceiling fans were rated better or much better in comparison to previous experiences. Moreover, positive experiences on the day of the experiment went along with a positive rating of the experience compared to past experiences with fans, indicating the effectiveness and acceptability of the personalized ceiling fan.

4.6. Limitations

Limitations related to unknown factors influencing afternoon and morning sessions have to be seen. A potentially too short acclimatization phase in the afternoon, non-observed aspects such as type of food and influence on metabolism when comparing morning and afternoon may be aspects to be considered in the future. Furthermore, the arrangement of the participants' position concerning the ceiling fan could be optimized to obtain higher air velocities provided by the ceiling fan and consequently, improve the participants' thermal comfort. An investigation of participants' expectations of the personal fan and its cooling capacity could address the participant's acceptability with the cooling device. Another limitation of this study are the small sample ($N = 11$) for the repeated measurements (comparison between thermal conditions and analysis of the 31 °C thermal setting) and the limited variance in the climatic background, which do not allow to generalize the results without further data collection and analysis.

5. Conclusion

This study aimed to examine the performance of a personalized ceiling fan to enhance thermal comfort at moderately high indoor temperatures. The effects of temperature conditions, the direction of supplied air and the possibility of personal control at different activity levels were tested. The main conclusions are as follows:

- The personal comfort system tested in this study fulfilled participant's thermal comfort at indoor temperatures of 28 °C and 31 °C. By providing air movement at the upper part of the participants' body, air velocities even lower than 0.4 m/s were within the acceptable comfort range. By repositioning the participants' workstation and adjusting the fan's grille, higher air velocities could be achieved to enhance comfort at higher indoor temperature conditions.
- The design of the personalized ceiling fan allowed the flexibility to direct the supplied air at a horizontal distance up to one meter (between the fan and the occupant), achieving occupants' comfort independent of the direction of the air coming from above.
- The possibility of controlling the ceiling fan speed enhances thermal comfort for participants with a slightly higher metabolic rate, in this case resulting from performing tasks in a standing position.
- Previous positive experiences with ceiling fans are associated with higher levels of thermal comfort and evaluation of the device.

Findings from this study show the potential for the implementation of personalized ceiling fans, especially for the refurbishment of existing buildings. Arguments for their implementation are their flexibility concerning the supplied air directions and the potential increase in energy efficiency in comparison to the incorporation of active cooling. Finally, the use of a personalized ceiling fan could compensate for inter- and intrapersonal differences in thermal requirements. Further research should focus on different cultural and climatic backgrounds to assess preferences in air velocities.

CRediT authorship contribution statement

Romina Rissetto: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Software. **Marcel Schweiker:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Andreas Wagner:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.110721.

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COMFORT AT THE EXTREMES 2022

The effect and influence of personalised ceiling fans on occupants' comfort and physiological response

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Abstract: Personal environmental control systems (PECS), such as fans, have been widely implemented as an effective strategy to increase energy efficiency and occupants' satisfaction with indoor environmental conditions. This paper explores significant differences between thermal sensation votes and participants' physiological responses when using personal ceiling fans. In an experimental study in summer of 2018, 45 participants were exposed to two thermal conditions (28°C and 31°C) and different airflow speeds and directions in a climate chamber that simulates a typical office environment. Indoor environmental, psychological and physiological responses (skin temperature and heart rate) were recorded during the entire session. We tested differences in physiological responses between different demographic, contextual groups and airspeed levels. Results showed that at 31°C, participants had a significantly higher distal skin temperature and that airspeed helped reduce proximal skin temperature. Overweight participants showed a significantly lower proximal skin temperature than average weight participants. Heart rate results yielded statistically significant differences between age groups. Besides, findings suggest that skin temperature follows indoor temperature changes. By increased airspeed, physiological adaptations can be stimulated to restore comfort. Overall, personal ceiling fans are an effective cooling solution that can target occupants' body parts and individual characteristics to increase their comfort.

Keywords: skin temperature; heart rate; personal comfort system; thermoregulation; thermal comfort

1. Introduction

The study of personal environmental control systems (PECS) has gained relevance in recent years, as they can improve occupants' satisfaction with the indoor environment and potentially increase energy savings in buildings. PECS targets occupants' proximity by conditioning only the occupied zone of the building space; hence, there might be less energy consumption than systems that condition the entire building volume, such as air conditioning systems. As a type of PECS, the use of fans has been widely implemented, as the cooling effect of the air movement increases occupants' thermal comfort and acceptability range in moderately warm thermal conditions. Furthermore, localised convective cooling of transitional spaces and work areas by ceiling or desk fans represents a way to enhance comfort recovery (Zhai et al., 2019).

The study of PECS is sustained in the paradigm that shifting thermal comfort toward a wider temperature range might stimulate the thermoregulatory system and not only achieve comfort but improve occupant's health (Ivanova et al., 2021; Luo et al., 2022). For instance, mild cold exposure can increase the human body's daily energy expenditure, contributing to maintaining a healthy weight and improving glucose metabolism. On the other hand, heat exposure can improve cardiovascular functioning after hot water immersion, decrease systolic blood pressure, and improve glucose metabolism (Ivanova et al., 2021). On the contrary, maintaining a stable indoor climate design could decrease the body's thermal resilience, in other words, the ability of the body to adjust to non-neutral conditions (Luo et al., 2022).

The human thermoregulation system responds to various indoor climate conditions through skin temperature adjustments and other physiological responses to keep the body core temperature within narrow temperature limits (Rawal et al., 2020). Skin temperature acts as one and an important sensor of the human body's thermoregulatory system (ASHRAE, 2017). Local skin temperature results from the complex balance between metabolic heat production, heat dissipation to the environment and tissue temperature (Binek et al., 2021). Differences in skin temperature could arise from body composition, health status, metabolic rate, circadian rhythm and ambient temperature (Neves et al., 2017). The underlying adaptive mechanisms to restore comfort are (a) behavioural, (b) physiological and (c) psychological adaptation. While minimising the availability of behavioural adaptation, physiological responses may occur. For instance, PECS can minimise thermal discomfort of targeted body parts which may activate thermoregulation. Very few studies have investigated the human body's physiological response to an increased airspeed due to the use of ceiling fans.

Luo et al. (2022) studied 18 participants between 18 and 40 years old in a climate chamber in autumn and winter. They tested two main scenarios (PECS and no PECS) and the indoor air temperature ranging from 17°C to 25°C. Results showed that skin temperature follows the same increasing pattern as the indoor air temperature. Distal and head skin temperature were significantly affected when using PECS, but this was not the case with torso skin and underarm-finger temperature gradient. Significant differences in lower limb temperature between 10 male and six female highly trained subjects were observed by Binek et al. (2021) under resting conditions but not during exercise. Regarding heart rate, Luo et al. (2022) reported no apparent relation with the indoor environment temperature ramp from 17°C to 25°C. However, there was a small but significant increase in hand skin blood flow and a significant increase in the average heart rate by 2.2 BMP ($p < 0.001$).

Finally, some researchers look into the ability to include physiological parameters to estimate thermal comfort responses better. Kingma et al. (2017) looked into the physiological thermoneutral zone (TZN) as a proxy to understand the thermal sensation. Some authors (Chaudhuri et al., 2018; Wu et al., 2017; Zhang and Lin, 2020) found a relationship between overall thermal sensation and mean skin temperature and proposed that the latter could predict thermal votes.

Existing research highlights the impact of physiological responses in thermal comfort studies; however, little is known about the cooling effect of the air movement due to ceiling fans in warm conditions. The study hypothesises that human thermoregulation can be moderately stimulated while providing comfort using personal comfort systems and investigates differences between demographics and contextual differences in human physiology.

2. Objective (Hypothesis)

The study focuses on the evaluation of the effect of personal ceiling fans on skin temperature and heart rate differences due to personal (sex, age, BMI), contextual characteristics (daytime, air temperature), and psychological responses (thermal sensation votes) for the given indoor environmental conditions. The main research questions are as follows:

- RQ1: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to increased airspeed from personal ceiling fans?

- RQ2: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to different levels of airspeed?
- RQ3: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects felt comfortable or uncomfortable based on reported thermal sensation for different levels of airspeed?

3. Methodology

To investigate the above-mentioned research questions, we conducted a 3-weeks experimental study in the test facility LOBSTER in Karlsruhe, Germany (Schweiker et al., 2014) during the summer of 2018.

3.1. Facility and experimental procedure

The facility consists of two office rooms equipped with a personal ceiling fan, which is integrated into an acoustical ceiling panel. Participants took part in a three hours 30 minutes session in one of the two rooms of the climate chamber, either in a slot between 9:00 and 12:30 (morning) or 13:30 and 17:00 (afternoon). During the first 30 minutes, the participants acclimatised to the given conditions in the room (acclimation phase). After this period, they experienced six different workstation configurations in a randomised order for 20 minutes concerning the ceiling fan position. For each configuration, participants were exposed to a constant fan speed for 10 minutes ('fixed' condition) and afterwards were given the possibility to adjust the fan speed level for the following 10 minutes ('adjustable' condition). They performed office tasks during the whole session, such as reading or working with the computer. The rooms were set with a room temperature of 28°C (50% RH), and a selected number of participants (N = 11) repeated the session another day with a room temperature of 31°C (50% RH). A detailed description of the study and the ceiling fan is explained in Rissetto et al. (2021).

3.2. Participants

Forty-five participants between 18 and 34 (Adult) and 50–70 year (Elderly) (age young 30.67 ± 4.04, age elderly 65.48 ± 6.45; BMI 24.7 ± 3.72 kg/m2) took part of the study. They were asked to wear long trousers, a t-shirt, and closed shoes (M = 0.44 clo-value; SD = 0.12). Table 1 shows the distribution of participants according to their age group, age, body mass index (BMI < 25 kg/m2 = normal and BMI > 25 kg/m2 = overweight) and sex.

Table 1. Participants' distribution according to personal characteristics (age, sex, BMI).

		Age		**Subtotal**
Sex	**BMI**	**Adult**	**Elderly**	
Male	Normal	8	7	15
	Overweight	3	8	11
	Subtotal	11	15	26
Female	Normal	7	2	9
	Overweight	1	9	10
	Subtotal	8	11	19
	Total	19	26	45

3.3. Materials and data collection

Physiological data. We measured the skin temperature of the single participants in four points with temperature loggers (iButton model = DS1921H; r = 0.125°C; a = +/- 1°C). The proximal skin temperature was measured at the back of the neck and the right shoulder, and the distal skin temperature was measured at the back of the left hand and the right shin. Their heart rate was measured with chest strap sensors (Model: EcgMove 4; r = 12 bit; Input range CM = 560 mV, DM = +/-5 mV). All data was recorded in a 1-minute interval.

Temperature and airspeed. We also collected with AHLBORN comfort meters located at 1.1 m height and 0.25 m away from the participant's head the following parameters: air temperature (r = 0.01 °C; a = ±0.2 K), globe temperature (r = 0.01 °C; a = ±(0.30 K + 0.005 × T)), relative humidity (r = 0.1%, a = ±2.0%) and air velocity (r = 0.001 m/s; a = ±(3% measured value + 0.01)). Participants' interactions with the ceiling fan during the adjustable condition were collected using a remote controller with a reference level from 0 to 100%. The device was connected to the building management system (BMS), and the fan speeds could be derived from the recorded levels.

Psychological data. Participants completed several questionnaires at different times during the session, including thermal sensation (7-point; *cold* ←→ *hot*), comfort (5-point; *comfortable* ←→ *extremely uncomfortable*), preference (7-point; *much cooler* ←→ *much warmer*), acceptability votes (4-point; *clearly acceptable* ←→ *clearly not acceptable*), perception of air quality and airspeed, among others.

3.4. Data analysis

Data preparation and analysis were conducted with the software environment R Version 4.1.3. Both physiological parameters (heart rate and skin temperature) and airspeed are measured on interval level and therefore assessed using parametric tests. Data normality was tested using Shapiro-Wilk's test, distal skin temperature is normally distributed ($W = 0.988$, $p = 0.071$), and proximal skin temperature ($W = 0.985$, $p = 0.025$) and heart rate ($W = 0.969$, $p = 0.000$) are non-normally distributed. An independent t-test was conducted to test differences between demographics and contextual factors when the studied variables had two groups when data was normally distributed. Furthermore, an ANOVA (F) test was used when the studied variables had more than two groups. Whenever data follows a non-normal distribution, comparisons between two levels were tested using the Mann-Whitney and Kruskal-Wallis (H) for three levels of analysis. Moreover, a paired t-test was conducted to test the significant difference between distal and proximal temperatures. All t-tests were calculated with a significance level of 0.05. Finally, effect sizes are interpreted as small ($d = 0.10$), medium ($d = 0.30$), and large ($d = 0.50$), based on Cohen's suggestions (Cohen, 1988). Table A 1 shows the mean and standard deviation for each analysed group's distal and proximal skin temperature and hear rate scores.

To evaluate the effect of an increased airspeed due to the use of personal ceiling fans in physiological responses, data corresponding to the acclimation period and airspeed below 0.05m/s was discarded from the analysis. To evaluate significant differences in physiological responses between participants' personal (sex, age, BMI) and contextual characteristics (daytime, air temperature) (*RQ1*), we conducted a series of independent-samples t-tests and Mann-Whitney tests to compare the average values of skin temperatures and the average heart rate during the whole session. The effect of different air velocities in participants' physiological responses (*RQ2*) was analysed at three levels of air velocity: Low = airspeed < 0.4m/s, Medium = airspeed between 0.4m/s and 0.8 m/s, High = airspeed > 0.8 m/s. To evaluate significant differences in skin temperature and heart rate between participants who reported thermal sensation for different airspeed levels (*RQ3*), thermal sensation votes (TSV) were classified into two groups: neutral (TSV ≥ 3 ≤ 5) and non-neutral (TSV < 3 and > 5). A correlation between physiological and psychological was performed using Kendall's rank correlation coefficient Tau.

4. Results and discussion

4.1. Differences between personal and contextual characteristics

Fehler! Verweisquelle konnte nicht gefunden werden. shows the results of the t-tests conducted for skin temperature and heart rate to identify differences between personal characteristics (age, sex, and BMI) and between contextual characteristics (daytime and temperature). All groups showed homogeneity of variance for the analysed variables (Table A 2**Fehler! Verweisquelle konnte nicht gefunden werden.**), except for the BMI groups for heart rate scores, which showed inequality of variance across samples. Additionally, we found a significant difference between proximal skin temperature (M = 34.07, SD = 0.89) and distal skin temperature (M = 33.26, SD = 0.68, t (44) = -5.80, p < .001, r = .66, N = 90).

Table 2. Central tendency comparison for skin temperature (distal and proximal) and heart rate measurements between independent groups (sex, age, BMI, time of day and temperature).

	Sex	**Age**	**BMI**	**Time of day**	**Temperature**
Skin t° distal	t (37.34) = 1.50 p = 0.141 M = 33.08 (f); 33.39 (m)	t (31.41) = -0.52 p = 0.608 M = 33.32 (y); 33.21 (e)	t (39.89) = 1.81 p = 0.08 M = 33.42 (n); 33.07 (o)	t (42.96) = -0.56 p = 0.578 M = 33.31 (m); 33.20 (a)	t (15.43) = -5.02 **p < 0.01**** M = 33.05 (1); 34.00 (2)
Skin t° proximal	W = 185 p = 0.159 M = 34.43 (f); 33.88 (m)	W = 196 p = 0.249 M = 34.30 (y); 33.88 (e)	W = 373 **p < 0.01**** M = 34.38 (n); 33.57 (o)	W = 284 p = 0.492 M = 33.96 (m); 34.35 (a)	W = 137 p = 0.198 M = 33.92 (1); 34.42 (2)
Heart rate	W = 278 p = 0.487 Mdn = 73.19 (f); 75.11 (m)	W = 157 **p = 0.039*** Mdn = 77.78 (y); 72.79 (e)	W = 227 p = 0.581 Mdn = 72.97 (n); 75.59 (o)	W = 215 p = 0.398 Mdn = 77.00 (m); 73.82 (a)	W = 168 p = 0.861 Mdn = 73.86 (1); 74.46 (2)

Note: The following abbreviations correspond for each group: Sex = f: female, m: male; Age = y: young, e = elderly; BMI = n: normal, o: overweight; Time of day = m: morning, a: afternoon; Temperature = 1: 28°C; 2: 31°C.

Results showed that heart rate values were significantly higher for younger participants than for the elderly group, with a medium effect size (d = -.31). At the same time, no differences were found in the skin temperature between groups. Reported psychological responses of the participants were previously analysed (Rissetto et al., 2021), and results showed that younger participants evaluated the temperature as significantly less comfortable, expressed a preference for a cooler temperature and found the temperature less acceptable than older participants. Besides, participants with normal weight showed higher proximal skin temperature than participants with overweight during the session, with a large effect size (d = -.42). However, there were no differences between heart rate scores and comfort votes between BMI groups.

Although Rissetto et al. (2021) showed that female participants perceived the temperature as significantly hotter and less comfortable, we found no statistically significant differences in skin temperature or heart rate values between female and male participants.

Differences in skin temperature between women and men have been previously assessed, as in Wu et al. (2017), who found no statistically significant difference between groups in the hand skin temperature for warm thermal sensation votes at an average air velocity of 0,2 m/s and 26°C indoor temperature. We analysed differences in the average air speed between sex groups, and no significant difference was observed (t (40.71) = -0.84, p = 0.408).

We found statistically significant differences in distal skin temperature between the temperature sessions (d = .79), showing higher levels of distal skin temperature when participants experienced the warmer temperature condition (31°C). At 31°C, participants reported the temperature conditions as significantly warmer and less comfortable. Even though studies showed that temperature changes could induce changes in the heart rate (Lan et al., 2011), we found no differences between thermal conditions. Differences in results could be explained as the mentioned study compared neutral to warm changes, while participants experienced only warm indoor conditions in our study. Besides, Rissetto et al. (2021) showed that afternoon participants perceived the temperature as higher, evaluated the temperature and air velocity as less comfortable and chose a higher selected level of fan speed; in the present study, physiological responses did not significantly differ between daytime sessions.

4.2. Effect of airspeed levels for different thermal sensation votes and temperature settings

Table 3 summarised the differences in physiological responses between air speed levels. RQ2 needs to be rejected in this analysis. In this first analysis, the level of airspeed seemed not to influence physiological adaptations, as no significant differences were found for skin temperature, neither proximal nor distal, and heart rate between the different levels of airspeed.

Table 3. Central tendency comparison for skin temperature (distal and proximal) and heart rate between air speed groups.

	Normality	**Central tendency**	**Test**	**p-value**	**Effect size**
Skin t° distal	W = 0.988, p = 0.303	M = 33.3 (l), 33.3 (m), 33.2 (h)	F (2, 203) = 0.178	0.774	0.18
Skin t° proximal	W = 0.982, p = 0.303	M = 34.1 (l), 34.1 (m), 34.0 (h)	F (2, 124) = 0.147	0.048	0.05
Heart rate	W = 0.969, p = 0.303	Mdn = 73.8 (l), 75.8 (m), 74.6 (h)	H (2) = 0.570	0.752	-0.03

Note: The following abbreviations correspond for air speed groups = l: low, m: medium, h: high.

Results of a correlation showed that the expressed sensation votes during the session were significantly related to the distal skin temperature (τ = 0.16, p < .01) and the proximal skin temperature (τ = 0.22, p < .001). These results align with previous studies that found a linear relationship between overall thermal sensation and upper extremity skin temperature (Wu et al., 2017). Assuming a relationship between thermal sensation and skin temperature, we analysed the effect of different levels of airspeed on skin temperature for different thermal sensation groups and temperature configurations. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the results of the performed t-test.

Table 4. Central tendency comparison for skin temperature (distal and proximal) measurements between thermal sensation groups and thermal conditions for different air speed levels.

	Level	**Airspeed and sensation**	**Airspeed and temperature**
Skin t° distal	Low	t (25.3) = -2.29, **p = 0.030***, d = .41 C = 61 (n), 19 (nn); M = 33.2 (n), 33.7 (nn)	t (15.6) = -4.65, **p = 0.000***, d = .762 C = 35 (1), 10 (2); M = 33.1 (1), 34.0 (2)
	Med	t (8.22) = -1.46, p = 0.181, d = .454 C = 29 (n), 8 (nn); M = 33.2 (n), 33.7 (nn)	t (12.4) = -4.63, **p = 0.000***, d = .796 C = 28 (1), 9 (2); M = 33.1 (1), 34.1 (2)
	High	t (5.44) = -1.96, p = 0.103, d = .643 C = 52 (n), 6 (nn); M = 33.1 (n), 34.0 (nn)	t (16.2) = -5.12, **p = 0.000***, d = .787 C = 35 (1), 10 (2); M = 33.0 (1), 34.0 (2)
Skin t° proximal	Low	t (31.7) = -2.29, **p = 0.029***, d = 0.376 C = 61 (n), 19 (nn); M = 34.0 (n), 34.5 (nn)	t (19.1) = -1.35, p = 0.193, d = .295 C = 35 (1), 10 (2); M = 34.0 (1), 34.4 (2)
	Med	t (9.60) = 0.103, p = 0.920, d = .033 C = 29 (n), 8 (nn); M = 34.1 (n), 34.1 (nn)	t (18.4) = -1.75, p = 0.096, d = .379 C = 28 (1), 9 (2); M = 33.9 (1), 34.5 (2)
	High	t (7.21) = 3.160, **p = 0.015*,** d = .762 C = 52 (n), 6 (nn); M 34.0 (n), 34.9 (nn)	t (18.9) = -1.06, p = 0.301, d = .237 C = 35 (1), 10 (2); M = 34.1 (1), 34.3 (2)

Note: The following abbreviations correspond for each group: Thermal sensation = nn: non-neutral, n: neutral; Temperature = 1: 28°C, 2: 31°C.

RQ3 is partially supported. Regarding thermal sensation votes, participants who voted neutral thermal conditions showed statistically significant lower distal and proximal skin temperature (0.5°C difference), when the air speed was below 0.4m/s, compared to participants voting feeling warmer (non-neutral). On the other hand, a 0.9°C difference between participants voting neutral and non-neutral is not significantly different when the airspeed is above 0.8m/s for distal skin temperature. This could be interpreted as at low fan speed values, the cooling effect of the airflow was not sufficient to restore comfort, slightly increasing participants' skin temperature, consequently reporting warmer thermal conditions. Although thermal conditions were perceived differently at elevated fan speeds (medium and high), it seems that participants did not require to thermoregulate their bodies, as the cooling effect provided by the fan airflow was higher. However, at airspeeds higher than 0.8 m/s, participants who voted neutral showed lower proximal skin temperature than participants who voted non-neutral thermal conditions. A possible explanation could be the direct cooling effect of the airspeed on the skin temperature in the upper body parts (shoulder and neck), which allowed a higher reduction of the skin temperature in some participants (neutral group), consequently leading them to perceive the indoor conditions as neutral. Although the effect sizes for the different tests are either medium or large, the sample size of the non-neutral group is relatively small, which could lead to different results.

In terms of thermal conditions, participants showed significantly higher values of distal skin temperature when the indoor temperature was 31°C, regardless of the airspeed level. Contrarily no significant difference in proximal skin temperature values was found between thermal conditions. This could be interpreted as a reduction of the skin temperature at warmer thermal conditions was achieved by the cooling effect of the air movement in the proximity of the participant's body, generating no difference in skin temperature between the two temperature conditions. In the case of the distal body parts, an increase in temperature resulted in an increase in skin temperature, in which no skin temperature reduction was possible as no direct airflow was directed to those body parts.

5. Conclusions

This study aims to understand the relationships between human physiology and perceptions of the indoor environment quality when using a personal ceiling fan. The effects of airspeed from and personal control over the fan and personal and contextual characteristics of participants were investigated. The main conclusions in this study could be described as physical differences due only to demographics or physical characteristics, and differences due to environmental conditions (airspeed and air temperature).

Regarding physical differences among participants, it was observed that overweight participants showed a significantly lower proximal skin temperature than participants with average weight, while a higher mean heart value was measured for young participants, showing that body composition and ageing can affect physiological responses under the same indoor environmental conditions. Studies on women subjects have reported non-significant differences in core temperatures between normal and obese body mass (Chudecka 2014.) However, the mean body surface temperature decreases with an increasing percentage of body fat in the abdominal area, while the opposite relation was observed for the hand area, opposite to what was reported in this study. Furthermore, as it has been previously reported, younger adults are usually metabolically more active, and heart rate decreases with age (Kumral 2019). Thus, the observed differences in body composition and heart rate cannot be only attributed to the differences in the indoor environment. Further studies are required to better understand the main physiological variables involved in adapting, acclimating and resilience to more extreme indoor environmental conditions.

On the other hand, the main conclusions regarding skin temperature due to differences in the indoor environmental conditions could be summarised as follows:

The skin temperature corresponds to changes in indoor temperatures and consequently with participants' perception of the indoor environment. At increasing moderately warm indoor temperatures, participants had a significantly higher distal skin temperature and rated the thermal condition significantly warmer and less comfortable.

- Participants selected a significantly higher air velocity for the warmer condition to restore thermal comfort. When the airspeed was insufficient to achieve thermal neutrality, it could be assumed that a thermoregulation process took place in body extremities, increasing the distal skin temperature.
- The effect of the air movement in the proximity of the human body affected the skin temperature of the participants and, consequently, their thermal perception of the environment.

Despite results on physical results are not conclusive, different levels of airspeed provide insightful results to inform the definition of the thermoneutral zone. For instance, at medium or high airspeed, the thermal sensation does not directly affect the distal skin temperature as it does the air temperature. Furthermore, a difference in the range of 0.5 to 0.9 degrees in proximal skin temperature could be conclusive in terms of perceiving a neutral or non-neutral thermal sensation regardless of the air temperature in the assessed environment.

Findings in this study suggest that personal environmental control systems can improve thermal comfort by stimulating human thermoregulation processes targeting specific body parts. Moreover, these systems allow multiple configurations to target individuals' body composition to achieve individual comfort.

Abbreviations

r	resolution
a	accuracy

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Appendix

Table A 1. Count, mean and standard deviation (sd) for distal and proximal skin temperature and heart rate scores for each analysed group.

Group	**Levels**		**Distal temp. (°C)**		**Proximal temp. (°C)**		**Heart rate (bpm)**	
		Count	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Age	Young	19	33.3	0.8	34.2	0.9	79.9	11.6
	Adult	26	33.2	0.6	33.9	0.9	72.8	8.2
BMI	Normal	24	33.5	0.8	34.5	0.8	75.9	13.1
	Overweight	21	33.1	0.5	33.6	0.8	75.8	6.5
Sex	Male	26	33.4	0.6	33.9	0.8	76.0	8.6
	Female	19	33.1	0.7	34.3	1.0	75.6	12.5
Temperature	28°C	35	33.1	0.6	34.0	1.0	75.7	11.3
	31°C	10	34.0	0.5	34.3	0.7	76.2	6.7
Time day	Morning	23	33.4	0.7	34.2	1.0	77.5	10.1
	Afternoon	22	33.2	0.7	33.9	0.8	74.3	10.5

Table A 2. Levene's test for equality of variance.

	Sex	**Age**	**BMI**	**Time of day**	**Control**	**Tempera-ture**
Skin t° distal	F = 0.01 p = 0.961	F = 2.78 p = 0.103	F = 3.93 p = 0.054	F = 0.02 p = 0.896	F = 0.11 p = 0.736	F = 0.03 p = 0.874
Skin t° proximal	F = 1.19 p = 0.282	F = 0.02 p = 0.894	F = 0.27 p = 0.607	F = 3.36 p = 0.078	F = 0.05 p = 0.820	F = 1.46 p = 0.233
Heart rate	F = 1.36 p = 0.249	F = 2.57 p = 0.116	F = 5.72 **p = 0.021***	F = 0.17 p = 0.685	F = 0.03 p = 0.867	F = 1.50 p = 0.228

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Comfort and Economic Viability of Personal Ceiling Fans Assisted by Night Ventilation in a Renovated Office Building

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Abstract: An expected increase in the use of air conditioning by 2050 will significantly increase electricity demand and come at a cost to the environment. Implementing passive cooling strategies and focusing on personal environmental control systems (PECSs) could help to address this issue. While numerous studies have investigated the positive impact of PECSs on thermal comfort and energy savings, their overall economic benefit has been poorly addressed. We present an economic evaluation of personal fans for an office building in Germany. Building performance simulation was used to compare passive and active cooling concepts, and sensitivity analysis was performed for different climate scenarios. A cost-benefit analysis was carried out, including an assessment of investment and operating costs and the monetary value of relative performance. The transferability of comfort and productivity into costs is the novelty of this paper. The results showed that by supplementing night ventilation with personal fans, discomfort hours could be reduced by up to 50%. However, the initial investment of the fan is not compensated by savings in productivity losses compared to night ventilation alone. A reduction in the cost of the technology could help to economically offset the investment. The results contribute to the literature on the economic evaluation of a PECS by proposing a framework to motivate its implementation in buildings.

Keywords: personal environmental comfort system; cost-benefit analysis; energy efficiency; thermal comfort; passive cooling; night ventilation; productivity loss; sensitivity analysis; building simulation; building monitoring

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1. Introduction

The impact of climate change on energy use has raised concerns as the global contribution of buildings has reached 31% of total energy consumption [1]. The expected rise in the frequency of hot days caused within the context of global warming assures an upward trend in cooling demand in the future [2]. The increase of indoor temperatures outside the comfort range brings along a rising demand for building services, in which the growth of HVAC system energy use has been playing a significant role [3]. As a result, several initiatives yield to reduce the operational energy demand in buildings. The German national "Climate Action Plan" posits as one of its main objectives to reduce 80% of primary energy consumption by 2050. Alongside improvements in the thermal performance of buildings during the winter period and decarbonization of the cooling source, the need to minimize cooling loads requires a paradigm shift in the design of buildings to achieve this goal.

While decarbonization of heating and cooling systems impacts emissions, some authors advocate for climate-responsive designs as the first step for energy efficiency. Besides early-stage building design strategies, such as thermal insulation or orientation optimization, Lechner [4] described the importance of including passive or hybrid systems, such as night ventilation, in warm climates. Night ventilation can reduce initial cooling loads between 10% and 40%, with an average of 26% [5], and can increase occupants' acceptance of indoor conditions by reducing indoor temperatures [6]. However, the effectiveness of night ventilation presents some limitations for climate zones and varying building characteristics [7]. The need to include additional mitigation measures to achieve effective night ventilation has been investigated. He et al. [8] described the benefits and use of fans in non-residential buildings, as they can increase occupant satisfaction via increased air velocity while at the same time maintaining energy consumption at relatively low levels.

Along with passive cooling strategies, attention has been drawn to the use of personal environmental control systems (PECSs) to target the direct thermal environment of occupants by conditioning their personal space in contrast to the entire building [9]. These systems are an effective solution to provide acceptable comfort levels for occupants [10,11] along with improvements in energy performance [12,13]. While most PECS studies of PECSs have focused on assessing thermal comfort and energy savings, cost-effectiveness analyses have rarely been performed. A recent review paper [14] found that only 16% of the analyzed studies mentioned costs as an analysis dimension of PECSs. The lack of studies assessing the economic aspects of PECSs motivates the investigation of a comprehensive economic viability analysis and framework to evaluate the feasibility of PECSs for real building applications. It is, therefore, the objective of this paper.

1.1. Background

HVAC systems have been widely installed in non-residential buildings to maintain acceptable indoor environmental conditions. During hot summer months, air conditioning systems (ACSs) provide constant room temperatures and contribute to employee satisfaction within the indoor environment. However, ACSs can lead to building overcooling, which can be associated with dissatisfaction [15] and even health issues [16]. Additionally, the use of air conditioners is still not seen as an adaptation measure for thermal comfort, especially with centralized systems in multi-occupant spaces that do not provide personal control, often resulting in increased dissatisfaction rates.

Along with high installation and maintenance costs, ACSs bring along high energy usage during operation. The growth in ACSs' and electric fans' energy use is particularly significant, accounting for 20% of the total electricity used in buildings worldwide and 18% of the total increase in global emissions between 2016 and 2050 [17]. Additionally, occupant behavior plays a key role in energy consumption [18]. Nakaya et al. [19] found that passive occupant behaviors, such as opening windows and using fans, can reduce AC-use rates by up to 20% and decrease temperature setpoints at which ACSs are switched on for temperatures between 25 °C to 30 °C.

To reduce energy costs and be in line with sustainable development, low-energy strategies are alternatives to active cooling. By including night ventilation, particularly in buildings with a high mass and high thermal inertia, indoor temperatures can potentially be reduced and consequently allow a reduction of cooling loads during the daytime. Based on monitoring results of a building in a continental climate, Pfafferott et al. [20] concluded that night ventilation strategies could achieve acceptable indoor thermal conditions without increasing electricity demand. Kolokotroni et al. [21] pointed out that the difference in cooling loads between a building with night ventilation and a typical office building with air conditioning in the UK can reach up to 10 kWh/m^{2}a. Moldovan et al. [22] analyzed the cooling energy demand of an office building in a temperate continental climate, concluding that night ventilation allowed significant energy consumption savings, achieving a reduction of energy use up to 33% in the hottest months.

However, the effectiveness of night ventilation can vary according to certain parameters, mostly related to the type of construction, control strategies, and climatic conditions [5]. Landsman [23] compared the performance of night ventilation regarding indoor thermal conditions in three buildings in mild and hot/humid climates. He concluded that buildings with night ventilation in mild climates successfully kept the indoor operative temperature below the upper 80% acceptability comfort limit. In contrast, the thermal acceptability in the building in the hot and humid climate went above the upper 80% comfort limit on the hottest days of the year. To guarantee sufficient cooling, night ventilation can be optimized by coupling it with other energy-efficient techniques and supplementary systems. For instance, Landsman [23] recommends combining night ventilation with low-energy strategies, such as ceiling fans, to improve thermal comfort.

Fans can improve occupants' thermal comfort without using compressor-based cooling by effectively cooling human bodies via elevated airspeed [24,25]. Previous studies [26,27] showed that at indoor temperatures above 28 °C, occupants rated indoor conditions in a warm-humid environment as still acceptable when increasing air velocity was provided by ceiling fans. Zhang et al. [28] concluded that ceiling fans were normally operated at indoor temperatures above 28 °C in naturally ventilated buildings in hot-humid climates; Lipcznska et al. [29] found that thermal satisfaction in a warm environment was significantly higher with operating ceiling fans even in spaces of 26 °C when split air conditioners were provided. Additionally, fans can achieve cooling energy savings of up to 47% when using fans at elevated indoor temperatures [30].

Providing an acceptable indoor environment to increase thermal comfort and reduce energy savings can be achieved using PECSs. Zhang et al. [9] reviewed the performance of several types of PECSs and estimated potential HVAC energy savings greater than 30% as a relaxation of the comfortable indoor temperature range could reduce the total HVAC energy at a rate of 10% per degree Celsius. According to He et al. [10], personal fans can achieve higher energy efficiency than other personal cooling systems while addressing individual differences in perceived air quality and thermal comfort. Rissetto et al. [11] studied the performance of personal ceiling fans and concluded that they are a viable approach to reaching high satisfaction rates.

Increasing individual thermal satisfaction in the workplace has been related to productivity [31]. Lipcznska et al. [29] studied the performance of personal fans and found that increasing thermal satisfaction positively affected the reported work performance. This becomes of relative importance, as air conditioning costs account for about 1% of the labor cost in developed countries [32]. Seem and Braun [33] concluded that a potential 15% increase in the HVAC energy use produced by PECSs could be offset by a 0.08% increase in occupants' productivity associated with personal environmental control.

While most PECSs studies have focused on assessing thermal comfort and energy savings, cost-effectiveness analyses have rarely been performed. In a recent review [14], the authors concluded that only 30 studies in the literature included cost considerations in their analyses; most of them only considered one cost aspect. Table 1 shows a summary of the number of papers analyzing each cost aspect.

Table 1. Summary of cost aspects analyzed in publications about PECSs.

Cost Aspect Analyzed	Number of Studies Assessing that Aspects
Low initial costs of small PECSs [1]	4
Low running costs of small PECSs [1]	5
Reduced maintenance cost measured as reduction of labor costs	1
Increased initial costs for ventilation PECSs	7
Increased maintenance costs for ventilation PECSs	2
Increasing productivity on overall economics	6
Reduced energy costs	4
No change in energy costs	2

[1] Small devices like fans and foot warmers.

To fill this gap, the authors proposed a framework to holistically assess the costs related to the implementation of PECSs. Table 2 shows an adaptation of the proposed methodology, which consists of a comparison between a system with a PECS and an alternative "classic" system without a PECS, named a conventional system.

Table 2. Proposed framework for assessing the cost-effectiveness of a PECS solution combined with a conventional system. Adapted from [14].

Type of Solution	PECS + Conventional System	Conventional System without PECS
Direct installation costs (system itself)	X-times costs of PECSs (number of devices) + 1-time (reduced) costs of conventional system	1-time costs of conventional system
Indirect installation costs (ductwork, installations, etc.)	X-times costs of PECSs (number of devices) + Y-times (reduced) costs of conventional system	Y-times costs of conventional system (number of elements belonging to the system)
Maintenance costs	Costs of PECSs + (reduced) costs for conventional system	Cost of conventional system
Operation costs	Increased or decreased costs	Cost of conventional system
Energy costs	Savings in overall conditions + costs to drive PECS	Cost for conventional system
Productivity	Potentially increased productivity through PECS	

The existent tradeoff between implementing cooling strategies in buildings to provide high levels of satisfaction while reducing energy usage and costs is yet to be researched in depth. A detailed assessment in terms of economic viability may help establish the prominence of PECSs over conventional air conditioning methods.

1.2. Research Gap and Scientific Contribution

Despite the benefits of personal comfort systems in improving occupants' comfort levels and energy savings, the implementation of such devices in commercial buildings is still limited. The lack of a comprehensive assessment of the economic viability of PECSs motivates the investigation of PECS implementation in real building conditions. The present work is developed within the framework of a district office building renovation in Dillingen, Germany. To reduce energy consumption while improving the thermal comfort of the employees, night ventilation was implemented, and personal ceiling fans were installed individually at each workplace.

This paper aims to assess the effort and benefits of personal ceiling fans in terms of energy demand, cost, and thermal comfort compared to alternative active and passive cooling solutions. While thermal comfort levels provided using personal environmental control systems have been widely studied, this paper contributes to the research on PECS' economic viability. A comprehensive examination of thermal comfort and productivity transferred into costs, including monitoring data from an existing office building, constitutes the novelty of this paper.

2. Materials and Methods

Figure 1 presents the workflow of this study. To evaluate the economic viability of personal ceiling fans, the performance of the ceiling fans is compared to other cooling strategies in a simulation study, assessing different locations and climatic scenarios. The following cooling concepts were modeled (Table 3).

Table 3. Simulated cooling strategies.

Cooling Concept	Description
NoCooling	No night ventilation or air-conditioning. This concept represents the situation before the building renovation.
NV	Night ventilation.
NVandCF	Night ventilation (NV) and ceiling fans (CF). This concept represents the implemented solution in the building (after the renovation).
ACS	Air-conditioning system (decentralized, ideally modeled).

A base case study with the office building in Dillingen was used for the modeling and simulation of the cooling concepts and cost calculation. A building energy model was necessary to simulate the temperature distribution and the building cooling energy demand for all cooling concepts—except night ventilation and ceiling fan, from which monitoring and project data were available. The building model and boundary conditions are derived from the project data. Based on monitoring data, a behavioral model for fan usage was created. The building was calibrated and validated with monitoring data. The main outputs of the simulation were the indoor environmental conditions (indoor temperature) and energy consumption, namely from the air conditioning system and the ceiling fans. The energy consumption was used to calculate the electricity costs. Both comfort and productivity assessments were carried out using well-established models. Indoor temperatures and ceiling fan usage are inputs for the comfort models to obtain occupants' discomfort hours and productivity losses. Results from the productivity model were then translated into cost values. The different cooling strategies' investment, installation, operation, and maintenance costs were estimated based on building data and the available literature. The comprehensive economic assessment of the base case was then compared to other locations in Germany and future climatic scenarios to assess the potential of the personal cooling solution.

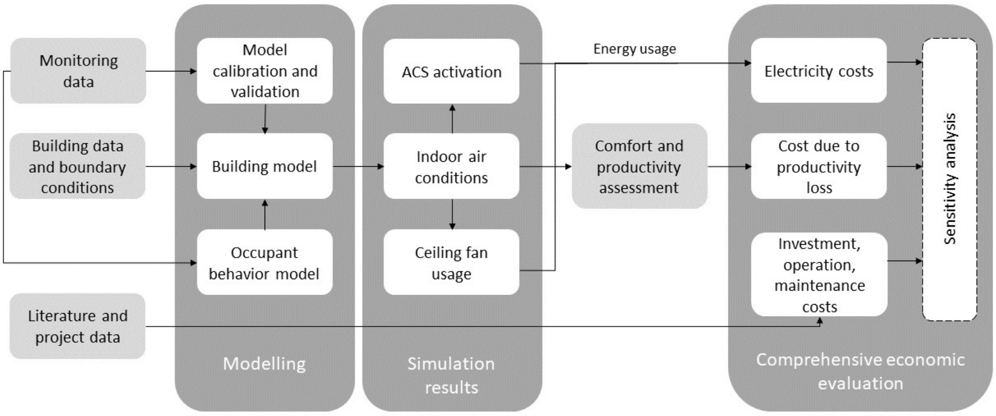

Figure 1. Methodology flowchart.

2.1. Building Description

The district administration building is in Dillingen an der Donau, Bavaria (Germany). The building has four floors and a basement, with 92 service and office rooms. A refurbishment of the existing building was carried out, including improving the façades' thermal transmittance, new windows with a control system for night ventilation, and a decentralized ventilation unit for each office room. Figure 2 (left) shows a typical office room. Further information about the existing building can be found in Table A1. Together with the renovation, the building was extended with new offices equipped with an air-conditioning system. The new building has been excluded from the analysis as it is irrelevant to this work.

Most offices are around 20 m^2 for one or two employees and have two windows with external blinds. The windows can be manually operated and have an automatic opening system for night ventilation. The night ventilation system does not use any additional mechanical ventilation. Ceiling fans integrated into an acoustic panel were added as part of the building renovation to enhance thermal comfort in summer. These fans were installed in every office workspace and can be individually operated. This system is a custom-made solution, shown in Figure 2 (right). More details are available in [11].

Figure 2. Example of an office room, showing the new window system (**left**) and integrated personal ceiling fan in an acoustic panel with a removable grid to adjust the airflow direction (**right**). Copyright (left image): 2021, Bergische Universität Wuppertal.

2.2. Monitoring Data

The monitoring campaign was carried out between August 2020 and September 2021. Table 4 describes the collected data relevant to this study and its characteristics. Building energy usage was measured, but it was not relevant to this study.

Table 4. Overview of monitoring data: measured parameters, sensor location, measurement interval and range.

Parameter	Sensor Location	Interval	Range
Indoor temperature	All rooms	5-min	0–50 °C.
Humidity	6 rooms	5-min	10–95%
CO_2 concentration	6 rooms	5-min	400–10,000 ppm
Ceiling fan speed	All rooms	By change	0–100%
Window position-tilted	All rooms	By change	Open–closed
Window position-open	All rooms	By change	Open–closed
Night ventilation windows status	All rooms	By change	Open–closed

2.3. Simulation Setup

This section provides a description of the building model and the modeling procedure. Building simulation calculates the cooling energy usage and the indoor air conditions necessary to assess comfort and productivity. Simulations were performed using the software environment EnergyPlus 8.9 [34].

2.3.1. Building Model

This section describes the assumptions for and adaptations to the building model. The basement was not considered as there are no office rooms. Therefore, the setpoint temperature for the night ventilation (the cooling and heating setpoints for the ACS) was used as the boundary condition for the ground temperature. A cooling setpoint of 24 °C was given to the new building with an ACS to model the heat transmittance realistically on the side of the building where the new building was attached. The building was divided into 51 thermal zones following the approach from Klein et al. [35], merging rooms with the same orientation and on the same floor. Figure 3 shows the thermal zones on the ground floor. Floors one to three were modeled similarly due to their similarity in layout.

Building thermal mass included the omitted internal walls. Thermal mass from furniture was neglected as it was negligible compared to the building envelope with internal walls [36]. Regarding the internal loads, the heat gain from people was set to 115 W/Person [37] and from laptops to 61 W/Person. The internal loads from lighting were calculated following the ASHRAE approach [37] in W/m^2. Further details are available in Knudsen [38].

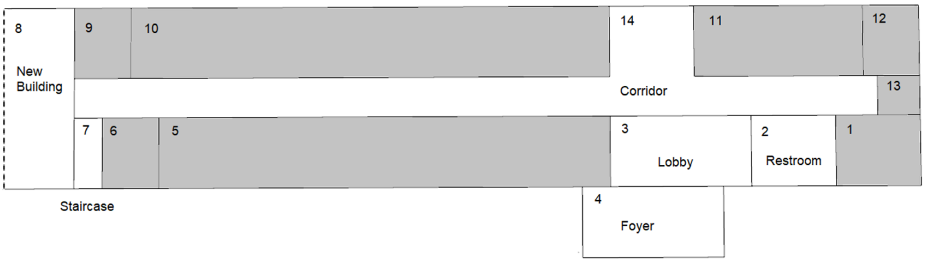

Figure 3. Thermal zones plan on the ground floor. Numbers indicate each thermal zone.

2.3.2. Boundary Conditions

As Ulm is close to Dillingen (50 km), the available typical meteorological year (TMY) weather file from Ulm was used for the simulation. Assumptions regarding building systems operation and occupant presence are described as follows.

Night ventilation window opening and blind position run according to a building automation system (no manual operation). Night ventilation windows are opened between 7 pm and 7 am when the indoor air temperature is 2 °C higher than the setpoint temperature, and the outdoor air temperature is 2 °C lower than the indoor air temperature. Deactivation occurs at a given indoor air temperature and certain outdoor conditions. The blinds close above a radiance threshold value of 192 W/m^2 [39].

For the window opening behavior, the stochastic model by Haldi and Robinson [40] was used. A sensitivity analysis was performed [38], which showed no significant differences between a single opening behavior for all windows or the application of individual behaviors. Therefore, a single window opening behavior for all windows in the building was used. We estimated the flow rates for open windows and night ventilation based on Wang et al. [41].

For the occupancy estimation, an algorithm was developed to estimate occupancy based on CO_2 concentration in every office [38]. As a result, average values of arrival and departure to the office were derived and applied globally to all the offices for the simulation: arrival = 07:55; departure = 15:40 (Monday–Thursday), 12:15 (Friday). The occupancy was then calculated based on the average working hours per week in Dillingen, which were taken from the results of previous comfort questionnaires in the building. A fraction of the occupancy hours was calculated considering absence due to vacation or sick leaves, part-time employees, and home office hours due to the COVID pandemic in 2020.

2.3.3. Ceiling Fan Usage

A ceiling fan manual operation model was developed based on the collected monitoring data. The ceiling fan speed (in %) was monitored for an entire year. For the sake of simplicity, the operation of the ceiling fan was modeled with an on-off approach. The fan was considered active (turned on) when the fan speed was equal to or greater than 5%.

Logistic regression is one of the most popular modeling techniques for variables with a binary output [42] This modeling approach has been extensively used to represent the occupant behavior for building simulation purposes: presence [43], window opening [40], blinds [44], lights [45], thermostat set point [46], and even to model the operation of desk and ceiling fans in offices [47–49]. The algorithm establishes a linear relationship between multiple explanatory variables and the logit function of the probability of an event happening and applies the logit function to this probability p. This linear relationship is expressed in the following equation:

$$ln(\frac{p}{(1-p)}) = \alpha + \beta_1 x_1 + \cdots + \beta_n x_n \tag{1}$$

p is the probability of an event happening,
α is the intercept,

β is a coefficient,
x is a set of explanatory variables.

For the case of the ceiling fan, the explanatory variables were selected based on the adaptive comfort theory, where the comfort state is proportional to the indoor temperature and the running mean of the outdoor temperature. The modeled probability p represents the probability of observing a fan turned on. Models were fitted using the "stats" package in the software environment R Version 3.6.3 [50]. The total dataset comprises six rooms. Only the data from June 2021 was considered since it is the only month when employees actively used the fan. Table 5 shows the obtained intercept and model coefficients.

Table 5. Coefficients of the logistic regression model to simulate ceiling fan operation (*** = $p < 0.001$, $R^2 = 0.10$).

Intercept	Indoor Temperature	Outdoor Temperature Running Mean
−30.56 ***	0.91 ***	0.26 ***

2.3.4. Calibration and Validation

A comparison between simulated and measured indoor temperatures was performed to validate the model. The results of the monitoring campaign during spring and summer (April–September, when the building is not heated) were used. Weather data were obtained from the installed weather station in Dillingen. The measurements of the German Weather Service-DWD [51] for Dillingen were used to complete the missing data. The simulation setup and boundary conditions are the same as the previous sections.

The comparison was performed separately for each thermal zone in the simulation model. The average of the measured room temperatures was taken for the thermal zones that include more than one room in the office building. The simulation was performed in hourly time steps due to the resolution of the weather data. The results were evaluated using the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) as suggested by ASHRAE Guideline 14 [52]. ASHRAE Guideline 14 considers a building model to be calibrated when average hourly MBE values are within ±5% and average hourly CV(RMSE) values are less than 15%. Table 6 shows the resulting average zone value for both indicators. Table A2 in Appendix A shows the individual results for each thermal zone.

Table 6. Average zone value for MBE and CV(RMSE).

Value	Mean Bias Error (MBE)	Coefficient of the Variation of the Root Mean Square Error (CV(RMSE))
Average	2.53	5.56

2.4. Comfort, Productivity and Cost Evaluation

Thermal comfort and productivity are assessed as part of the economic evaluation of the cooling strategies. Results from the latter were then translated into monetary values and added up to the cost analysis. Data were analyzed using the software environment R Version 3.6.3.

The simulated indoor air conditions were analyzed to evaluate comfort and the resulting productivity loss due to dissatisfaction. As the focus was on comfort loss due to overheating in summer, the period from April to September was analyzed, and the simulation results were reduced to the occupancy times. The adaptive thermal heat balance model (ATHB) was selected to evaluate comfort due to the high accuracy of the model in predicting thermal comfort and acceptability votes in naturally ventilated buildings [53]. Two indices were used: the predicted mean vote (PMV) [54] and the standard effective temperature (SET) [55]. The original PMV model by Fanger et al. [54] applies to controlled environments with ACSs and an air velocity lower than 0.2 m/s. Therefore, it is only used to evaluate the comfort of the ACS concept. Gagge et al.'s original SET model [55] was used for the concepts NoCooling, NV, and NVandCF, as it was applicable for elevated air speeds. Comfort votes for indoor conditions are expressed in PMV and predicted thermal sensation (PTS) for active and passive cooling strategies, respectively, and were calculated with the package "comf" [56]. The input and output variables for each model are listed in the following table (Table 7).

Table 7. Thermal comfort indices using the ATHB model and their input and output variables. T_a = air temperature; T_r = radiant temperature; RH = relative humidity; AV = air velocity; T_{rm} = outdoor temperature running mean; met = metabolic rate; clo = clothing value; psych = psychological adaptive coefficient.

Index	Input Variables	Output
$ATHB_{PMV}$	T_a, T_r, RH, AV, T_{rm}, met, psych	Predicted mean vote (−3 to +3)
$ATHB_{PTS}$	T_a, T_r, RH, AV, clo, met, psych	Predicted thermal sensation (−3 to +3)

T_a, T_r, and RH values were obtained from the simulation. A value of 0.61 was assumed for clothing insulation level (light clothing: trousers, long-sleeve shirt) and 1.1 for the metabolic rate as an average value of sitting and standing [37]. The air velocity was assumed constant at 0.05 m/s without an active ceiling fan and 0.6 m/s with an active ceiling fan [11]. The psych variable was neglected (value 0).

Several studies have tried to quantify the productivity loss produced by a reduction in thermal satisfaction in buildings. Productivity models quantify the worker's performance regarding indoor environmental conditions. The Maximal Adaptability Model (MAM) developed by Hancock and Warm [57] relates thermal stress to work performance. Contrary to other proposed models [58,59], the MAM includes the concepts of adaptability in both physiological and psychological aspects to human stress and, therefore, attention capability. This way, the model proposes that human performance remains relatively stable in a range of temperatures achieving maximal productivity (100%), but rapidly decreases outside this range (U-shaped function). Porras-Salazar [60] suggested adapting the MAM model to fit different performance databases. The relative performance (*RP*) of an employee is calculated as a function of the indoor temperature *T* for different temperature ranges and results in the following equation.

$$RP = \begin{cases} 12.057 \cdot T - 0.257 \cdot T^2 - 41.293, & T < 23\ ^\circ\mathrm{C} \\ 100, & 23\ ^\circ\mathrm{C} \leq T \leq 27\ ^\circ\mathrm{C} \\ 13.657 \cdot T - 0.257 \cdot T^2 - 81.293, & T < 27\ ^\circ\mathrm{C} \end{cases} \tag{2}$$

As the MAM model considers only the indoor air temperature and neglects the cooling effect from elevated air speed, the concept of ceiling fans cannot be correctly represented. Therefore, we propose to calculate the *RP* using the SET (RP_{SET}) instead of the room air temperature to include air velocity.

Monetary costs of the decrease in relative performance were computed according to the following formula:

$$Costs_{PerformanceLoss} = (1 - RP) * \frac{Salary_{year}}{2} * Employees \tag{3}$$

As we assumed half a year (six months) for the cooling period, a factor of $\frac{1}{2}$ was applied to the previous formula. Productivity results are converted into monetary values by considering the time lost by employees to complete their work as salary costs. An average salary ($Salary_{year}$) of €45,000 per year was estimated [61], as no information on the employment structure was available.

The energy (electricity) consumption was a result of the simulation. Costs for electricity were assumed to be 38.25 Cent/kWh [62]. The energy use of the ceiling fans was calculated with total running hours and a nominal power of 10 W. For the split-ACS, the coefficient of performance was presumed to be 3.5. Other considered costs were the investment, installation, planning, and operation-maintenance (O & M) costs. The assumed costs for the cooling strategies are presented in Table 8.

Table 8. Component costs overview.

	Building Control	**Acoustic Panel**	**Ceiling Fans**	**Night Ventilation**	**Air Conditioning**
Investment [€]	24,900	15,700	73,790	34,750	119,600
Installation [€]	3735	2355	11,069	5213	174,800
Planning costs [€]	6077	3829	11,355	8480	29,171
O & M [€/a]	1245	0	3690	1737	15,640

The assumptions and calculations for each aspect of the cost structure are as follows:

- The investment costs for the building control, night ventilation, and ceiling fans were obtained from the project, and approximately €100 were assumed for the acoustic panel [63].
- Based on the project, installation costs for all concepts excluding ACSs are approximately 15% and were proportionally allocated to the investment costs of building control and automation, ceiling fans, night ventilation, and acoustic panels. The same goes for the planning costs (24.4%). Operation and maintenance costs (O & M) were assumed to be around 5% of the investment costs [64]. O & M costs were neglected for the panels as they have no moving parts, and consequently, minimal maintenance effort.
- The costs for the ACSs were assumed based on the literature [65], having a total of 92 decentralized ACSs (one per room). It was assumed that the planning costs for the ACSs would have the same investment-to-planning ratio as the other cooling strategy components (24.4%).
- Building control costs are common to every concept. The acoustic panels were considered for all concepts due to their positive impact on room acoustics.

One indicator of investment efficiency is the net present value (NPV). The NPV was calculated assuming a service life of 20 years (n) and an interest rate (i) of 8% [66]. A positive NPV implies that the installation was worthwhile, as the cash flows (R_t) during the service time (t) outweigh the initial investment (Y). A positive NPV indicates that the cash flows (R_t) during the service time (t) outweigh the initial investment (Y); thus, the installation is worthwhile. There is no real income (positive cash flows) when a cooling concept or system is planned. However, the cheapest solution can be assessed by directly comparing all associated costs (negative cash flows) throughout the system's life span, such as operative costs (energy, maintenance) and associated discomfort costs represented by productivity losses. Thus, the resulting NPV values will be negative.

$$NPV = Y - \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{4}$$

The baseline case is a solution without a cooling concept, and the ΔNPV compares the costs for each concept. When a cooling concept provides higher cost savings than the reference NPV (NPV$_{NoCooling}$), the ΔNPV becomes positive.

$$\Delta NPV_{concept} = NPV_{concept} - NPV_{NoCooling} \tag{5}$$

3. Results

In this section, the results of the energy consumption, thermal comfort and productivity assessment, and cost evaluation are described. Based on the previous assumptions, simulation results, and results from the thermal comfort and productivity models, the different cooling concepts were compared in terms of cost analysis with a baseline case study. A sensitivity analysis was carried out using distinct locations and climate predictions.

3.1. Base Case

3.1.1. Energy Consumption

The energy evaluation was assessed regarding the electricity usage for the ceiling fan and air conditioning concepts, as night ventilation alone and the no-cooling concept have no relevant energy usage for cooling. With the application of the developed behavioral model, the running time of the ceiling fans is 84 h on average per room (for the analyzed period). Table 9 shows the results for energy consumption.

Table 9. Electrical energy consumption for the analyzed cooling concepts.

	NoCooling	**NV**	**NVandCF**	**ACS**
Energy [kWh/a]	0	0	132	1473

3.1.2. Thermal Comfort Evaluation

The PMV and the PTS were calculated using the ATHB model for all concepts for the comfort evaluation. According to ASHRAE [37], PMV values outside of +/−1 are classified as uncomfortable. As the present study focused on summer conditions, only comfort votes within the warm-hot range (greater than +1) were evaluated as discomfort. The percentage of summertime discomfort hours—i.e., hours outside the comfort range—was calculated for the potential cooling period from April to September within the occupancy hours for three different comfort zones: votes greater than +1 (“slightly warm”), greater than +2 (“warm”) and equal/greater than +3 (“hot”) (Table 10).

Table 10. Percentage of discomfort hours for different PMV/PTS votes for each cooling concept using the ATHB model.

Comfort Zone		**NoCooling**	**NV**	**NVandCF**	**ACS**
PMV/PTS $\geq$ +1	slightly warm	32.52%	17.79%	14.17%	0.00%
PMV/PTS $\geq$ +2	warm	0.45%	0.00%	0.00%	0.00%
PMV/PTS = +3	hot	0.00%	0.00%	0.00%	0.00%

More than 30% of the occupied hours for the NoCooling concept were considered “slightly warm.” The introduction of night ventilation reduced this value to 18%. The number of PTS votes “slightly warm” was reduced further to 14% due to the ceiling fan air movement. The ACS always provided maximum comfort by keeping the air temperature at the desired setpoints. For PMV/PTS values greater than +2 (“warm”), the discomfort values were reduced to 0% already for night ventilation, given the overall low ambient temperatures in summer.

Figure 4 displays PMV and PTS values for different indoor temperature values. For the concept ACS, the cooling setpoints of 20 and 24 °C can be seen, and no PMV values higher than zero were observed. However, some PMV values reached a value of −2 (“cool”), exceeding the comfortable range and showing a risk of overcooling. However, comfort votes could be improved (closer to neutral) if greater values for clothing were considered, as the recommended values for activity level (met = 1), and clothing insulation level (clo = 0.5) for an indoor temperature of 26 °C [67] were used for this calculation.

The diagrams for the concepts NoCooling, NV, and NVandCF are similar as the same model was applied. In the NoCooling concept, temperatures higher than 30 °C can be observed, which were perceived as “warm” and “hot.” In contrast, for the concepts including night ventilation, the temperature did not exceed 30 °C. For those concepts, a PTS value higher than +2 (“warm”) corresponds to a temperature of 29 °C. In the NVandCF concept, two data point areas can be observed. The black area is the same as for NV, while the grey area corresponds to the data points when the ceiling fan was active. This results in a lower SET and, consequently, lower PTS votes.

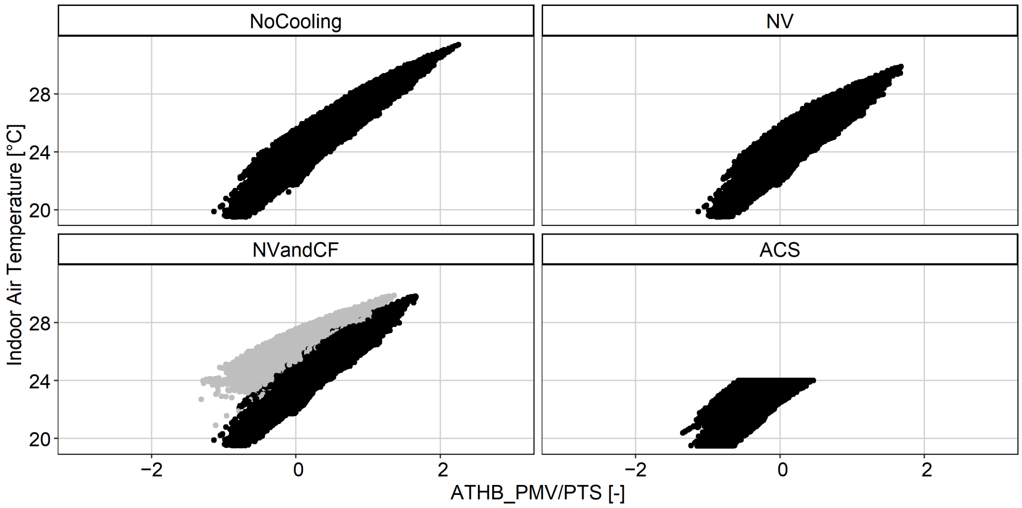

Figure 4. PMV (ACS) and PTS (NoCooling, NV, NVandCF) values vs. indoor air temperature using the ATHB model (black points). The grey points correspond to the data when the ceiling fan was active.

3.1.3. Productivity Evaluation

The relative performance (RP) was calculated according to the productivity model from Hancock and Warm [57] previously introduced. The results can be seen in Table 11. The difference in relative performance between all concepts seems to be marginal. The impact of the productivity losses on the cost assessment is therefore analyzed in the next section.

Table 11. Average productivity for each analyzed concept.

	NoCooling	**NV**	**NVandCF**	**ACS**
RP$_{ATHB-SET}$ [%]	99.44	99.80	99.85	100

3.1.4. Costs Evaluation

The results of the economic evaluation are displayed in Table 12. An ACS's investment and O & M costs are around two times higher than the ceiling fan and night ventilation concept. The same relationship applies between the ceiling fan and the night ventilation concept. The electricity costs of the ACS are 10 times higher than the ceiling fan concept. Compared to the costs due to productivity losses, the electricity running costs are lower, especially when using the ceiling fan. The ΔNPV is positive for only night ventilation, as savings in productivity losses do not compensate for the initial investment in the case of the ceiling fan and ACS.

Table 12. Cost overview and the difference between NPV for all cooling concepts.

	NoCooling	**NV**	**NVandCF**	**ACS**
Invest [€]	52,861	96,090	192,304	354,468
O & M [€/a]	1245	2982	6672	15,640
Electricity [€/a]	-	-	51	564
Productivity [€/a]	19,782	7065	5299	0
ΔNPV [€/employee]	-	445	−247	−1417

To assess the impact of different salaries and interest rates in the base case, the boundary values for ΔNPV = 0 were calculated. Figure 5 shows the results for an interest rate from 0% to 10%. The value combination of salary and interest rate that leads to a ΔNPV = 0 is the minimum value in which the investment of the installed cooling system is economically viable. For lower salary costs and high-interest rates, the concept without cooling is always more profitable, as the associated costs to productivity losses decrease. For lower interest rates or higher salary values, the future operative costs of the cooling system are more relevant to the total costs. To sum up, the most profitable investment is the curve with the lowest values on the y-axis. The ACS concept becomes profitable with a salary of 110,000 and an interest rate of 8%, while the ceiling fan becomes profitable with a salary of around 60,000. The interest rate plays a secondary role compared to the salary for the investment efficiency calculation. Thus, in the next section, the interest rate is further assumed to be 8% without analyzing the sensitivity to this variable.

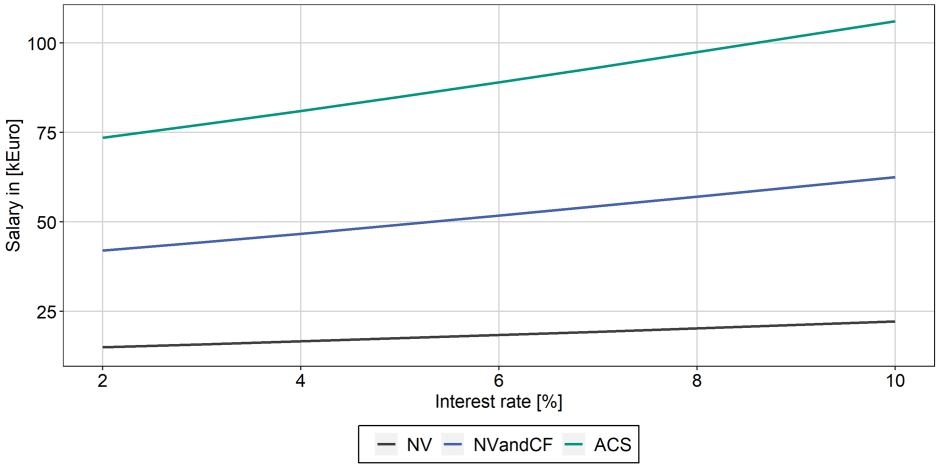

Figure 5. Interest rate and salary for ΔNPV = 0.

3.2. Sensitivity Analysis

A sensitivity analysis simulating other locations in Germany with different climatic scenarios was carried out to comprehensively evaluate the personal ceiling fans' performance and costs. The cities of Mannheim and Potsdam were selected, as Potsdam is often used as a reference location for the climate in Germany, and Mannheim has shown elevated temperatures compared to the German average. Figure 6 shows the cumulative distribution of the outdoor air temperature for Ulm (baseline case) as well as for Mannheim and Potsdam for a typical meteorological year (TMY) of the early 2000s and for a predicted test reference year 2035 (TRY 2035). The highest temperatures correspond to the prediction of Mannheim in 2035, while Ulm shows the lowest temperatures.

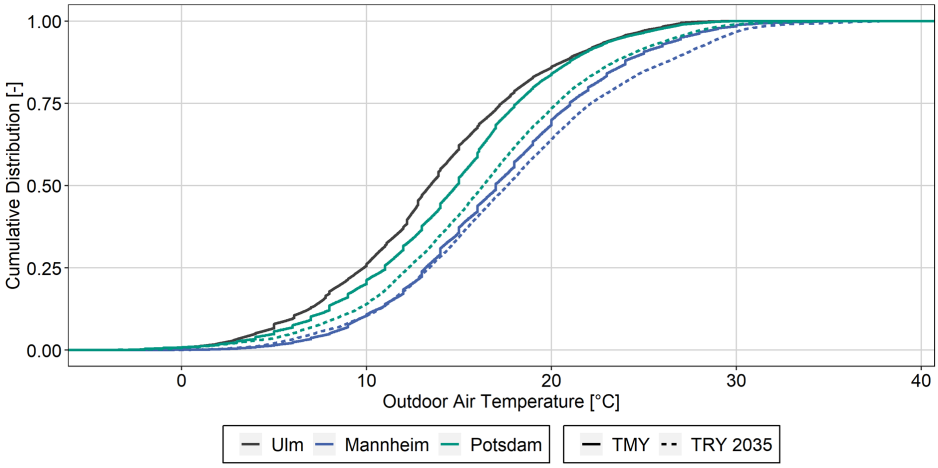

Figure 6. Cumulative outdoor air temperature distribution for the selected locations and climate scenarios.

3.2.1. Energy, Thermal Comfort and Productivity

Table 13 shows an overview of energy-related indicators, including the maximum power and electricity usage for the ACS concept and the usage hours and related energy consumption for the ceiling fan concept. Results for Ulm and Potsdam TMY are similar for all indicators and values for Mannheim TMY and Potsdam 2035 as well. Energy consumption for ACSs and ceiling fans increases by a similar factor of around two between the baseline and Mannheim TMY/Potsdam 2035 and around three between the baseline and Mannheim 2035. The maximum cooling power for the building differs by 30% between the two extreme scenarios (Ulm TMY and Mannheim 2023).

Table 13. Overview electricity usage for all locations and climatic scenarios.

Concept	Indicator	Ulm TMY	Potsdam TMY	Potsdam 2035	Mannheim TMY	Mannheim 2035
ACS	Maximum power [kw]	30.22	29.2	34.69	36.31	39.66
ACS	Electricity cooling [kwh]	1473	1503	2955	3181	4519
Ceiling fan	Hours of usage per person [h]	84	96	181	213	291
Ceiling fan	Usage energy [kwh]	132	151	284	334	457

Figure 7 shows the energy consumption and the percentage of hours where PTS votes were above +1 (“slightly warm”) for the ceiling fan concept. Three groups with similar energy and comfort values can be identified: Ulm and Potsdam TMY, Potsdam 2035 and Mannheim TMY, and Mannheim 2035. Each group’s representative location and scenario will be kept for further analysis: Potsdam TMY, Mannheim TMY, and Mannheim 2035.

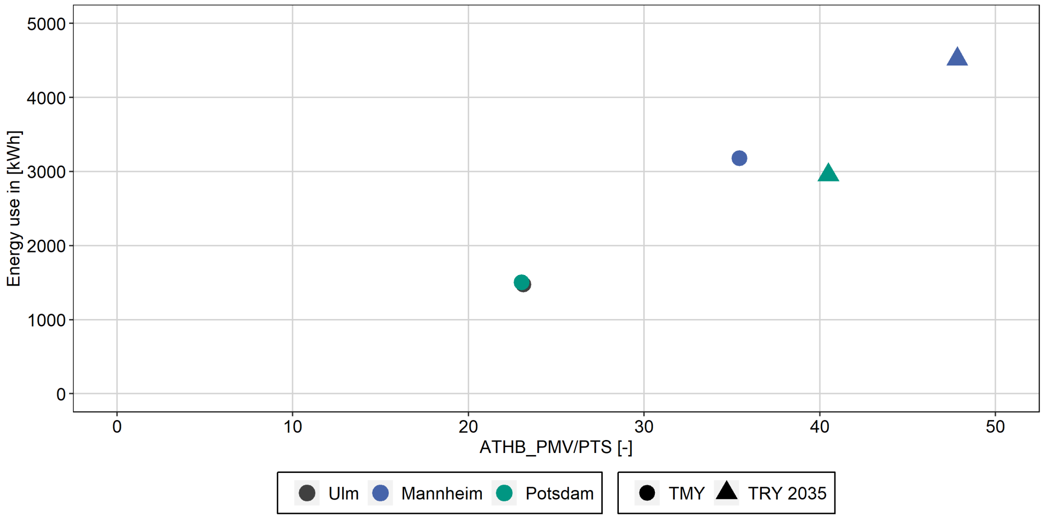

Figure 7. Energy use and percentage of discomfort hours for PMV/PTS greater than 1 (“slightly warm”) for all locations and climate scenarios.

Figure 8 shows the cumulative distribution of PMV and PTS votes for all four cooling strategies for the different climatic scenarios. In each cooling concept, all scenarios show a similar pattern. The higher impact of warmer climates (Mannheim 2035) can be seen in the NoCooling and NV concepts. This shows the positive impact of ceiling fans on thermal comfort.

Table 14 shows the percentage of PMV/PTS values greater than +1 (“slightly warm”) and +2 (“warm”) for the different scenarios and cooling concepts. In warmer climates, the potential of the ceiling fan to reduce discomfort hours is higher: for a PMV/PTS > 1 category, the ceiling fan reduces discomfort in Potsdam by 19%, and in Mannheim 2035 by 35%. For PMV/PTS > 2 categories, a night ventilation strategy decreases discomfort significantly.

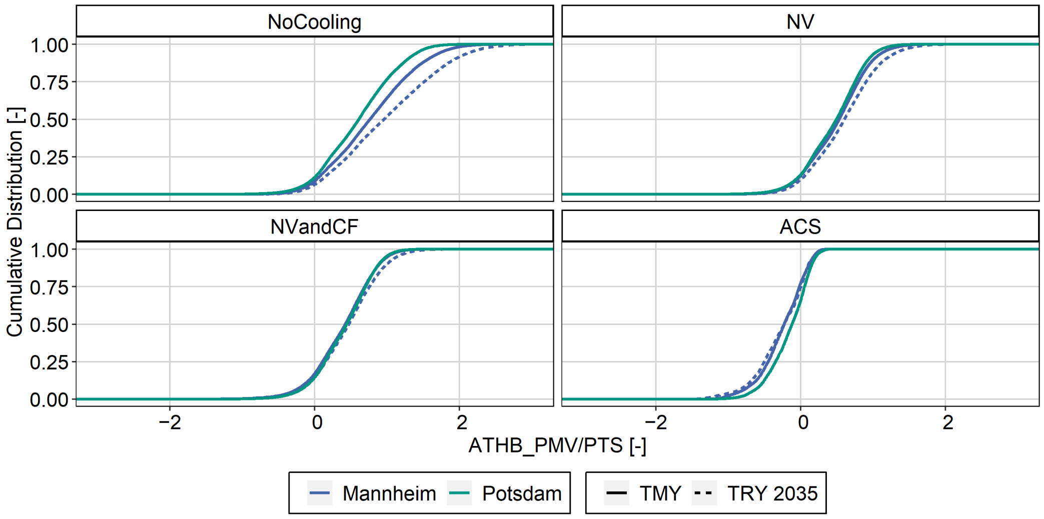

Figure 8. Cumulative PMV (ACS) and PTS (NoCooling, NV, NVandCF) values for all climate scenarios, using the ATHB model.

Table 14. Percentage of discomfort hours for PMV (ACS) and PTS (NoCooling, NV, NVandCF) using the ATHB model, values greater than +1 and +2 for different locations and climatic scenarios.

Comfort	Scenario	NoCooling	NV	NVandCF	ACS
PMV/PTS ≥ 1	Potsdam TMY	30.92%	16.24%	12.47%	0.00%
	Mannheim TMY	37.85%	16.72%	9.76%	0.00%
	Mannheim 2035	46.26%	21.06%	11.09%	0.00%
PMV/PTS ≥ 2	Potsdam TMY	0.41%	0.01%	0.00%	0.00%
	Mannheim TMY	1.93%	0.06%	0.01%	0.00%
	Mannheim 2035	4.36%	0.20%	0.01%	0.00%

Table 15 shows the relative performance of all cooling strategies for the three groups. The lowest relative performance can be observed for Mannheim 2035, with 98.62% for the NoCooling strategy. The ACS always provides 100% comfort. The higher the temperatures from the climatic scenario, the higher the difference in relative performance between cooling strategies.

Table 15. Relative performance values [%] for the three representative groups.

Scenario	NoCooling	NV	NVandCF	ACS
Potsdam TMY	99.46	99.81	99.87	100
Mannheim TMY	99.13	99.78	99.89	100
Mannheim 2035	98.62	99.69	99.88	100

3.2.2. Costs and Investment Evaluation in Future Scenarios

In this section, the results of the investment efficiency in different climates and a sensitivity analysis of the affected variables (salary and energy costs) are reported. Table 16 summarizes the values of the ΔNPV for the different climates and cooling concepts. In line with the results in Section 3.1.4, night ventilation is always profitable compared to NoCooling. The ceiling fan becomes profitable in warmer climates (Mannheim, both present and future climate); however, it is always behind night ventilation. Especially in future climates, this indicates that a technology cost reduction might help compensate for the investment in the ceiling fan with the additional performance losses economically. The ACS becomes slightly positive compared to the NoCooling strategy in future climates.

Table 16. ΔNPV for different climates and cooling concepts.

ΔNPV	NoCooling	NV	NVandCF	ACS
Potsdam TMY	-	423	−248	−1463
Mannheim TMY	-	1099	536	−760
Mannheim 2035	-	2046	1660	355

Furthermore, we studied the sensitivity of the ΔNPV to changes in the cost structure, namely salary and energy costs. Figure 9 shows the impact on ΔNPV when changing the assumed salary costs. The interpretation relates to the description in Section 3.1.4, where it was explained that the cooling concept with the lowest curve along the y-axis provided the lowest cost. The best investment efficiency is provided by night ventilation in all scenarios. The curves are mostly parallel, confirming that the obtained results are also valid for other salaries. In future climates, the ΔNPV is more affected by salary changes, as the performance costs are higher.

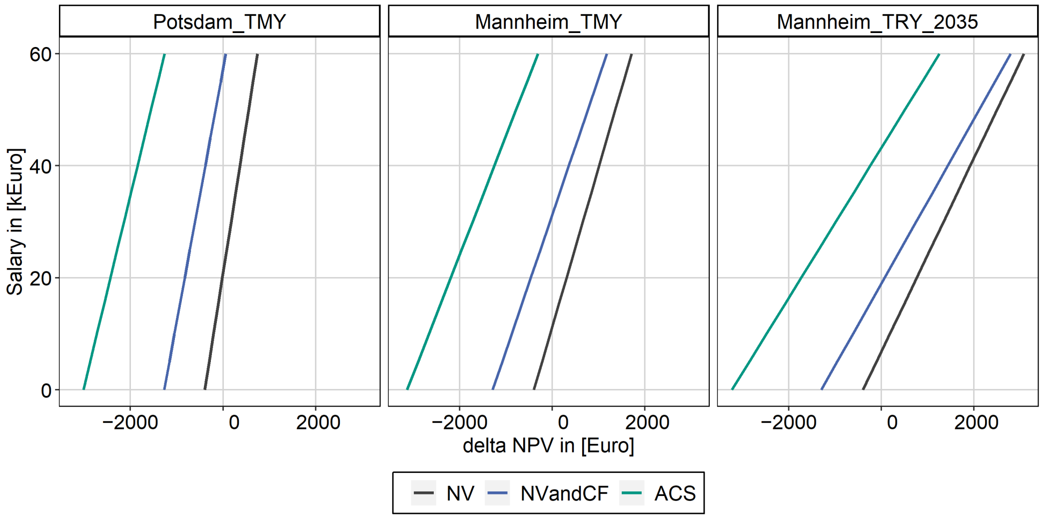

Figure 9. ΔNPV sensitivity to salary changes.

Figure 10 shows the impact on ΔNPV when changing the assumed energy costs. The interpretation relates to the previous figure, where night ventilation provides the best investment efficiency in all scenarios, and the curves are mostly parallel. The NV curve is vertical since it is not affected by energy cost changes (energy consumption of the automation system was neglected in the simulation). ΔNPV results are less sensitive to energy cost changes than salary costs.

3.2.3. Technology Cost Structure in Present and Future Scenarios

In the previous section, we concluded that it was impossible to make the ceiling fan more profitable than night ventilation alone when varying the salary or energy costs. Therefore, a technology cost reduction was calculated to estimate the maximum ceiling fan costs to make it profitable against night ventilation alone. Figure 11 shows the increase of the investment efficiency with falling investment costs, with a salary of €45,000 and an interest rate of 8% as boundary conditions.

The current customized solution comes with approximately €613 per ceiling fan investment. In the case of colder locations (Ulm and Potsdam TMY), the cost savings due to additional comfort (performance increase) are considerably low compared to the additional investment—which results in a required ceiling fan cost of €152. In warmer climates, the contribution of the ceiling fan becomes economically more significant. To be profitable against night ventilation alone, the ceiling fan must cost €203 in Mannheim TMY and €287 in Mannheim TRY 2035. This emphasizes the need for a cost reduction in the ceiling fans to be profitable in future scenarios.

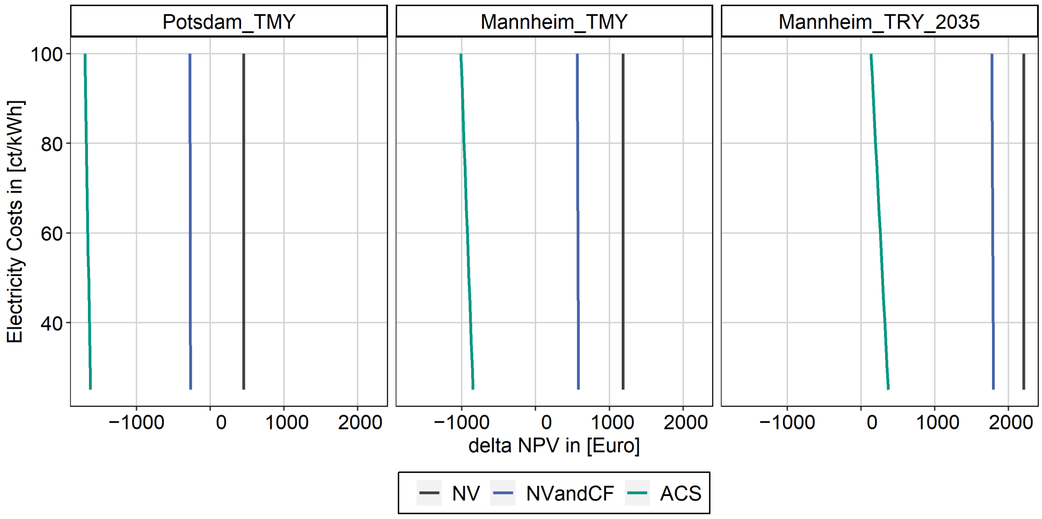

Figure 10. ΔNPV sensitivity to costs changes.

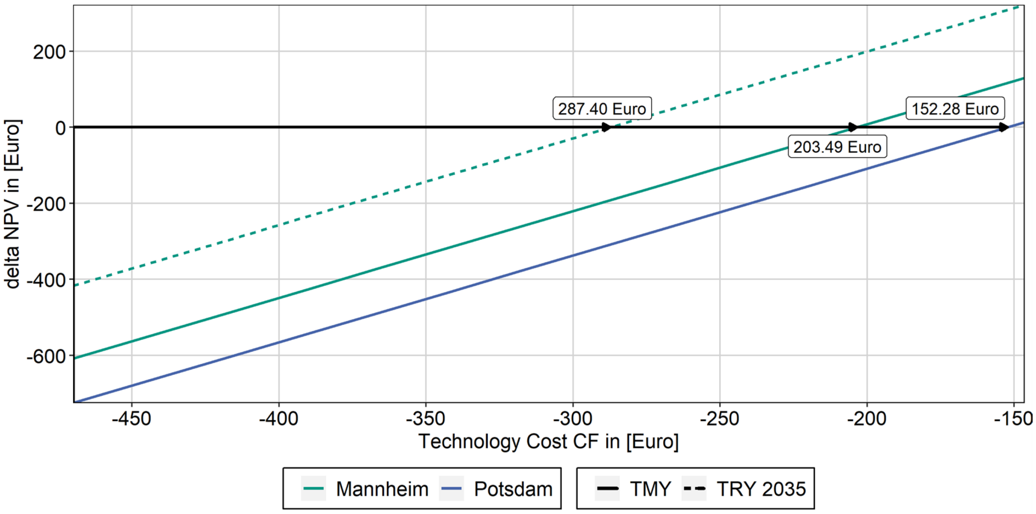

Figure 11. ΔNPV of the ceiling fan strategy against night ventilation for the three representative locations and climatic scenarios.

4. Discussion

The discussion is organized in the following subsections, where we thematically discussed the results and the limitations of each part of the study.

4.1. Fan Use Model

For the purpose of this study, we developed a fan-use behavior model for the district building in Germany. Results showed that the probability of using the fan ranges between 71–96% and between 94–99% at 28 °C and 30 °C indoor temperature, respectively (within a range of outdoor running mean temperature between 23–32 °C). These probabilities are comparable to the fan model developed by Nicol [47]. He found that 80% of building occupants use fans at 28 °C, and the operation is almost universal above 30 °C in Pakistan and Greece. However, probabilities corresponding to temperatures lower than 25 °C differ between studies, being relatively low in the present study. These differences might be related to the data collection method for the fan operation, as the model presented here is based on monitoring data (Nicol's model is based on survey data) and includes outdoor running mean temperature as a predictor variable. Moreover, cultural and climatic differences between Germany and other countries might lead to differences in operation. For instance, in the experimental study from Schweiker et al. [49], the authors found that below an operative temperature of 26 °C, the probability of German participants using the ceiling fan was lower than 20%, while the study from Zhang et al. [28] also showed lower probabilities of using a ceiling fan in a hot, humid area. The model presented in this study presents limitations in terms of generalization due to limited data from the monitoring. The model was fitted with data from one month, as it was the only period in which active use of the ceiling fan was observed.

4.2. Thermal Comfort Analysis

The resulting thermal comfort votes for the different cooling strategies, locations, and climatic scenarios were analyzed. Results showed that including night ventilation in the analyzed building design can reduce occupants' slightly warm sensation by 50% and reduce to zero their warm sensation. The discomfort hours were reduced to less than 18% during the year. As shown in the simulation study from Pfafferott et al. [20], the level of operative temperatures in a German office building could be lowered by incorporating automated night ventilation in combination with mechanical ventilation, reducing the indoor temperature above the comfort range to 10% during working hours. Including the ceiling fan in the night ventilation solution can reduce the slightly warm sensation by around 20% compared to the night ventilation solution alone. The positive effect of air movement on thermal sensation and comfort has been investigated in previous studies [11]. The presented sensitivity analysis showed that at higher observed outdoor temperatures, the impact of the ceiling fan on reducing thermal sensation votes increased by around 10%. However, the positive effect of perceived control on thermal satisfaction [68,69] could not be accounted for in the analysis with the used thermal comfort models. A reduction in occupants' perceived warm comfort sensation could be expected by incorporating personal control of cooling strategies as predicting factor in the thermal comfort models.

4.3. Productivity Analysis

We assessed the impact of the different cooling strategies in terms of productivity. Using Hancock and Warm's model [57] to calculate relative performance did not allow the inclusion of airspeed provided by fans. Therefore, we proposed replacing the indoor temperature with the SET to calculate the effect of elevated air speed on productivity. However, the validity of this calculation remains questionable and further proof is needed. Moreover, previous studies [70–72] indicate that users' control over thermal conditioning systems is a key aspect affecting people's satisfaction and can help improve workplace productivity. Like the comfort analysis, the positive effect of personal control over the fan could not be accounted for in Hancock and Warm's model, which might underestimate a potential increase in relative performance. Regardless of the model limitations, existent productivity assessment methods present a series of uncertainties regarding their theoretical foundations and applicability. Some authors [29,73] suggest that productivity is mostly influenced by thermal comfort and could not find any relationship between temperature and work performance [60]. Moreover, they suggested that current methods for measuring productivity are quite simplistic and prone to bias. However, the authors could not provide a model with a better prediction performance than Hancock and Warm's model. This may question the assumptions in productivity models based on indoor temperature, and their validity in assessing the performance in the workplace.

4.4. Cost Analysis

The cost structure is comparable with results from Olesen [74], who calculated average costs for improving indoor environmental quality from a lower to a higher building category regarding ventilation rates. In the present study, we compared the ACS solution with the higher category from Olesen. Olesen's results showed a cost structure of the improved building category of 97% for investment costs, 2% for maintenance, and 1% for energy, which is in line with our results. Slightly higher values correspond to the electricity and investment costs for Olesen's structure, which can be explained by the fact that he calculated the costs for the whole building system, including heating and cooling.

Given the high influence of productivity losses, the variation in the salary affects the NPV calculation. We proposed a calculation method to transfer productivity losses into monetary costs based on salary, number of employees, and cooling period. Even though the sensitivity of the results to variations in the salary was studied, different combinations of assumptions were not assessed. They could lead to different results from the ones presented. Considering the assumed interest rate, previous publications [75,76] suggest that higher interest rates might jeopardize the breakthrough of clean energy technologies in the market. In this study, those interest rates for private loans are above 8%, which was chosen following a conservative approach. This assumption is key to properly evaluating the ceiling fans' economic potential. Further studies may focus on developing validated productivity assessment methods and the qualification of productivity loss in terms of economic values.

Technology cost reduction was assessed in Section 3.2.3. As mentioned before, the existing cost structure of the ceiling fan corresponds to a customized solution from a field trial. On the one hand, industrializing the manufacturing process may seem a possible path to significantly reducing costs. On the other hand, to further support the installation of passive cooling technologies, different incentive schemes (i.e., from the government) could be considered to supplement the cost reduction threshold in the manufacturing process.

4.5. Assessment Method for PECSs: Uncertainties and Challenges

Finding a compromise between the provision of high satisfaction levels in buildings and the reduction of energy usage and costs is yet to be researched in depth [77]. In the context of climate change and increasing warm outdoor temperatures, this takes particular importance when implementing passive and active cooling strategies. We focused this work on the cost-benefit analysis of personal environmental control systems. We proposed a detailed assessment method in terms of economic viability to promote the incorporation of personal ceiling fans over conventional air conditioning methods. Following the proposed framework of Rawal et al. [14], we compared conventional cooling systems (without a PECS) and a system with a PECS, in this case, a personal ceiling fan. The work was based on building simulation and modeling techniques to compare different climatic and building scenarios. Apart from the limitations of the fan model and productivity calculations mentioned above, this comes with a series of limitations concerning the reproducibility of this assessment method due to the inherited assumptions and uncertainties proper to the nature of simulation methods. Further research could focus on developing a series of indicators to facilitate the assessment of and comparison between cooling systems and contribute to the standardization of a cost-benefit analysis for PECSs. Zhang et al. [9] developed the standardized indicator, the corrective power, to assess the comfort increase and energy savings potential of PECSs. A similar concept could be extended to assess the overall economic viability of PECSs based on the assessment proposed within this study. Additionally, future monitoring campaigns could be designed in such a way as to gather relevant data necessary for the proposed cost-benefit assessment, and in turn, serve as simulation work validation. As we conducted a single-case assessment, results cannot be generalized, but they serve as the first attempt to assess the cost-benefit of PECSs broadly.

4.6. Practical Implications

As mentioned by Prieto et al. [3], even though there is an increasing amount of cooling research, there is a need for specific research regarding possibilities for application, architectural integration, and performance issues of cooling systems. Within this study, we performed a real case building assessment, where not only the system's cooling performance was evaluated but also its incorporation into the building in terms of compatibility with the existing building features and employees' real behavior was assessed. The proposed PECS brings along benefits in terms of comfort requirements, maintaining energy consumption, and running and investment costs to a minimum extent. Indirect benefits of this system were not quantified within this work, such as the low environmental impact of this passive solution and the flexible design that allows easy integration within the building design, especially in existing buildings. The latest trends in building design focus on methodologies that minimize costs during the life cycle and maximize environmental benefits, showing that energy savings can be higher than the initial investment cost [78]. Within this study, we intend to follow this approach by promoting a sustainable building design in line with economic targets and climatic conditions.

5. Conclusions

This study evaluated the economic viability of personal ceiling fans within an office building renovation in Germany. A comprehensive cost-benefit analysis of energy consumption, direct and indirect costs, operation and labor costs, and thermal comfort was performed. The implemented ceiling fan solution was compared to alternative active and passive cooling strategies for different locations, and climatic scenarios through building performance simulation. Results showed that personal ceiling fans, assisted by night ventilation, are an effective and profitable cooling solution for warmer locations in Germany. These findings may have implications for applying personal environmental control systems (PECSs) and passive cooling strategies against purely active cooling solutions in buildings in favor of sustainability and economics. Additionally, we presented a cost-benefit assessment method for a PECS, including the calculation of labor costs, which contributes to the economic assessment of personal comfort system literature. Further research should focus on broadening the economic evaluation of PECSs in real-case buildings.

Author Contributions: Conceptualization, R.R., N.C. and M.S.; methodology, R.R. and N.C.; software, M.K. and N.C.; formal analysis, R.R. and N.C.; writing—original draft preparation, R.R. and N.C.; writing—review and editing, R.R., M.K., N.C., M.S. and A.W.; visualization, M.K.; supervision, R.R., N.C., M.S. and A.W.; project administration, R.R.; funding acquisition, M.S. and A.W. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

PECS	Personal Environmental Control System
NoCooling	No night ventilation or air-conditioning
NV	Night ventilation
NVandCF	Night ventilation (NV) and ceiling fans (CF)
ACS	Air conditioning system
HVAC	Heating, Ventilation, and Air Conditioning
PMV	Predictive Mean Vote

ATHB	Adaptive Thermal Heat Balance model
SET	Standard Effective Temperature
PTS	Predicted Thermal Sensation
MAM	Maximal Adaptability Model
T_a	Air temperature
T_r	Radiant temperature
RH	Relative Humidity
AV	Air velocity
$T_r m$	Outdoor temperature running mean
met	Metabolic rate
clo	Clothing value
psych	Psychological adaptive coefficient
RP	Relative Performance
NPV	Net present value
ΔNPV	Delta Net present value
O & M	Operation and Maintenance
TMY	Typical Meteorological Year
MBE	Mean Bias Error
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error

Appendix A

Table A1. Building characteristics and additional information.

Parameter	Value
Gross floor area	5500 m^2
Net floor area (ground floor to 3rd floor)	3488 m^2
Building orientation	345°
Thermal transmittance north façade	0.13 $W/m^2 \times K$
Thermal transmittance roof	0.713 $W/m^2 \times K$
Infiltration (assumed)	0.1 ACH
Night ventilation window size	0.239 m^2
g-value window and glazing	0.55
Window/wall ratio	0.22
Number of employees	157

Table A2. Absolute value of Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) for each building thermal zone.

Thermal Zone	MBE	CVRMSE	Thermal Zone	MBE	CVRMSE
TZ01	2.32	5.17	TZ27	3.31	7.42
TZ05	0.89	1.98	TZ29	3.36	7.31
TZ06	2.45	0.56	TZ32	2.41	5.24
TZ09	0.94	2.06	TZ33	2.07	4.54
TZ10	0.90	2.00	TZ36	3.14	6.61
TZ11	0.90	2.04	TZ37	2.87	6.17
TZ12	2.02	4.67	TZ38	4.14	9.20
TZ13	1.03	2.35	TZ40	5.59	12.27
TZ15	2.22	4.95	TZ43	3.67	8.05
TZ19	1.46	3.22	TZ44	3.83	8.34
TZ20	1.03	2.27	TZ47	4.40	9.64
TZ21	0.64	1.42	TZ48	4.05	8.90
TZ24	2.14	4.52	TZ49	4.59	9.95
TZ25	1.71	3.72	TZ50	6.36	13.77
TZ26	1.24	2.77			

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Thermal expectation: Influencing factors and its effect on thermal perception

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ABSTRACT

Thermal expectation is mentioned as one aspect of psychological adaptation to indoor thermal conditions. However, there is a lack of studies in the built environment assessing expectations directly and the relationship between expectations and thermal perception. Therefore, this paper studies potential influences on occupants' expectations of indoor thermal conditions and the implications of their expectations on thermal perception. A combination of data from laboratory and field studies was analysed, where the same 47 participants participated in both of them. Subjects experienced different temperature conditions and were asked directly about the congruence between their thermal expectations and actual experience together with their actual thermal perception. The question regarding participants expectations applied in this study can be considered as the most straightforward way to ask for their expectations. The data was analysed by ordinal mixed effect regression analysis. Results show that there is a significant influence of the level of expectation on thermal sensation and comfort votes for the field and laboratory study. Indoor temperature, the day of experiment (first, second, or third) and the location (laboratory vs. field) show significant influences on thermal expectation. However, participants state their expectation of the indoor environment independent of the outdoor conditions or indoor-outdoor temperature difference. The discussion of implications of these results for adaptive approaches of room conditioning, which relay on the acceptance of higher fluctuations of indoor thermal conditions, suggests to carefully address expectations in future studies.

1. Introduction

Thermal comfort standards include definitions for the requirements for thermal indoor conditions in buildings. However, research frequently reports a gap between the provision of these standardized indoor thermal conditions and actual desired conditions [1–3]. Consequently, questions arise regarding the validity and completeness of the assumed variables in the implemented thermal comfort models [4,5].

To fill the gap between predicted and actual thermal responses, several efforts have been focused on capturing and understanding one or more of the underlying three mechanisms in adaptive processes of occupants in buildings, namely behavioural, physiological and psychological [6–9]. One aspect of psychological adaptation mentioned in the literature is people's expectation with respect to indoor thermal conditions. Fountain, Brager, and de Dear [10] state that after persons are exposed to variations in indoor climate all perceived as comfortable, their expectations to those conditions may become more relaxed. According to Höppe [11], the expectation of specific thermal conditions is the major aspect for the subjective assessment and satisfaction.

Accepting that future expectations are partially shaped by contemporary experiences, modifying them seems to be an alternative path to redefine comfort in the face of climate change. Fulfilling occupants' expectations may help to improve indoor control strategies towards healthier, more comfortable and efficient buildings [12]. However, understanding factors influencing occupants' expectations of indoor thermal conditions and the implications of their expectations on thermal perception is still a topic to be explored further and therefore, the objective of this paper.

1.1. Background / state of the art

Occupants' expectations in the built environment have been assessed and measured very differently among studies. Early in the 1980's, Auliciems [6] proposed a "psycho-physiological model", in which thermal expectations of a certain environment affect occupants' thermal satisfaction of the indoor space. Those expectations are formed by past thermal experiences together with behav-

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ioral and techno-cultural adjustments, which refers to adaptive opportunities provided by a building in a specific cultural context.

Following the same line of thought, Humphreys and Nicol [1] relate thermal sensation votes to “background expectations”. The correlation found between comfort temperatures and mean outdoor temperature may indicate that occupants' expectations of comfort are shaped by recent thermal experiences, also referred to as “thermal memory”. Luo *et al.* [13] deepened this concept by analysing thermal expectations as requirements or ‘demands’ for thermal comfort. They estimated expectations based on the level of discomfort within a group compared to a baseline group. The relationship between thermal history and thermal sensation votes has also been assessed by Chun *et al.* [14], showing that daily thermal exposure of outdoor temperatures and usage of air conditioning (AC) affect the thermal perception of an indoor environment.

Cândido *et al.* [15] deepened the concept of thermal history by correlating the usage of air conditioning and thermal preferences in office buildings. While no significant difference was found in thermal sensation votes between occupants exposed to AC systems and occupants of non-air-conditioned buildings, a significant difference was found in their thermal preferences. The AC occupants preferred not only “cooler” spaces in comparison to the other group, but also they selected AC systems as preferable cooling strategy. The authors relate people's rising expectations to the increased AC usage, leading to a lower tolerance to widened temperature bands.

Those results corroborate the findings of Rajkovich and Kwok [16]. They investigate human responses in transitional spaces, by assessing thermal votes in air-conditioned and naturally ventilated arcades. Results indicate that thermal sensation votes are not tied to specific ventilation types, but instead are influenced by occupants' expectations of the space. Differently from other studies, they assessed thermal memory and thermal expectations by asking the subjects to anticipate their thermal sensations before entering and after exiting the analysed place on a 7-point ASHRAE thermal sensation scale. This study presents a method to quantify thermal expectations.

Efforts have been done to include thermal expectations in the assessment of thermal comfort. Fanger and Toftum [17] incorporated occupants' expectations as a factor of dependence on air conditioning systems, based on the thermal sensation votes for the specific warm climatic condition of the analysed non-air-conditioned building. Kim and de Dear [18] found that occupants' expectations to IEQ performance, which are formed by their experiences in buildings with different ventilation types, lead to different responses to aspects of the indoor environment.

Thermal expectations are not only formed by continuous exposures to climatic conditions and building characteristics, but they can be shaped by adaptive opportunities of a building. Deuble and de Dear [19] assign differences in thermal sensation votes to changed expectations, depending on the operation mode in mixed mode buildings. They suggest that expectations adapt to changes in the degrees of freedom of adaptive opportunities (e.g. window opening).

In that sense, expectations have a higher influence on the perception of comfort when the indoor environment is controlled by the subject rather than when the users are passive [20,21]. Luo *et al.* [22] looked at dynamics of comfort expectation, showing differences in thermal sensation and acceptance based on different times after moving from one to another climate zone; suggesting the implementation of effective adaptive strategies to expand and enhance occupants' comfort range.

Brown and Cole [23] propose a different approach to assess expectations. They evaluate expectations through a “forgiveness” factor, by comparing mean values of overall comfort with mean values for specific comfort variables. Winzen and Marggraf-Micheel [24] relate overall comfort to expectations as well. They assessed satisfaction in an aircraft cabin, showing that the more positive the expectations, the more comfortable the rating of indoor climate parameters. Williams [25] as well as Bischof *et al.* [26] found a significant difference between male and female participants in consumers' expectation and thermal expectations in the built environment, respectively. In the context of outdoor thermal comfort, Nikolopoulou and Steemers [27] mention naturalness as additional element of psychological adaptation.

Previous studies show a common agreement that there is an effect of expectations on occupants' thermal and overall satisfaction and acceptance of indoor environments. However, it remains unclear how and to which extent expectations influence occupants' perception of comfort. In addition, while using the term expectation to describe the observed phenomena, with the exception of Rajkovich and Kwok [16], none of these studies actually assessed peoples' expectations or the congruence between expected and experienced indoor thermal conditions. Before doing so, it is important to review a) definitions of the term expectation, and b) theories related to expectations from other fields of science.

2. Definition

Thompson and Sunol's review of expectations (from [28]) covers a variety of perspectives – psychology, sociology, social policy, and marketing, among others. They distinguish between four types of expectations: *ideal* (aspiration, desire or preferred outcome); *predicted* (realistic, anticipated outcome, what users believe will happen); *normative* (what should or ought to happen); and *unformed* (users are unable to articulate their expectations). Similarly, Zeithaml (from [29]) define expectations in terms of performance: *ideal* or best performance; expected or likely performance; *minimum tolerable* performance; and *desired* performance. In the built environment, Teas [30] distinguish between ‘ideal’ expectations, that is, how inhabitants wish the building would perform, and ‘normative’ expectations, that is, how they think the building should or ought to perform.

Varying the nature of expectations may create a misleading indicator of consumers' expectation. If expectation level is used as a baseline comparison to which the product is judged, then it may *“represent a methodological problem because expectations are defined differently by consumers”* [29]. A lack of a common definition of expectations in the built environmental context, leads to a variety of assessment methods and ways to measure them. A clear definition is necessary for this paper: the level of expectancy is defined for this paper as the congruence between the thermal experience predicted by occupants, i.e. referring to the definition of “predicted expectation” by Thompson and Sunol, and the actual perceived thermal experience.

2.1. Theory

Theories of expectation can be found for example in literature on consumer satisfaction, which presents a large body of theoretical and experimental studies with respect to the relationship between consumers' expectations and satisfaction with products. Consumer expectations often derive from extrinsic cues (e.g. observable characteristics of a product without using it). These cues influence consumer evaluation of a certain product or service. However, those expectations are not always met, which is leading to discrepancies between the consumer's expected satisfaction and the satisfaction produced by the real performance. This discrepancy is called “disconfirmation of expectations“[31]. The assimilation-contrast theory [32] implies that there are some levels of consumer preferences regarding acceptance and rejection. If the discrepancy between expectation and product performance is rather small, assimilation occurs, which reduces the perceived discrepancy. If the discrepancy is large enough to fall into rejection, then a contrast effect arises, which would emphasize the discrepancy.

This theoretical approach implies that the magnitude of discrepancy between expectations and actual satisfaction may determine consumer's behavior, by changing their perception of the product or performance. Anderson [33] presents four theories of how expectations influence perception:

- Cognitive Dissonance (Assimilation): any discrepancy will be minimized to solve "mental discomfort" due to conflict. Related to thermal perception, this suggests that occupants will try to reduce any cognitive tension if there is a disparity between the expectations and the experience of thermal conditions by adjusting either the memory related to previous expectations or the actual perception to achieve consistency and to reduce the mental discomfort.
- Contrast: any discrepancy will be exaggerated. Continuing with thermal perception, any slight difference in expected thermal conditions and experienced thermal condition could magnify occupants' satisfaction or dissatisfaction with the conditions.
- Generalized negativity: any discrepancy will result in less favourable evaluation. A clear example is the bitter-sweet solution experiment [33]. Expecting a sweet taste and tasting bitter will rate the solution as more bitter than expected. In this sense, satisfaction with thermal conditions will always be negatively rated if a discrepancy between expectation and experience occurs, and the degree of negativity will vary with the amount of disparity.
- Assimilation-contrast: combination of assimilation and contrast theory. This theory assumes that consumers have levels or ranges of acceptance, rejection and neutrality, which will lead either to assimilation or to contrast.

Overall, theories suggests different effects of fulfilled or not fulfilled expectations on users' (occupants') satisfaction.

2.2. Research questions

The review of the state of the art has shown that there is a lack in studies assessing people's expectations directly and comparing these with their thermal perception. In addition, factors influencing the congruence between expectation and experience (defined here as expectancy) have not been dealt with for the built environment. Furthermore, the review of existing theories suggests different effects of expectancy on user's satisfaction, but neither these effects nor influencing factors on expectations have been assessed in research on the built environment.

Based on the state of art in combination with the theories presented, a preliminary framework for the assessment of expectancy was developed (Fig. 1), which summarizes previously investigated influences on thermal expectation and influenced factors by thermal expectation. Fig. 1 highlights that the majority of studies inferred the influence of thermal expectation on thermal perception without assessing expectation directly. In contrast, the two main research questions (RQ in Fig. 1) of this study are:

1) To what extent does the observed expectation affect the level of thermal sensation and comfort?
2) Which factors influence people's expectation of thermal conditions?

2.3. Hypothesis

Based on the existing literature and related to the above stated research questions, the following hypotheses will be investigated:

Related to research question 1, the hypotheses are

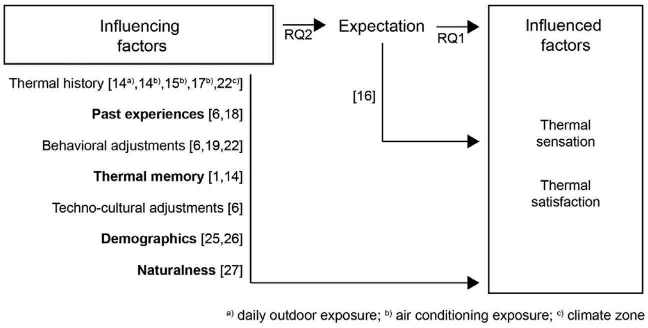

Fig. 1. Preliminary framework for the assessment of the relationship between expectation, influencing factors and influenced factors together with a summary of previous findings. Influencing factors addressed in this analysis are in bold face.

1.1 Thermal sensation is further away from neutrality when conditions were not as expected.
1.2 Thermal comfort is lower when conditions were not as expected.

Hypotheses 1.1 and 1.2 are based on the contrast theory of expectation [33], that discrepancies are emphasised, in case expectations are not met.

Related to research question 2, the hypotheses are

2.1 [Past experiences] Disregarding the thermal indoor conditions, a higher percentage of participants will rate thermal conditions "as expected" in a known environment, such as the typical workspace, compared to an unknown environment, such as an experimental facility. As such, past experiences will lead to a higher congruence between expectation and perception.
2.2 [Thermal memory] Expectations will be more likely not fulfilled when a) entering a new building for the first time (compared to the 2nd and 3rd time) or b) right after entering an office compared to a later period of the same day. When entering a building the first time or entering the office, expectations are less likely based on thermal memory.
2.3 [Demographics] Significant influences can be related to peoples' demographic characteristics based on results from studies in consumer studies and for the built environment suggesting sex differences in thermal expectation [25,26].
2.4 [Naturalness] The percentage of participants expecting the prevailing thermal conditions and the direction of non-agreement with expectation (warm or cool) depends on the relationship between indoor and outdoor thermal conditions. Based on their experiences with indoor-outdoor differences occurring in their daily life during previous days, occupants have a sense of the naturalness of such relationship and expect it to be similar during the present day.

3. Methodology

In order to assess above research questions, a combination of data from laboratory studies [34,35] and an unpublished field study was chosen as described below. All procedures were approved by the data protection officer and ethics committee of the Karlsruhe Institute of Technology and conducted according to the Declaration of Helsinki.

3.1. Participants

Participants were recruited via local job portals for students and had to be between 18 and 30 years in order to limit the effect of age. A reimbursement of 100€ were offered for three experimental days in the laboratory and an additional 25€ for participating in the field study. Subjects had to be either native speakers of German or a comparable level of German. Smokers were not permitted for this study. A balanced sex distribution was aimed at. Data from 47 participants (24 females, mean age 24.4±2.4 years), who agreed to participate in the laboratory and field study, could be used for this analysis – hence the same participants participated in the laboratory and field study.

3.2. Procedures of studies

Detailed procedures of the laboratory studies have been described previously [34,35]. Relevant for this analysis are the following aspects. Participants arrived on the first of three days at the test facility at 9 am, received detailed instructions regarding the procedures including the field study, which was followed by receiving written informed consent. On three non-consecutive days, participants received physiological sensors (not relevant for this analysis) and were guided into one of the offices of the test facility. Upon entering the office and taking a seat, participants were asked to fill out a start-of-day questionnaire. Around 30 minutes after entering the office, the first state questionnaire was filled out. In the following, subjects worked on their own work and were asked to fill out the state questionnaire 5 more times roughly every 90 minutes. Besides a lunch break of 30 minutes and freely chosen toilet breaks, participants remained in the office until 4:45 pm. At the end of the third day, participants were asked again regarding their participation in the field study. Participants were allowed to open or tilt two windows per office according to their own preferences at any time. Additional adaptive behaviours available to the participants were adjustments of their clothing insulation and a ceiling fan.

Upon agreeing to participate in the field study, participants received a HOBO temperature and humidity state logger and a set of questionnaires. They received instructions to fill out a start-of-day questionnaire and up to four state questionnaire each for three non-consecutive days at their normal work place. During this period, the HOBO device should be placed on the work desk outside of areas with direct sunlight or other heat sources.

3.3. Materials and data collection

The laboratory study took place in the field laboratory LOBSTER [36,37]. This laboratory consists of two office rooms (4 m width by 6 m depth by 3 m height) with one façade each. The façade appears as a common post and beam structure with the middle and upper part being transparent glazing. Indoor and outdoor parameters were collected in a 1-minute interval through the building management system (BMS) and equipped sensors. In addition, AHLBORN comfort meters were used to collect air temperature, globe temperature, relative humidity, and air velocity in the middle of the room at a height of 1.1 m and a 1-minute interval. The corresponding resolutions are 0.01°C, 0.01°C, 0.1%, and 0.001 m/s; the accuracies are +/- 0.2 K, +/- (0.30 K + 0.005xT), +/- 2.0% and +/- (3% measured value + 0.01) respectively. The analysis presented here is based on the data from the AHLBORN devices.

All questionnaires during the laboratory studies were provided through a web interface. Questionnaires for the field studies were paper-pencil based. Questionnaires for laboratory and field study had the same question texts and answer options. However, questionnaires used for the field studies lacked several questions applied during the laboratory study in order to be much shorter.

The start-of-day questionnaire was completed after entering the workspace either in the laboratory or at their normal workplace. The start-of-day questionnaire consists of questions related to the means of transport, actual clothing level, duration of sleep, and expectancy of indoor and outdoor conditions, among others. Expectancy was assessed through a skip-logic as shown in Fig. 2.

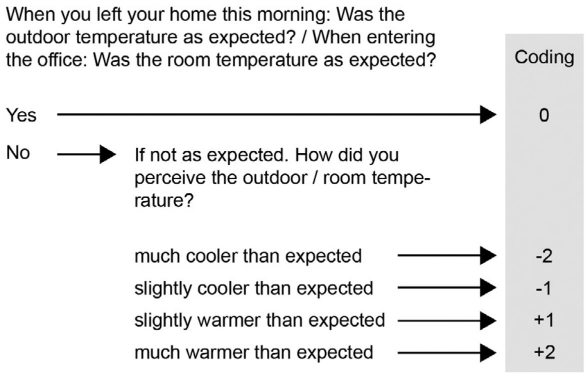

Fig. 2. Questions, rating scales, skip logic and coding for assessment of thermal expectation. Note that questions were translated from German and that expectations of outdoor and indoor conditions were assessed in separate questions.

3.4. Data preparation and analysis

All data preparation and analysis was conducted within the software environment R [38] Version 3.5.2.

The standard effective temperature (SET) was calculated using the function ‘calcSET’ from the R package comf [39]. Required input values were the indoor environmental parameters measured by the AHLBORN devices, the clothing insulation level based on answers to questionnaires in combination with values from ISO 7730, and a table value for metabolic rate for seated activity of 1.1 MET.

The temperature values from HOBO devices were calibrated according to calibration files from a three-point calibration in the LOBSTER facility at the end of the study.

The level of expectancy was coded as shown in Fig. 2.

Previous studies have questioned the equidistance assumption of thermal sensation and comfort vote scales [40,41]. Likewise, an equidistance between the individual levels of expectancy cannot be assumed. Therefore, linear regression analysis cannot be applied. In addition, a repeated measures design is present, so that ordinal mixed effect regression analysis was chosen using function ‘clmm2’ from the R package ordinal [42].

To analyze the data for RQ1, the dependent variables were either the thermal sensation votes or comfort votes, independent variables were indoor thermal conditions (SET for laboratory data, and room temperature from HOBO for field data) and expectancy as fixed effects and the subject identifier as random effect. For the assessment of RQ2, expectancy was set as dependent variable, and independent variables were indoor temperature, outdoor temperature, indoor-outdoor difference, sex, and location (laboratory or field) as fixed effects, and the subject identifier as random effect.

4. Results

4.1. Descriptive statistics

Descriptive statistics for the prevailing indoor thermal conditions (SET), the outdoor running mean temperature, and the indoor-outdoor temperature difference at the time of the first state questionnaire are presented in Table 1

Fig. 3 presents the distribution of expectancy votes separately for indoor thermal expectations and outdoor thermal expectations obtained through the laboratory and field studies. For indoor expectation, X^2-tests show significant differences for indoor expectation between laboratory and field study data (McNemar’s $X^2 = 4.5918$, df = 1, p-value = 0.032; Pearson’s $X^2 = 28.263$, df = 9,

Table 1
Indoor and outdoor conditions during the time of responses for laboratory and field study.

Data	Variable	N	Minimum – Median – Maximum	Mean ± std. dev.
Laboratory	SET [°C]	803	19.7 – 25.9 – 30.2	25.8 ± 1.7
	T_{rm} [°C]	803	22.5 – 24.8 – 26.4	24.9 ± 0.9
	Tout – Tin [K]	100	−12.8 – −6.8 – 0.9	−6.4 ± 3.1
Field	$T_{in\ HOBO}$ [°C]	609	18.9 – 24.8 – 34.4	24.7 ± 2.3
	T_{rm} [°C]	644	12.6 – 18.8 – 23.1	19.0 ± 2.3
	Tout – Tin [K]	96	−10.2 – −5.2 – −0.4	−5.4 ± 2.2

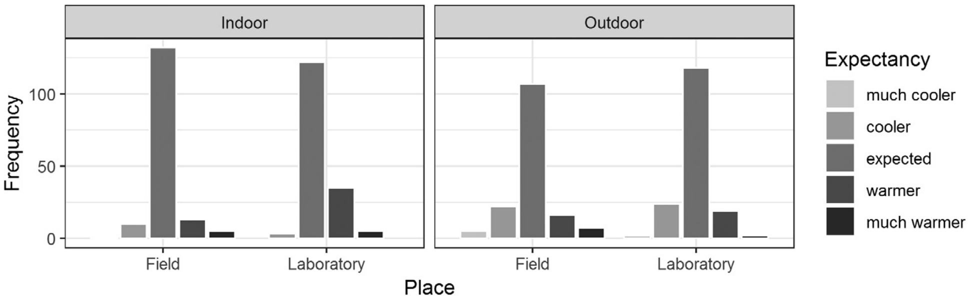

Fig. 3. Distribution of expectancy votes.

Table 2
Results of ordinal mixed effect regression analysis for laboratory and field data. Coefficients are presented in the format coefficient±standard error (z-test statistics; p-value). The column thresholds denotes the intercepts or the points where votes are predicted into a higher category. The numbers presented refer to the categories of votes, e.g. 2\|3 in model 1 refers the threshold between *cool* (2) and *slightly cool* (3) votes.

Model	Data	Dependent variable	Coefficients Thermal conditions (SET)	Cooler-than-expected	Warmer-than-expected	Thresholds (intercepts)
1	Laboratory	Thermal sensation	0.5±0.2 (z: 2.8; p: .005)	−1.6±1.3 (z: −1.3; p: .21)	1.2±0.5 (z: 2.5; p: .01)	2|3: 6.8±3.9 3|4: 9.3±4.0 4|5: 13.5±4.2 5|6: 17.0±4.4
2	Laboratory	Thermal comfort	0.5±0.2 (z: 2.2; p: .03)	2.2±1.6 (z: 1.4; p: .17)	2.9±0.8 (z: 2.5; p: .000)	1|2: 14.4±5.5 2|3: 6.0±3.0 3|4: 19.4±6.1
3	Field	Thermal sensation	0.5±0.1 (z: 4.6; p: <0.001)	−1.4±0.8 (z: −1.8; p. 07):	1.9±0.6 (z: 3.1; p: .001)	2|3: 8.0±2.6 3|4: 10.7±2.6 4|5: 14.3±2.8 5|6: 16.5±2.9
4	Field	Thermal comfort	0.07±0.1 (z: 0.6; p: .058)	1.8±0.9 (z: 2.1; p: .04)	2.0±0.7 (z: 2.9; p: .004)	1|2: 2.8±2.9 2|3: 5.9±3.0 3|4: 8.0±3.2

p = .001), but no difference in outdoor expectations (McNemar's $X^2 = 0.62069$, df = 1, p = .4308; Pearson's $X^2 = 16.123$, df = 16, p-value = 0.44). However, this figure is not accounting for differences in indoor thermal conditions.

4.2. RQ1. The effect of expectations on thermal perception

Ordinal mixed effect regression analysis shows a significant influence of the level of expectation on thermal sensation votes and thermal comfort votes for the field and laboratory study as summarized in Table 2.

Fig. 4 visualizes the predictions based on model 1 of Table 2. At a SET of 20°C, those who perceived conditions as "cooler" than expected, have the highest probability to vote "slightly cool", while those who expected the conditions or perceived conditions as "warmer" than expected are more likely to vote "neutral". The same tendency can be observed for higher values of SET, but shifted to the warm side. At a SET of 29°C, participants who perceived conditions to be "cooler" than expected, voted "neutral" with the highest probability, while this is "slightly warm" for those who perceived conditions as "warmer". The effect of a different perception is around 1 vote on the thermal sensation scale.

Fig. 5 presents the predictions for thermal comfort votes based on the laboratory data. At a SET of 20°C, the influence of the expectation is low. In all cases, conditions are perceived as comfortable with the highest probability. At a SET of 24.5°C, only for those who expected the thermal conditions, a "comfortable" vote remains as likely as for a SET of 20°C. For those who did not expect the conditions, the probability of a "comfortable" vote at a SET of 24.5°C is still the highest compared to other votes, but the probability of a "just comfortable" vote increases. At a SET of 29°C, this tendency is even stronger. For conditions not expected (either warmer or cooler than expected), the highest probability is a "just comfortable" vote. At the same time, for those who expected the conditions, the highest probability is still "comfortable".

Predictions based on the statistical models derived from the field data show very similar patterns compared to those from the laboratory data (see Fig. 6 and Fig. 7). For both cases, i.e. thermal sensation and thermal comfort votes, individual differences are large as shown by the lines for the 5th- and 95th- percentile. Still, also these lines show distinct patterns for different expectation votes.

The thermal sensation votes predicted by the statistical models (assuming an average person) can be compared to the observed votes by means of the true positive rate (TPR), i.e. the percent-

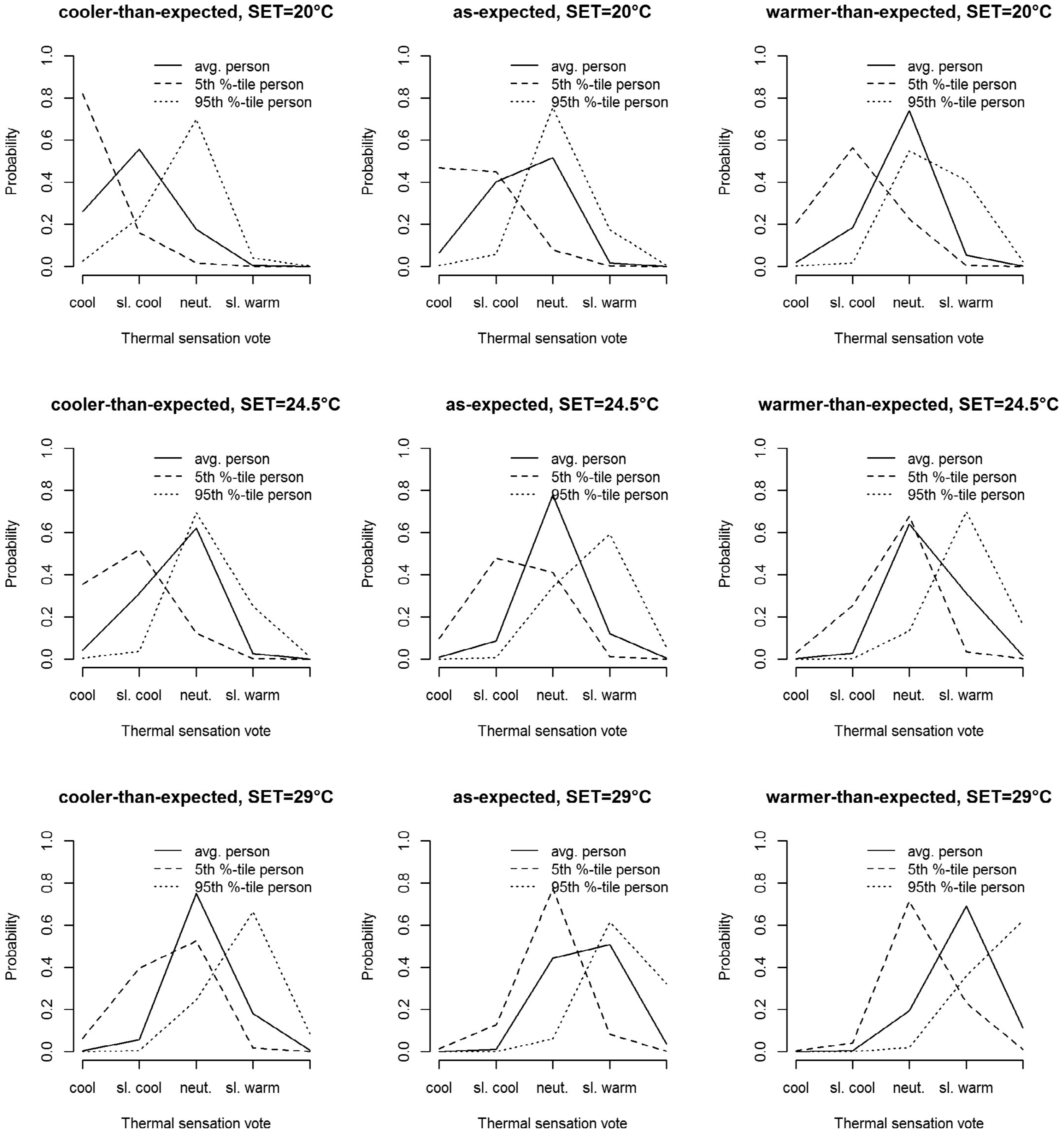

Fig. 4. Predicted probabilities for thermal sensation votes depending on SET and level of expectation based on data of laboratory study (Model 1 in Table 2).

age of correctly predicted votes (see Schweiker *et al.* [9] for further explanations). The TPR rates results in 62.1% and 57.9% for thermal sensation votes obtained from the laboratory and field studies respectively. The TPR for thermal sensation based on the laboratory data can be compared to the TPR of PMV and predicted thermal sensation votes from SET, PTS_{SET}, directly, because this dataset contains all required variables. PTS_{SET} is calculated with $PTS_{SET} = 0.25*SET - 6.03$ [43]. The TPR for PMV results in 59.1% and for PTS_{SET} in 53.8%. The TPR for the thermal comfort votes is 78.8% for the laboratory data and 69.1% for the field data set.

4.3. RQ 2. Influences on thermal expectation

The results of the ordinal mixed effect regression analysis on thermal expectation are presented in Table 3. Indoor temperature, the location (laboratory vs. field), and the day of experiment (first, second, or third) show significant influences on thermal expectation, while the effect of outdoor temperature, indoor-outdoor difference, and sex is not significant.

Stepwise model selection based on AIC value and p-values of individual predictors leads to the final model (AIC 342, thresh-

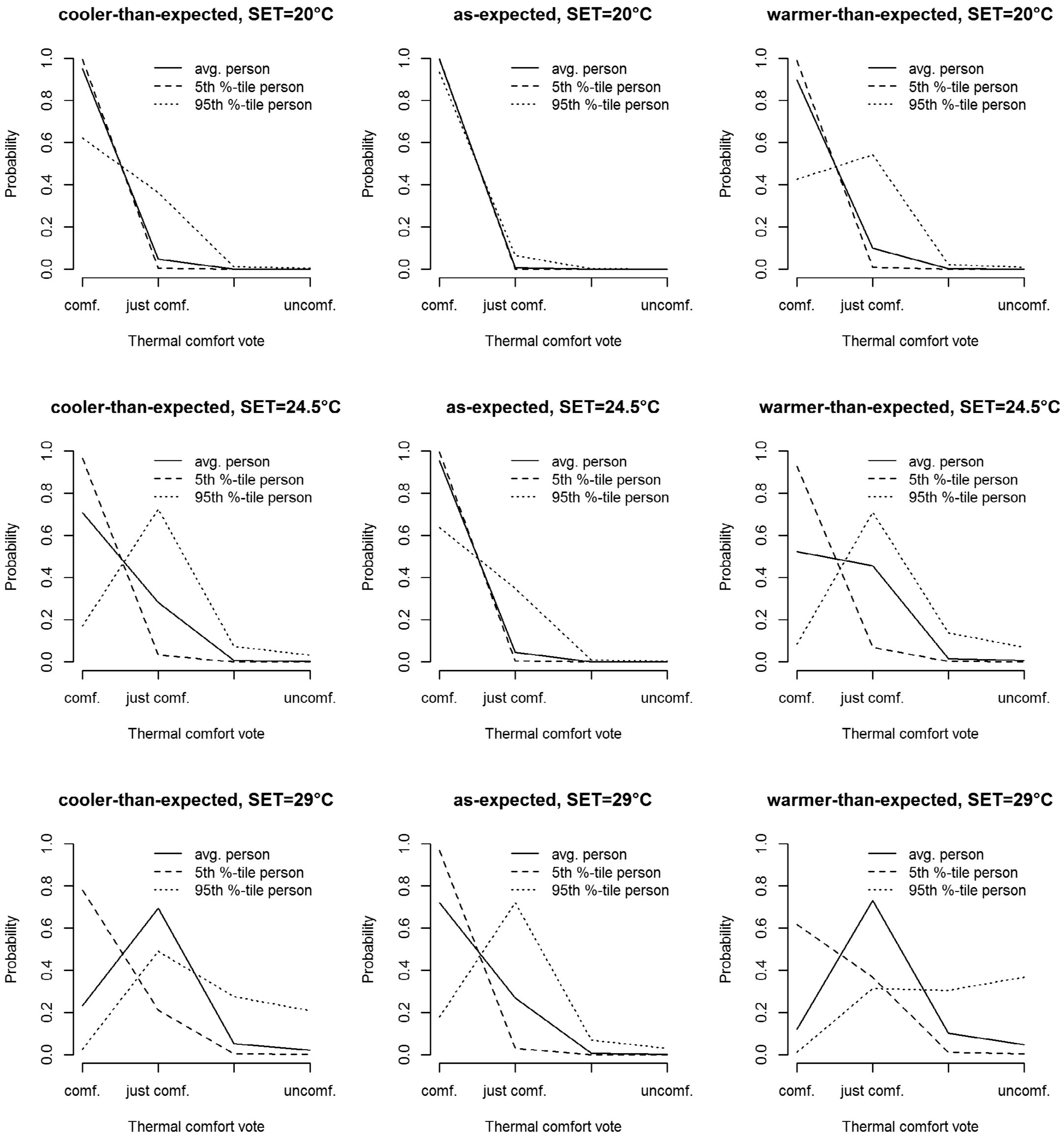

Fig. 5. Predicted probabilities for thermal comfort votes depending on SET and level of expectation based on data of laboratory study (Model 2 in Table 2).

old coefficients a) cooler | expected 8.8±2.6, z=3.3, b) expected | warmer 14.6±2.9, z=5.0) with Tin (0.50±0.11, z=4.4, p<.0001), Location (Lab 13.1±5.8, z=2.3, p<.02), and the interaction between Tin and Location (Lab −0.49±0.23, z=−2.1, p<.03). Fig. 8 visualizes this model. Over the full range of Tin shown here, expectations only slightly differ for the laboratory environment. The highest probability has the vote "expected", followed by a "warmer" perception compared to expectation. For the field dataset, expectation follows indoor thermal conditions: at Tin = 20°C, the probability of "cooler" is slightly increased, while at Tin = 29°C, the probability of "warmer" is as high as that of "expected". Overall "expected" has the highest probability.

Whether participants voted their expectation on their first, second, or third day in laboratory or field was significant when added as single predictor to the model, but was not adding information

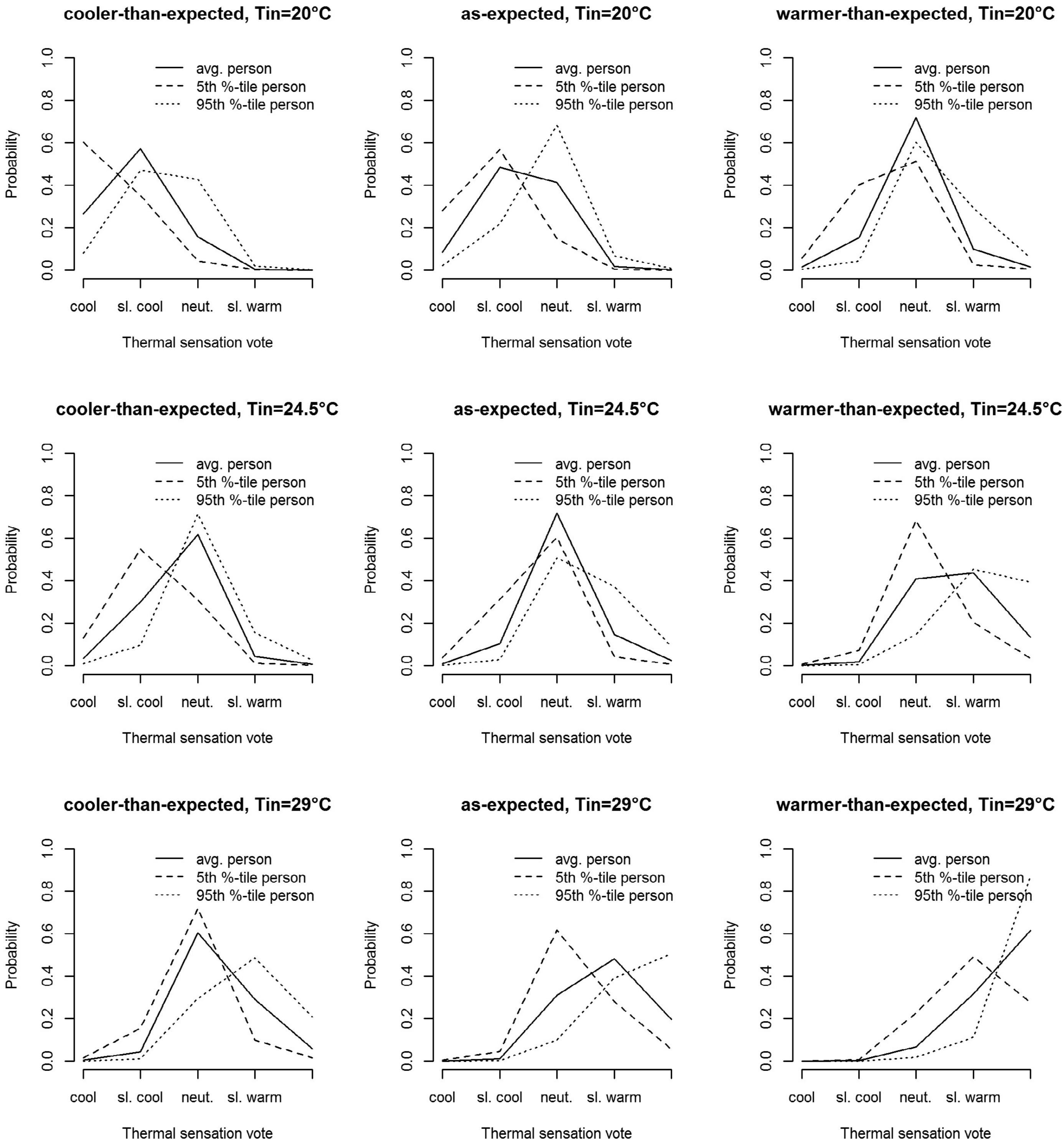

Fig. 6. Predicted probabilities for thermal sensation votes depending on room temperature and level of expectation based on data of field study (Model 3 in Table 2).

either as additional predictor or in interaction with Tin and the location. A more detailed analysis showed that the day of experiment is significant for the laboratory data (β=−0.64±0.26, z=−2.5, p=.01), but not for the field data (β=−0.16±0.29, z=−0.6, p=.58). The distributions shown in Fig. 9 support this result. While there is a tendency towards higher percentage of "expected" votes in the laboratory study, the level of "expected" votes does not change systematically for the field study. Fig. 9a shows that the percentage of "expected" votes in the laboratory study is comparable to those in the field study (Fig. 9b) on the third day of experiment. Thermal conditions are not significantly different during the three days in the laboratory (Day 1: M = 24.6°C, SD = 1.8; Day 2: M = 24.5°C, SD = 1.8; Day 3: M = 24.5°C, SD = 1.9). Hence, participants seem to adjust their expectations of thermal conditions very quickly based on few experiences with such new environment; especially given that the three days in the laboratory were not consecutive.

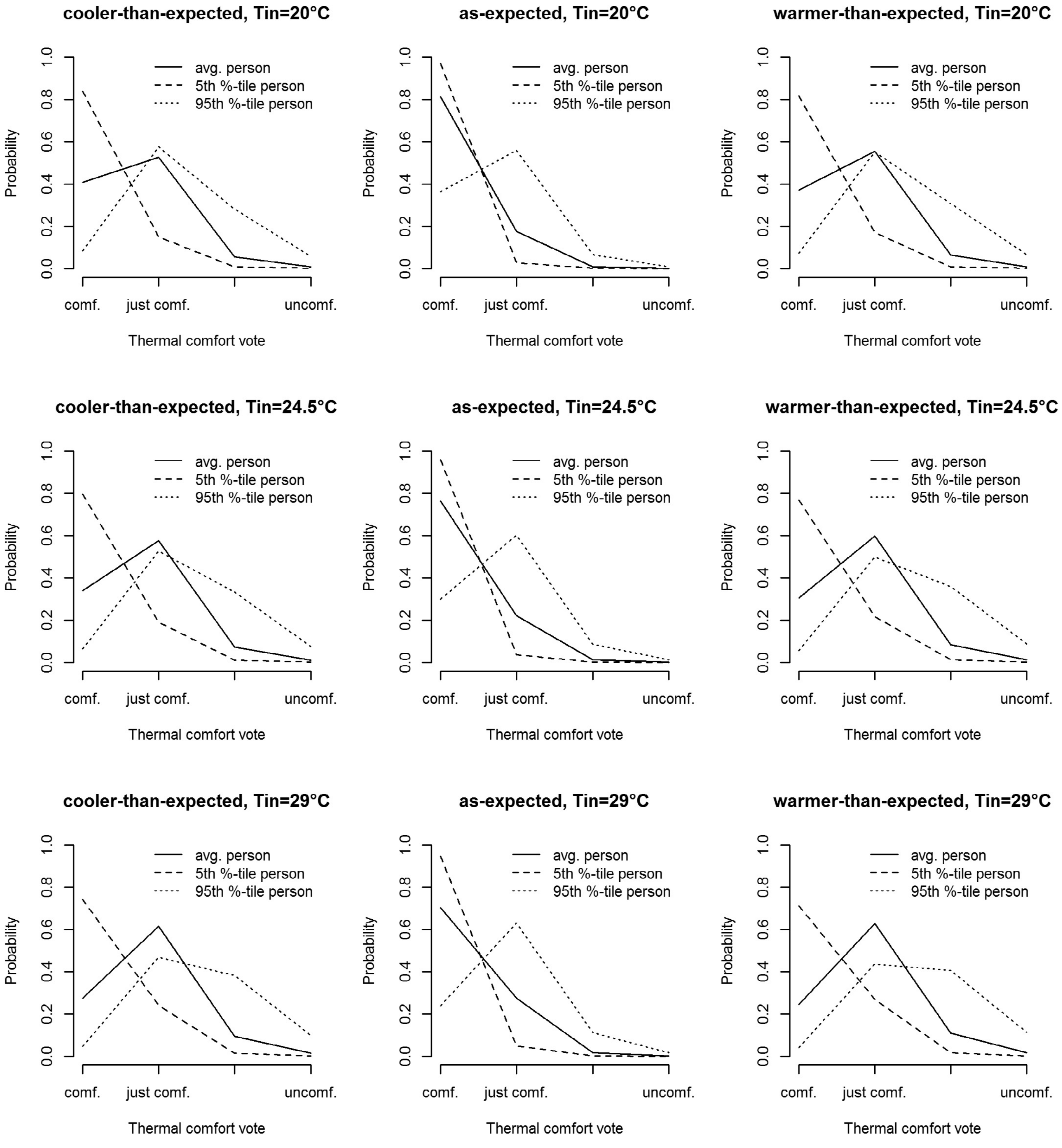

Fig. 7. Predicted probabilities for thermal comfort votes depending on room temperature and level of expectation based on data of field study (Model 4 in Table 2).

While the above analysis solely considered the first expectation and thermal perception vote, the laboratory study allows assessing potential changes in expectations over the course of a day (Fig. 10). The number of unexpected votes increases, but the SET also increases over the day according to the experimental protocol; the number of votes of day and thermal indoor conditions correlated with r = 0.29. Therefore, this data does not permit conclusions whether the increase in unexpected votes is due to the (unnatural) increase in indoor thermal conditions or other factors beyond the scope of this analysis.

5. Discussion

5.1. Results

With respect to research question 1 and hypotheses 1.1 and 1.2, results presented above confirm that the level of expectation has

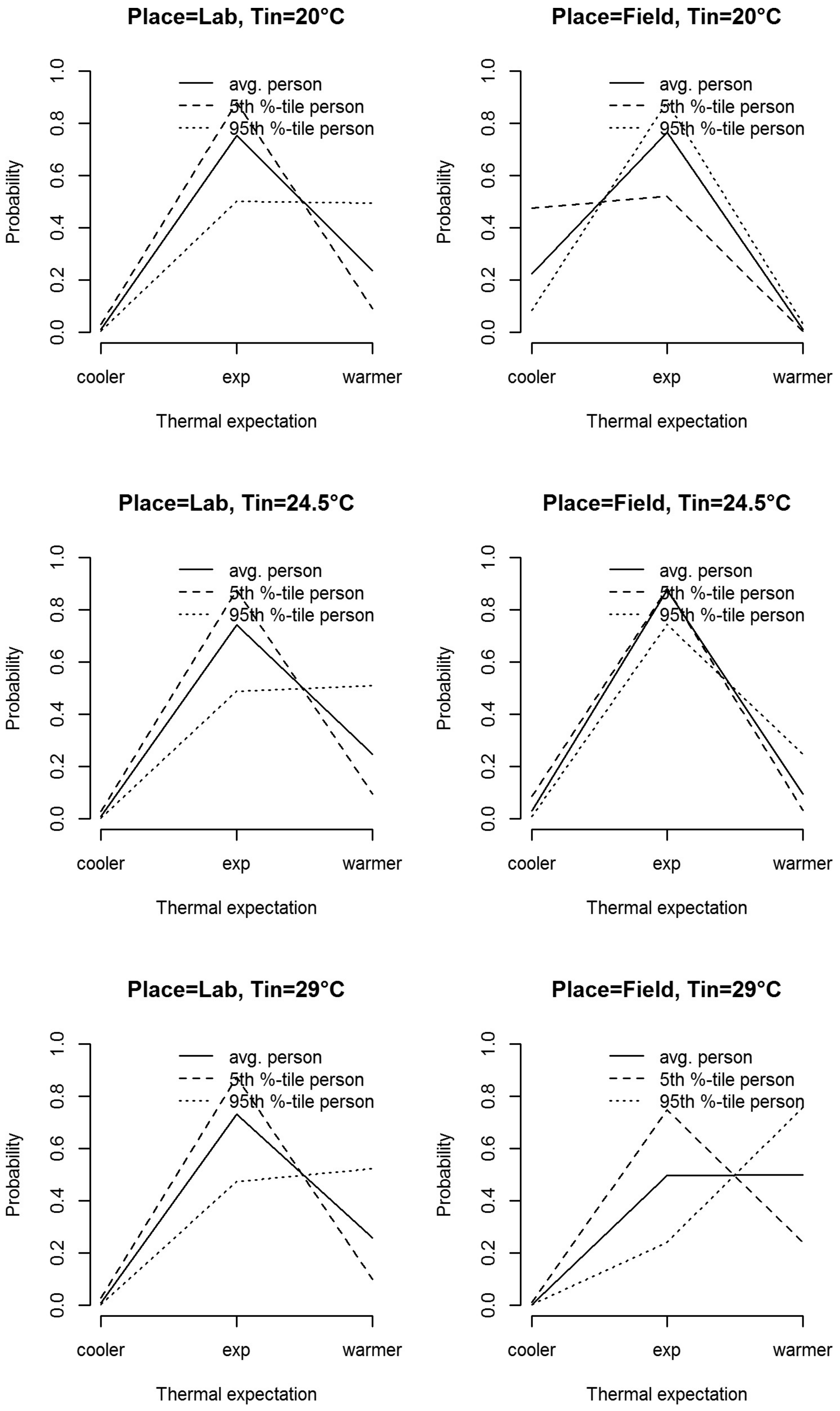

Fig. 8. Predicted probabilities for thermal expectation votes in relation to location (field vs. laboratory) and actual indoor thermal conditions.

an influence on thermal perception. Hypotheses 1.1 and 1.2 are confirmed here, which suggests that the contrast theory [33] is valid also for thermal perception. In contrast to previous studies [6,22], this relationship was shown directly by assessing the congruence between participants' expectations and experience and not by indirect measures (e.g. relating observed differences in the level of thermal sensation or comfort to differences in expectation). As such, the introduced questions seem promising for further applications in order to reveal differences in expectations (e.g. between AC and non-AC buildings). This method of assessing expectations is

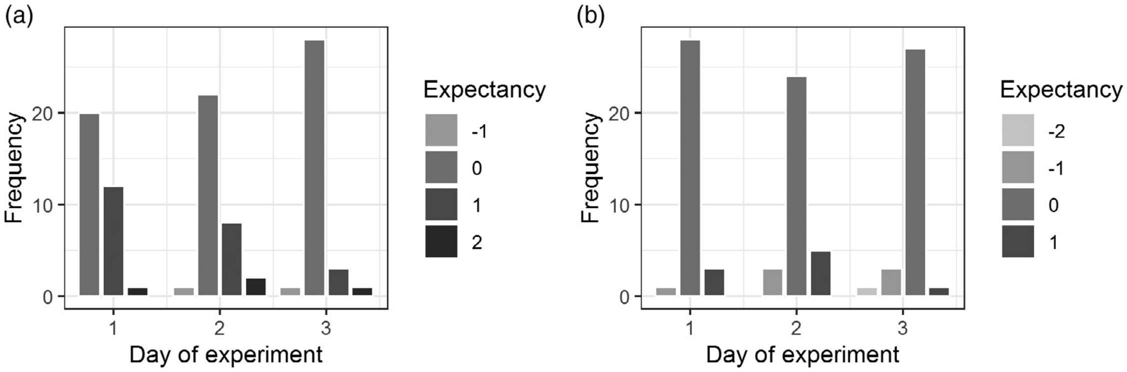

Fig. 9. Comparison of distribution of expectancy votes at each day of experiment for a) laboratory and b) field data.

Table 3
Results of single predictor ordinal mixed effect regression analysis on thermal expectation.

Predictor	AIC	p
Tin	351	<0.0001
Location	373	.0001
Day of experiment	383	.02
Sex	355	.11
Tout	388	.28
Delta Tin - Tout	372	.36

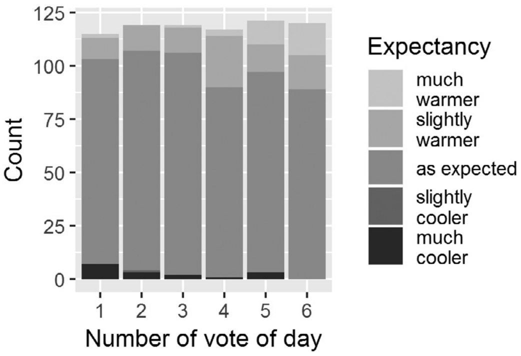

Fig. 10. Distribution of expectancy votes over the course of a day in the laboratory study.

comparable to that applied by Rajkovich and Kwok [16]. Likewise, in the presented study where the "expected" vote had the highest probability, subjects experiencing the arcades expected comfortable thermal conditions before entering the acclimatized space. At the same time, Rajkovich and Kwok found no significant variation in thermal expectations votes between AC and non-AC arcades. Those findings from Rajkovich and Kwok can be explained due to the particular study settings in transitional spaces, where subjects were not aware before testing whether the arcades were conditioned or naturally ventilated and might have expected in general comfortable conditions. Previous information and experience of the acclimatized space may alter participants' expectations of the thermal conditions they will encounter. As previously mentioned, knowledge and beliefs are shapers of people's expectations, so further analysis on how these factors influence expectations and consequently satisfaction is needed.

The true positive rates obtained for this study are higher than those in previous publications. For example, Schweiker and Wagner [9] were the first to report a TPR of 30% for PMV on the ASHRAE RP884 database [44], which was recently supported by a similar figure presented by Cheung *et al.* [45] based on the larger ASHRAE database II [46]. Schweiker and Wagner [47] later showed higher TPR's for SET based comfort predictions compared to PMV based predictions with TPRs for SET based predictions around 50%. The results from the laboratory data set presented here show a TPR for PMV (59.1%), which is higher than that of SET (53.8%), while the TPR of the SET based prediction including expectation is the highest with 62.1%. The reason for the high TPR compared to previous literature can be explained with conditions in the laboratory being more controlled compared to field study data. Still, the TPR for the SET based prediction including expectation for the field dataset (57.9%) is in the same range as that obtained from the laboratory dataset. The comparable TPR signifies that the consideration of expectation is a meaningful addition to existing comfort models. At the same time, these results require an external validation on a separate dataset – preferably obtained from a different climatic context. Such validation would be beyond the scope of this study.

TPRs for thermal comfort votes were even higher (78.8% and 69.1%) than those for thermal sensation votes. Such observation may be explained by the low variance in obtained thermal comfort votes, facilitating the prediction based on a statistical model of the same data set. Related to research question 2, hypothesis 2.1 can be partly confirmed. On the one hand, results show a significant influence of location on the level of expectation. On the other hand, results show that the majority of times, expectations are fulfilled. Even in the laboratory facility, the large majority of votes were "as expected". This may be due to several reasons: participants may

a) not have had specific (conscious) expectations before entering a room, i.e. *unformed* expectations according to Thompson and Sunol (from [28]),
b) have had a rather wide range of expected conditions,
c) have assimilated already their expectations based on processes suggested by the cognitive dissonance theory described introductory [33], or
d) not have been able to express their expectations afterwards.

Based on the existing data, it is not possible to decide, which explanation is correct. Still, the variability in expectations suggests that (1) expectations change over time as already suggested in the reference level model [48] and (2) people are able to compare their previous expectations with their actual experience. Future studies need to explore these questions further, for example by asking people beforehand about their expectations as done by Rajkovich and Kwok [16].

Hypothesis 2.2 can only be partly confirmed. On the one hand, results show that the number of "expected" votes increased with the number of days in the laboratory environment, which supports this hypothesis. On the other hand, the number of "expected" votes does not increase during the day of the laboratory experiments suggesting that also after experiencing a thermal environment, expectations may differ from experiences. The latter could be explained by the protocol of the laboratory studies, which showed in average an increase in indoor temperatures over the day by 0.5 K/hr, which might be beyond the increase, participants experienced in their normal work place with more stable thermal conditions.

Hypothesis 2.3 stated demographic differences in the level of expectation based on previous studies, which suggested that the integration of expectations and sensory experiences differs among individuals. Certain individual variables, such as confidence on own beliefs, may influence the acceptance or rejection of an assertion. Williams [25] found that heterogeneity across individuals could play a role in the effect of expectations in perceptions, by analysing choice patterns between men and women and subject's involvement level in the experiment. Similarly, Bischof *et al.* [26] assessed occupants' expectations in buildings and found significant differences in thermal expectations between sexes: females reported higher expectations towards indoor conditions. In this study, no significant difference was observed between males and females, which may be due to the small sample size or due to the same level of confidence in thermal expectations. The former argument is supported by the p-value of sex in the ordinal multiple regression analysis of 0.11, i.e. close to showing a tendency. A direct comparison between the studies by Bischof *et al.* and this study cannot be done, as the way of measuring expectations differs: Bischof *et al.* [26] defined expectations in relation to the importance each occupant assigned to different aspects of the indoor thermal environment such as humidity, temperature, air velocity, and air quality. Therefore, future studies may need to deal with higher sample sizes in order to re-analyze the effect of sex or assess additional personal variables in case individual differences are the focus of these studies.

Hypothesis 2.4 needs to be rejected based on the presented analysis. Results suggest that indoor conditions have the highest impact whether thermal expectations are met. This applies even for the first vote, only few minutes after entering the room, when participants state their expectation independent of the outdoor conditions or indoor-outdoor temperature difference. This is in contrast to introductory stated hypothesis, that people's expectations are based on outdoor conditions and common indoor conditions. In both studies (laboratory and field), the outdoor indoor difference is up to 14°K. The results suggest that non-professionals do not expect a relationship between indoor and outdoor conditions (anymore) due to stable conditions in most places. This could have implications and could be a barrier for adaptive approaches to room conditioning, which rely on the acceptance of a higher variance of indoor thermal conditions. Nevertheless, such statement is based on a homogenous group of participants, all being adapted to the same climate zone and construction standard. Results may differ for other climate zones or areas with a different construction standard, where the variability in indoor temperatures is higher and expectations potentially different. At the same time, outdoor-indoor temperature difference was not systematically varied in this study. Future studies may aim at systematic variations or test even higher temperature differences and comparing results from different climate zones and prevailing construction standards in order to explore this new assumption further.

5.2. Limitations

The questions used in this study only assess the intensity of agreement/disagreement of expected thermal comfort votes – analogue to thermal sensation, but not the evaluation of the actual condition in comparison to the expected one – which would be analogue to thermal comfort. The question regarding participants expectations applied in this study can be considered as the most straightforward way to ask for their expectations. Future studies need to refine this question and may need a closer analysis regarding the affective judgment of expectation. For example, participants could have expected conditions to be in a certain way, but either be satisfied that their expectations were met or still dissatisfied, because their expectation was that they would be dissatisfied. At the same time, they could be dissatisfied that the conditions are not as expected or – as stated introductory – they could be positively surprised and very satisfied, that conditions are not as expected, but better than expected. Therefore, future studies need to apply at least a two-dimensional method of assessing expectations, similar to assessing thermal sensation (intensity) and thermal comfort (affective) [40]. In order to test additional hypotheses related to expectations arising from the theories of expectation, an additional question assessing participants' evaluation is advisable. Such question could be "are the actual conditions compared to the conditions you expected much more / more / as / less / much less comfortable?".

Further limitations of this study have to be seen in the small sample size and limited variance in participants age and climatic background, which do not allow generalizing the results without further data collection and analysis.

6. Conclusions

This study investigated people's expectations in the built environment and their impact on thermal comfort and sensation by directly assessing the congruence between people's expectations and experience. In addition, influences on people's expectations were analysed. The following findings aroused:

1) People have a wide range of expectations to indoor conditions and results showed that they are mostly met. However, if expectations of the indoor thermal conditions are not met, thermal comfort decreases.
2) Indoor conditions and the amount of previous experiences in the current environment have the highest impact on thermal expectation in contrast to outdoor conditions and indoor-outdoor

The results suggest that non-professionals adapted to the climatic context and the construction standard of this study expect rather stable conditions even in unknown places such as a laboratory. Such expectation could be a barrier for adaptive approaches to room conditioning which rely on the acceptance of a higher variance of indoor thermal conditions. Further research is needed to confirm such observation together with a careful rethinking of current approaches to room conditioning: The often provided small range of indoor conditions in modern buildings influences expectations, so that high efforts might be required to loosen expectations again and promote less energy-intense adaptive approaches with higher fluctuations.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

CRediT authorship contribution statement

Marcel Schweiker: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Software, Supervision, Funding acquisition. **Romina Rissetto:** Writing - original draft, Writing - review & editing. **Andreas Wagner:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition.

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WINDSOR 2020

The effects of occupants’ expectations on thermal comfort under summer conditions

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Abstract: Climate change has led to higher indoor temperatures and more discomfort hours. This fact has encouraged an extensive assessment of users’ thermal comfort in office buildings. However, there is a gap between predicted-actual comfort votes and comfort-related behaviors. One reason could be differences in comfort expectations. This study investigates the impact of users’ expectations of indoor climate and behavioural adaptations on their thermal satisfaction in a working environment. We conducted a pilot study in a laboratory setting, where participants experienced moderately high indoor temperatures in two different appointments. A control group received information about an innovative ceiling fan, which after an acclimatization phase all participants could control. Participants’ thermal comfort and expectation responses were recorded. Results showed that comfort expectations in the first week were significantly different from those in the second week. Moreover, no significant differences were found in expectations of perceived air quality and between groups with different information provided. Results suggest that a first experience in a certain setting would set occupants’ expectations of indoor conditions for a second experience in the same environment. Besides, the implementation of an unknown personalized adaptive strategy fulfilled participants’ expectations of indoor conditions.

Keywords: comfort expectations, thermal comfort, perceived indoor air quality, adaptive behaviours

1. Introduction

In order to reduce the total energy consumption in both commercial and residential buildings, research on the interaction between occupants and building systems has shown high potential to achieve energy improvements. However, a non-occupant-centric design of building systems, could lead to a rebound effect on occupant behavior (Guerra Santin 2013).

In the past two decades, there has been a growing number of studies trying to explain occupant interactions with building systems through the lens of psychological theories (Wilson and Dowlatabadi 2007). Using interdisciplinary research approaches could provide insides into the drivers and decision-making of energy-saving behaviors in buildings without affecting occupant comfort. In other words, energy reduction strategies and comfort standards should consider factors such as occupants’ preferences and expectations, personal and social norms, needs and beliefs.

According to Chappells and Shove (2005) there is a trade-off between occupants’ thermal comfort, energy efficiency and building management requirements in office buildings. Although the discomfort experienced by the occupants will ultimately impact on their willingness to perform energy-efficient behaviors, there is a performance gap between assumed and actual comfort-related behaviors (Brown and Cole 2009). Auliciems (1981) defines satisfaction with an indoor climate as the result from matching actual thermal conditions in a given context and one’s thermal expectations of what the indoor climate should be like in that same context. Therefore, understanding the interaction between thermal expectations and adaptive behaviors seems a possible path to enhance comfort and predict comfort-related behaviors.

In this paper we propose an analysis of occupants' expectations of the indoor climate and its implications on their thermal comfort and behaviors. We focus on the study of influential factors on thermal and behavioral expectations within buildings.

2. State-of-the-art and background

In the built environment, several conceptual models have emerged to understand occupant behaviour and comfort by integrating them within psychological frameworks. For instance, D'Oca *et al.* (2017) integrated the MOA model with the DNAs conceptual framework to understand drivers motivating occupants to interact with building control systems. From another perspective, Schweiker and Shukuya (2009) combine findings from the field of neural science and present a sensor-control-action cycle as theoretical basis of occupant-behaviors. However, the inclusion of occupants' expectations in the prediction of thermal comfort and occupant behaviours has not been extensively assessed.

The work of Auliciems (1981) focuses on a "psycho-physiological model", in which thermal expectations of a certain indoor environment affect occupants' thermal satisfaction. According to the model, past thermal experiences and adaptive opportunities of a building are the main factors that shape occupants' expectations. From another perspective, Fanger and Toftum (2002) include occupants' expectations in the assessment of thermal comfort as a factor of dependence on air conditioning systems, based on the thermal sensation votes for specific warm climatic conditions of natural ventilated buildings.

Although the importance of assessing expectations in the built environment has been pointed by several authors (Fountain *et al.* 1996; Brown and Cole 2009; Luo *et al.* 2018), thermal expectations have been directly measured only by Rajkovich and Kwok (2003), and recently by Schweiker *et al.* (2020). The latter found out that there is a significant influence of the level of expectation on thermal comfort, and that indoor temperature, day of experiment and location (field vs laboratory) showed significant influences on thermal expectations.

According to Wigfield and Eccles (2000), individuals' behaviours can be explained by their beliefs about how well they will do on the activity (expectancies) and the extent to which they value it (evaluation). In other words, a person's attitude towards a behaviour and the valence of the attitude, will guide to a certain behaviour. This cognitive process approach is described in the Theory of Planned Behaviour (Ajzen 1991), which incorporates attitudes as a predictor of behaviours, and are consistently found to have greater predictive validity when they are directed towards a specific behaviour – in comparison to general attitudes (Ajzen and Fishbein 2005).

Moreover, it has been suggested that the magnitude of the attitude–behaviour relation may be moderated not by attitude accessibility but by other correlated factors such as amount of knowledge (Ajzen and Fishbein 2005). From the point of view of consumer satisfaction, Anderson (1973) suggests that a more favourable evaluation is obtained when a product is accurately described than when no information is provided. In this respect, Naddeo *et al.* (2015) analysed the positive effect of knowledge and biased information on higher perceived comfort. Similarly, Brown and Cole (2009) analyse the influence of knowledge of building performance on comfort expectations and behaviours.

However, when a new technology is implemented, there is often a gap between what is known and what actually is put in use. To evaluate the acceptance and adoption of a new idea, theories attempt to explain factors affecting whether individuals will adopt an innovation or technology. The diffusion of innovations (Rogers 1983) describes the innovation-decision process as the process in which an individual passes from first knowledge of a technology to form an attitude towards it, then adopt and implement it, and finally confirm the decision. Those innovations have five main attributes that affect individuals' behaviours and explain the rate of innovation adoption: relative advantage, compatibility, complexity, trialability and observability.

3. Research framework and hypothesis

The review of the state of the art and theories has shown that the interaction between people's expectations and their perception of comfort and behavioural performance has not been studied in depth in the built environment. In addition, influencing factors of expectations and the way to assess them need further study. Therefore, a study framework of expectations is proposed (Figure 1) from which the following research questions arise:

1. To what extent do comfort expectations (thermal conditions and air quality) affect occupants' comfort evaluation and consequently their perceived comfort?
2. Which factors influence people's indoor climate expectations?
3. To what extent do behavioural expectations affect occupants' performance evaluation and their consequently behaviour?
4. Which factors influence people's behavioural expectations?
5. To what extent do behavioural/performance expectations affect the perceived comfort?

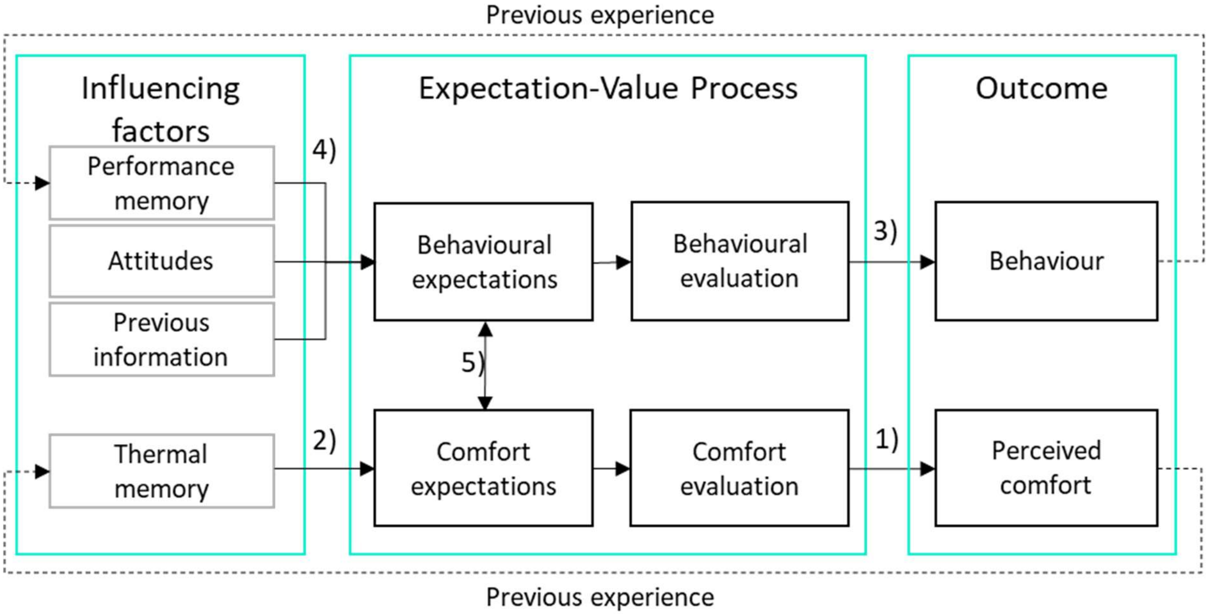

Figure 1: Psychological framework of expectations, comfort and behaviour.

Based on the existing literature and the proposed research framework and questions, the following hypothesis are investigated:

1.
    1.1. Perceived comfort: thermal comfort and perceived air quality will be lower when conditions were not as expected (Schweiker *et al.* 2020).

2.
    2.1. Thermal memory: first experiences in a certain environment will set expectations in a later experience in the same environment (Auliciems 1981).

3.
    3.1. Behaviour: behavioural adaptation will be lower when performance evaluation has a low value and expectations are not met (Wigfield and Eccles 2000).
4.
    4.1. Performance memory: first experiences with a certain behaviour will set expectations in a later performance (Auliciems 1981).
    4.2. Attitudes: positive attitudes towards behavioural performance will positively influence performance evaluation (Ajzen and Fishbein 2005).
    4.3. Previous information: knowledge and previous information will set positive performance expectations and consequently perceived comfort (Naddeo et al. 2015).
5.
    5.1. Behaviour-comfort expectations: negative expectations on the effect of adaptive opportunities on indoor climate conditions (temperature/air quality) will lower comfort expectations and consequently perceived comfort.

In order to avoid misleading interpretations of consumers' satisfaction and evaluation of a certain product (Kokthi and Kelemen-Erdos 2017), we need a common definition of expectations. The following definitions will be used in this paper:

- Predicted expectation: the realistic and anticipated thermal or behavioral experience, i.e. what the user believe will happen, in accordance to the definition from Thompson and Sunol (1995).
- Level of expectancy: congruence between the predicted thermal or behavioral experience, and the actual perceived experience (e.g. "is the temperature as expected?"), in accordance to Schweiker *et al.* (2020).
- Compared expectations: the actual vote of the thermal or behavioral experience in comparison to predicted expectation (e.g. "warmer than expected"). For the thermal assessment, both thermal comfort and sensation will be assessed.

4. Methodology: pilot study

In order to first assess the above research questions, a pilot study was conducted as explain below.

4.1 Facility and test conditions

The experiment was conducted between August and September 2018 in the climate chamber LOBSTER (Schweiker *et al.* 2014). Two office rooms and an entrance-/control room constitute the facility (Figure 2). Each room has two openable windows and is equipped with an innovative personalized ceiling fan, which has a diameter of 300 mm and is integrated in an acoustical ceiling panel (Figure 3).

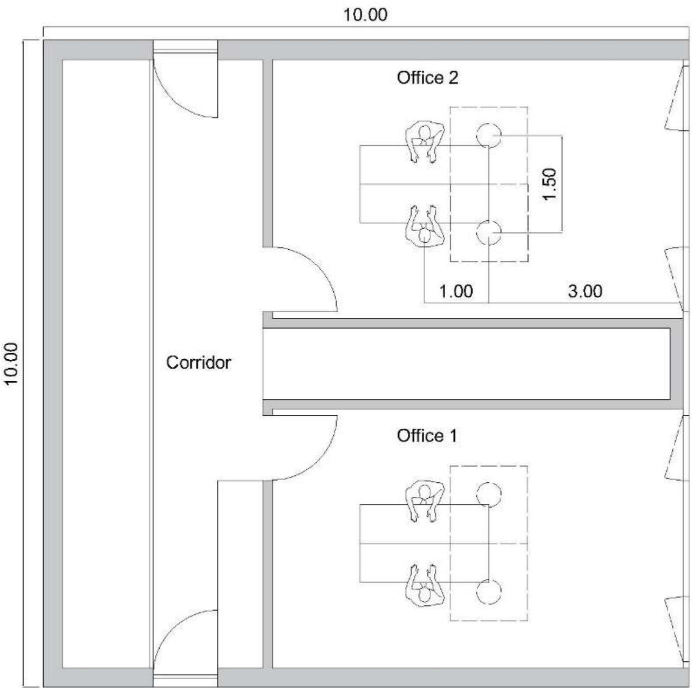

Figure 2: Floor plan and position of participants, ceiling fan and windows

Figure 3: Office room 2

Table 1 presents the room conditions and the correspondent control and experimental groups. Each subject participated twice. The room was set to warm conditions. The first appointment (M1) was set to 28°C / 50% RH, and in the second appointment (M2), only one room was set to 31°C / 50% RH. In the first appointment, half the participants were provided biased information about the personalized ceiling fan, such as benefits (energy efficient, quiet) and characteristics (personal, controllable).

Table 1: Thermal conditions and information groups for first (M1) and second (M2) appointments. Informed group (green); non-informed group (light green); 28°C (purple); 31°C (grey).

M1	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6	
Office	1	2	1	2	1	2	1	2	1	2	1	2
Participant	1, 2	3, 4	5, 6	7, 8	9, 10	11, 12		13, 14		15, 16	17, 18	
M2	Day 7		Day 8		Day 9		Day 10		Day 11		Day 12	
Office	1	2	1	2	1	2	1	2	1	2	1	2
Participant	1, 2	3, 4	5, 6	7, 8	9, 10	11, 12		13, 14		15, 16	17	

4.2 Participants

Eighteen male and female participants between 18-34 years old took part in a half-day experiment for the first test condition, from whom 17 repeated the experiment in the second appointment. Participants had to be German or show proficiency level of the German language, and be non-smokers.

4.3 Experimental procedure

The whole experiment lasted 3 hours 30 minutes, from 9 am to 12.30 am.

Figure 4 describes the daily schedule. In the first 10 minutes (T0) we explained the experiment in the front room and we provide a first questionnaire in paper format. Participants were asked about their a) thermal preference and b) their thermal expectations in the experiment room.

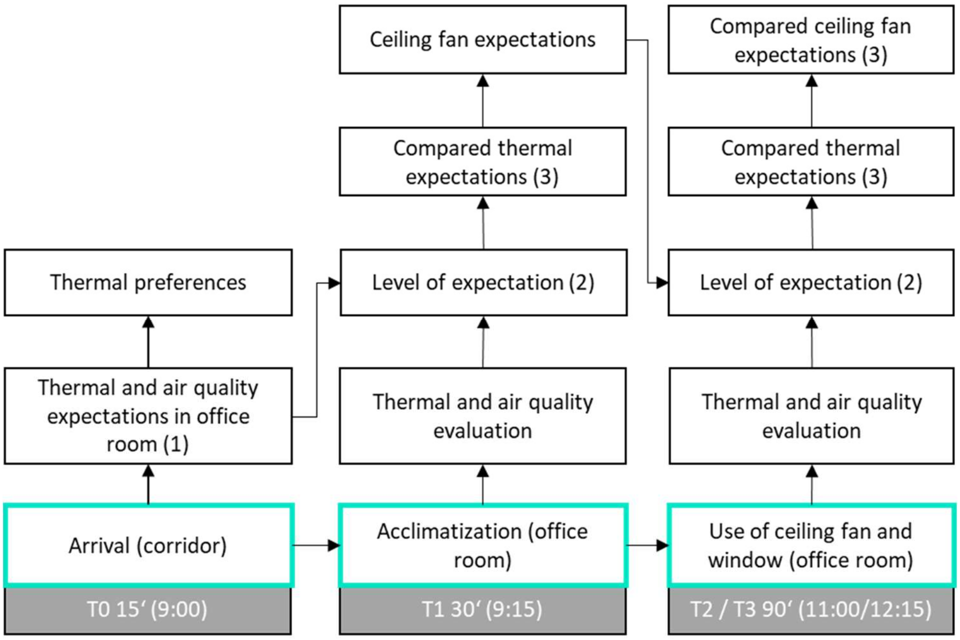

Figure 4: Daily schedule and correspondent questions. In grey: phase duration and start time questionnaire. T0: before entering the experiment room; T1: acclimatization phase; T2: first hour with the possibility of using the ceiling fan/windows; T3: end of experiment.

After entering the room, participants could work on their own tasks with the computers provided. During the first 30 minutes (T1), they adapted to the given warm conditions in the room and filled out the second questionnaire. Participants were asked about a) their actual thermal comfort, sensation, acceptability and preference, and air quality sensation and comfort, b) if the encountered thermal/air quality conditions were as expected, c) their thermal/air quality expectations in comparison to the actual vote, and d) their expectations about general ceiling fans and the personalized ceiling fan from the experiment.

After the acclimatization phase, they had the possibility to turn on the ceiling fan and choose the desired air speed by means of a control dial, and tilt the windows. After 90 minutes (T2) a new questionnaire with the same questions as T1 was provided. The last questionnaire was filled 15 minutes before ending the experiment (T3).

Ceiling fan’s expectations were quantified with several items based on Rogers’ main attributes of innovations in a 7-point scale (“strongly agree” to “strongly disagree”). Moreover, 5 categories were assessed: expectations of ceiling fans in general, expectations of personalized ceiling fans, compared expectations of personal ceiling fans (only in M2), importance of using ceiling fans and attitudes towards the use of ceiling fans. Thermal and air quality expectations were quantified as follow:

1. Predictive Sensation/Comfort 7-point scale (only in T0): “How do you expect the thermal conditions/air quality in the room?“ [“warm/good” to “cold/bad” and “uncomfortable” to “comfortable”].
2. Skip logic question: “Are the encountered thermal conditions/air quality as expected?” [“Yes/No”];
3. Sensation 7-point scale: “If not as expected, how were the thermal conditions/air quality in comparison to the expected?” [“much warmer/much better as expected” to “much cooler/worse as expected”];
4. Comfort 7-point scale: "If not as expected, how do you find the thermal conditions/air quality in comparison to the expected?” ["much more uncomfortable as expected” to “much more comfortable as expected”].

5. Results and Discussion

5.1. Outdoor temperature

Figure 5 shows the outdoor temperatures from 8 am to 9 am and the running mean outdoor temperature (Trm) for the first (Day 2 to Day 6, Day 9) and second appointment (Day 11 to Day 13, Day 16 to 18). In both weeks, outdoor temperatures fluctuated from 15°C to 23°C from 8 am to 9 am. The Trm did not significantly vary along the experimental days in each appointment, but a decrease can be observed comparing the first and the last days of experiment.

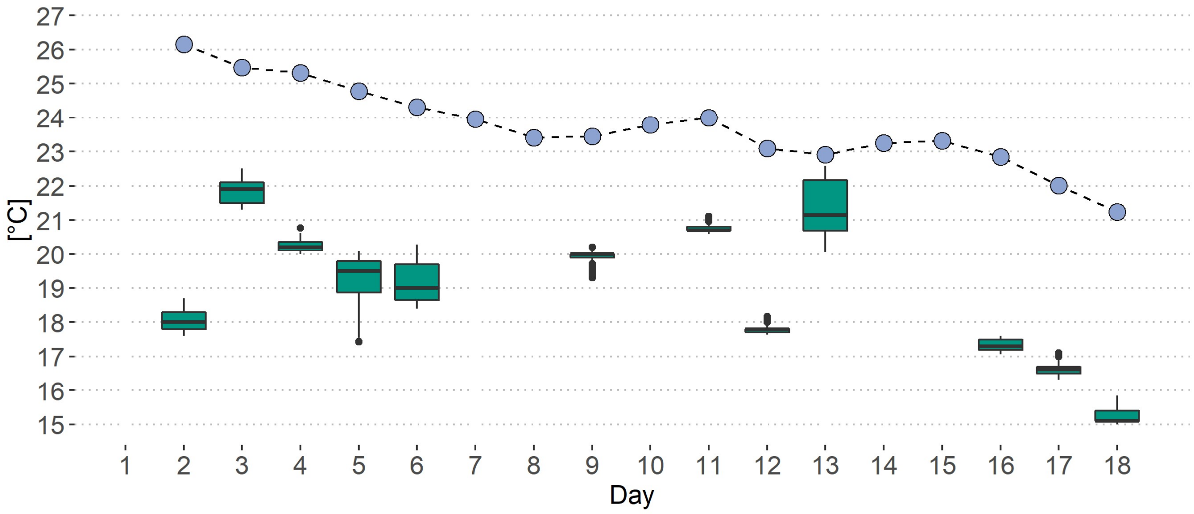

Figure 5: Boxplot of outdoor temperatures for each day of experiment between 8-9:00 am and running mean outdoor temperatures in M1 and M2.

5.2. Thermal comfort and perceived air quality

5.2.1. Temperature sessions

Figure 6 presents the distribution of thermal sensation votes in the acclimatization phase (T1) separately for session groups (paired). The group experiencing 28°C in both appointments voted in average “slightly warm” and “warm” with no significant difference (Figure 6 left).

A significant difference in thermal sensation votes was found for the group experiencing 28°C in the first appointment and 31°C in the second appointment (Figure 6 right). They rated thermal conditions as “slightly warm“ and “warm” respectively (M1: Mdn = 5; M2: Mdn = 6; p = .039; N = 10). A significant difference was also found for thermal acceptability and preference votes: the first experience was rated as “slightly acceptable” while the second as “slightly unacceptable” (M1: Mdn = 3; M2: Mdn = 2; p = .016; N = 10). They would prefer thermal conditions “slightly cooler” and “cooler”, for the first and second appointments respectively (M1: Mdn = 3; M2: Mdn = 2; p = .008; N = 10).

Air quality was perceived as “slightly bad” and “slightly uncomfortable” in the acclimatization phase (T1) in both sessions and no significant difference in perceived sensation between temperature conditions was found.

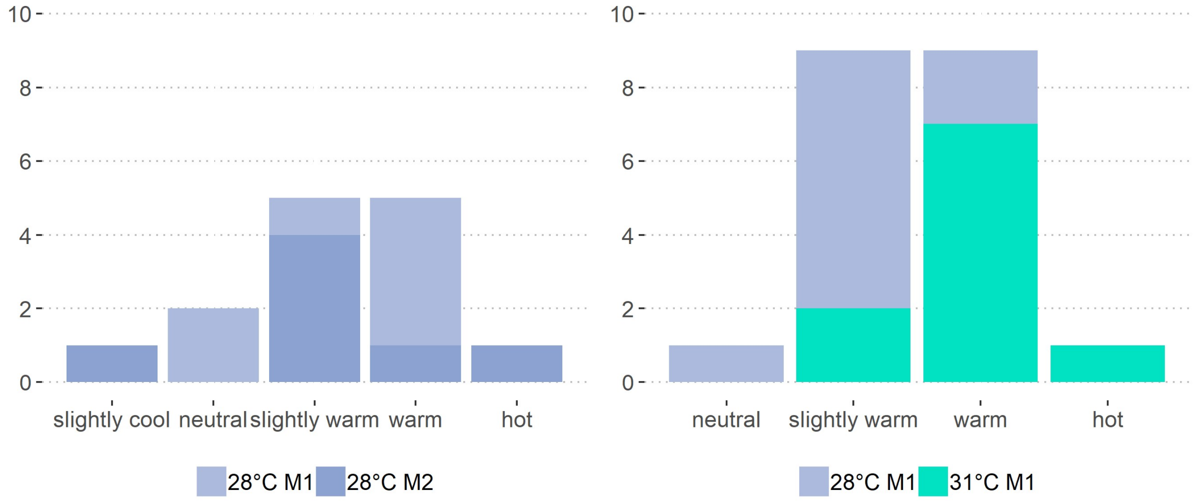

Figure 6: Thermal sensation votes for different session groups in T1. Group experiencing 28°C-28°C for the first and second meeting respectively (left) and group experiencing 28°C-31°C respectively (right).

5.2.2. Timing

Figure 7 presents the distribution of thermal sensation votes for the acclimatization phase (T1), the first hour after the acclimatization phase (T2) and after two hours (T3), separately for the first session and the second session at both temperature conditions (28°C and 31°C). While T1 was mostly rated as "slightly warm" and "warm" (31°C), both T2 and T3 were rated as "neutral".

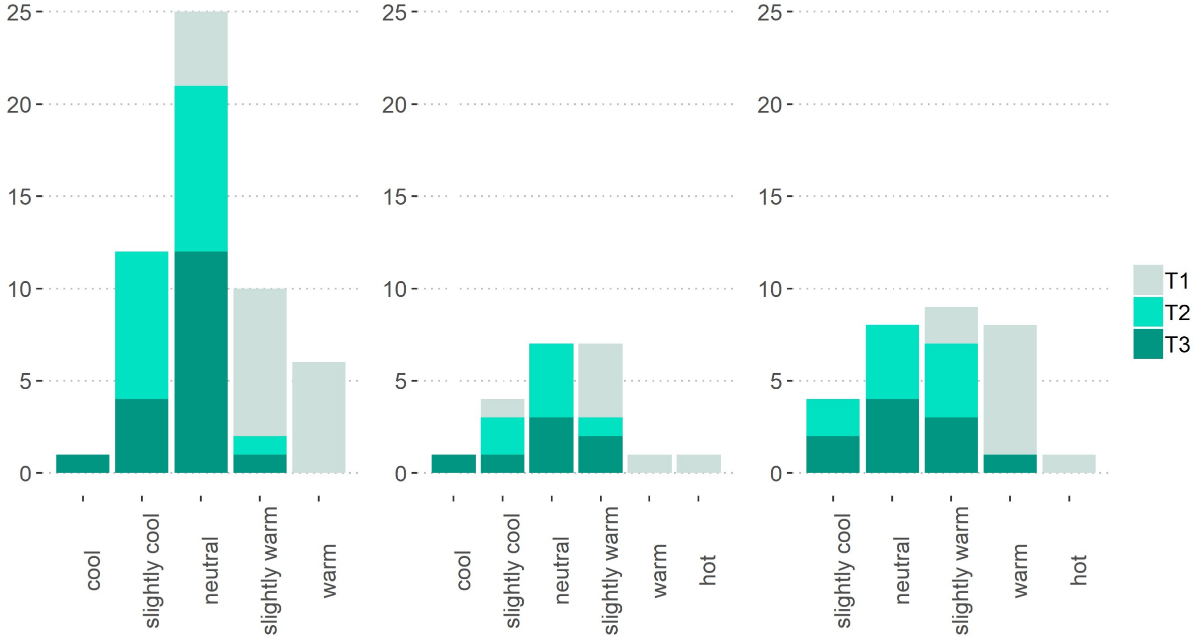

Figure 7: Thermal sensation votes for different times (T1,T2,T3) for the first session (left) and the second session for the 28°C group (middle) and the group with 31°C (right).

Table 2 compares thermal sensation, comfort, acceptability and preference votes in timing for both appointments (M1 and M2). In both sessions, a significant difference for sensation, comfort and acceptability was found between T1 and T2 and T1 and T3, but no difference was found between T2 and T3. In both sessions, a significant difference for thermal preference was found between T0 (Mdn="no change") and T1 (Mdn-28°C= "slightly cooler"; Mdn-31°C="cooler"), T1 and T2 (Mdn= "no change") and T1 and T3 (Mdn= "no change").

Table 2. Friedman test for thermal sensation, comfort, acceptability and preference of perceived thermal conditions. Paired groups correspond to four points in time (T0, T1, T2, T3) in M1 and M2. Significant values (p-values), effect size (r-values) and non-significant results (NS).

	M1				M2			
	T0 –T1	T1 - T2	T1 - T3	T2 - T3	T0 - T1	T1 - T2	T1 - T3	T2 - T3
Sensation	-	$p_{adj.}$= .000 r = .31	$p_{adj.}$ = .001 r = .28	NS	-	$p_{adj.}$ = .001 r = .31	$p_{adj.}$ = .003 r = .27	NS
Comfort	-	$p_{adj.}$= .018 r = .22	$p_{adj.}$ = .003 r = .26	NS	-	$p_{adj.}$ = .000 r = .31	$p_{adj.}$ = .002 r = .29	NS
Acceptability	-	$p_{adj.}$ = .008 r = .24	$p_{adj.}$ = .003 r = .26	NS	-	$p_{adj.}$ = .001 r = .31	$p_{adj.}$ = .008 r = .25	NS
Preference	$p_{adj.}$ = .000 r = .34	$p_{adj.}$ = .022 r = .29	$p_{adj.}$ = .033 r = .28	NS	$p_{adj.}$ = 001 r = .40	$p_{adj.}$ = .000 r = .44	$p_{adj.}$ = 005 r = .36	NS

Table 3 presents differences in the perceived air quality sensation and comfort for different points in time for both sessions (M1, M2). Most significant differences were found in the perceived sensation and comfort between T1 (“slightly bad”; “slightly uncomfortable”) and T2 (“slightly good”; “comfortable”) and between T1 and T3 (“good”; “comfortable”).

Table 3. Friedman test for sensation and comfort of perceived air quality. Paired groups correspond to three timings (T1, T2, T3) in M1 and M2. Significant values (p-values), effect size (r-values) and non-significant results (NS).

	M1			M2		
	T1 - T2	T1 - T3	T2 - T3	T1 - T2	T1 - T3	T2 - T3
Sensation	**$p_{adj.}$= .006 r = .24**	**$p_{adj.}$ = .011 r = .23**	NS	**$p_{adj.}$ = .024 r = .22**	**$p_{adj.}$ = .001 r = .29**	NS
Comfort	**$p_{adj.}$= .037 r = .20**	**$p_{adj.}$ = .037 r = .20**	NS	NS	**$p_{adj.}$ = .001 r = .30**	NS

5.2.3. Previous information

Thermal comfort and perceived air quality was analysed between ‘information’ groups in the first appointment. Although, they rated thermal comfort in the acclimatization phase differently (Mdn= “slightly warm” and “warm”), no significant difference in thermal perception (comfort, sensation, acceptability and preference) and in perception of indoor air quality (comfort and sensation) between groups was found both in the acclimatization phase and along the experiment.

5.3. Expectations of indoor climate

Table 4 presents the median votes for expected thermal comfort and sensation before entering the experimental room (predictive expectation), the level of expectancy after entering the room, the actual vote compared to expectations (compared expectation) and the actual vote in the acclimatization phase.

Table 4: Median votes for predictive expectation, level of expectancy, compared expectations and thermal comfort and sensation votes in T0 and T1 for M1 and M2.

	M1				M2			
	T0	T1			T0	T1		
	Predictive	Level	Compared	Vote	Predictive	Level	Compared	Vote
	28				**31**			
Sensation	slightly cool	no	slightly warmer	slightly warm	warm	no	warmer	warm
Comfort	neutral		slightly more uncomfort.	slightly uncom fort	slightly comfort.		slightly more uncomfort.	uncomfort.
	28				**28**			
Sensation	slightly cool	no	warmer	warm	warm	yes	as expected	slightly warm
Comfort	slightly comfort.		slightly more uncomfort.	slightly uncom fort.	slightly uncomfort.		as expected	slightly uncomfort.

Table 5 presents the median votes for level of expectancy, compared expectation for air quality comfort and sensation and the actual comfort and sensation vote in T1, and level of expectancy for T2 and T3. No significant difference was found in the level of expectancy in the acclimatization phase between temperature groups in the second appointment.

Contrary to previous studies (Zhai *et al.* 2017), sensation and comfort votes for perceived air quality in the acclimatization phase did not significantly differ between temperature setting. Moreover, the level of expectancy did not differ between 28°C and 31°C room settings in the second appointment. These results could suggest that 1) expectations do not have an impact on the perception of air quality at moderately high indoor temperatures, or 2) that expected conditions were within the acceptability range of participants. Further analysis is needed to confirm the proposed observation.

Table 5: Median votes for level of expectancy, compared expectations and comfort and sensation votes for air quality in T1, T2 and T3 for M1 and M2.

	M1					M2		
	T1			T2	T3	T1	T2	T3
	Level	Compared	Vote	Level	Level	Level	Level	Level
	28					**31**		
Sensation	no	slightly worse	slightly bad	yes	yes	yes	yes	yes
Comfort		slightly more uncomfortable	slightly uncomfortable					
	28					**28**		
Sensation	no	slightly worse	slightly bad	yes	yes	yes	yes	yes
Comfort		slightly more uncomfortable	slightly uncomfortable					

5.3.1. Perceived comfort and sensation

In the first appointment, the encountered thermal conditions were not as expected (Mdn=”no”). The group expecting “slightly comfortable” conditions rated the encountered thermal conditions as “warmer as expected” and the actual vote was “warm”. However, the group expecting “neutral” conditions rated the same thermal conditions as “slightly warmer as expected” and the actual vote was “slightly warm”. With respect to hypothesis 1.1, an effect of expectations can be observed on thermal comfort votes in both groups from the first appointment: under same expected thermal sensation votes but different expected thermal comfort in the acclimatization phase, the group expecting more comfortable conditions had a higher disparity with the encountered conditions (not as expected), resulting in warmer thermal sensation votes. These results suggest the importance of assessing previous and compared expectations in a two-dimensional way, i.e. asking about the intensity of expectations (e.g. "warmer as expected") and affective aspect (e.g. "more comfortable as expected").

5.3.2. Thermal memory

In the first appointment, conditions were unknown and expected as "slightly cool" before entering the room (T0). However, in the second appointment conditions were expected to be "warm". A significant difference in the expectancy of sensation in T0 was found between the first session with 28°C, expecting "slightly cool" conditions, and the same group participating the second session with 31°C, expecting "warm" (Paired sample sign test, M1: Mdn = 3; M2: Mdn = 6; p = .039; N = 10). Similarly, a significant difference in the expectancy of comfort in T0 was found between the first session with 28°C, expecting "slightly comfortable" conditions, and the same group participating the second session with 28°C, expecting "slightly uncomfortable" (M1: Mdn = 5; M2: Mdn = 3; p = .016; N = 7).

With respect to hypothesis 2.1, an effect of thermal history on expectations can be observed after repeating the experiment. After experiencing an unknown environment for the first time, participants expected a "slightly cool" and "slightly comfortable" conditioned room. After knowing the environment, participants were expecting the same thermal conditions in the second appointment as the one they experienced in the first appointment ("warm"/"slightly uncomfortable"). These results could suggest that a first experience in a certain indoor environment would set expectations of indoor conditions for a second experience in the same environment, under similar thermal outdoor conditions between appointments. This statement is in line with the model from Auliciems (1981) which includes previous thermal experiences as influencing factors of expectations. Moreover, it is of importance to mention that the preferred indoor conditions in comparison to the outdoor conditions before entering the experimental room was rated as "neutral" for all sessions, meaning that outdoor temperature conditions before entering the climate chamber were within the acceptable thermal conditions, and no effect of outdoor conditions was expected for the sessions. These results support previous work (Schweiker *et al.* 2020) where the outdoor temperature or the outdoor-indoor temperature difference did not have an impact on thermal expectations. Future analyses could focus on the effect of a higher range of outdoor temperatures within thermal expectations.

In the second appointment, although both conditions were expected to be "warm", the session with 28°C expected "slightly uncomfortable" thermal conditions, while the session with 31°C expected "slightly comfortable" thermal conditions (Mann-Whitney-U-Tests, 28°C: N = 7; Mdn = 3; 31°C: N = 10; Mdn = 4.5; U = 17.000; p = .088; r = 0.44). An influence of thermal memory on performance expectations can be observed in group experiencing 31°C in the second appointment, who expected to feel "slightly comfortable" despite the expected warm conditions. These results may suggest that, as the effect of adaptive opportunities (window and ceiling fan) was sufficient to achieve comfortable conditions in a warm environment in the first appointment, participants set their expectations for the second appointment by adjusting the memory related to previous experiences or fulfilled expectations, and consequently minimizing thermal discomfort. These results support the analysis from Luo *et* *al.* (2016), suggesting the implementation of effective adaptive strategies to expand and enhance occupants' comfort range. A potential link between performance expectations and perceived comfort could be proposed according to hypothesis 5.1.

In the second appointment, a significant difference in the expected conditions in T1 was found between the sessions. Participants from the session with 28°C "expected" the encountered thermal conditions, while the session with 31°C did "not expect" them (Mann Whitney-U-Tests; 28°C: N=7, Mdn = 1; 31°C: N=10, Mdn = 0; U = 13.500; p = .033; r = 0.61). This result indicates the influence of significant changes in indoor temperatures on level of expectation of thermal conditions in an already known environment.

5.3.3. Timing

Figure 8 presents the distribution of the expected thermal conditions at three times of the half day. A pairwise comparison was conducted (N = 9; p = .017; χ^2 = 10.15) and a significant difference in expected conditions was found in the first session between the acclimatization phase and the first hour of experiment after opening the window ($p_{adj.}$ = .24; r = .22), but no difference at the 5% level was found after using the ceiling fan or at the end of the experiment. Although, no significant difference at the 5% level was found in the second session between points in time, Cochran-Q-test found differences between all T1-pars (N = 11; p = .037; χ^2 = 8.50). As before mentioned, thermal expectations in a warm environment were fulfilled as adaptive behaviors were implemented.

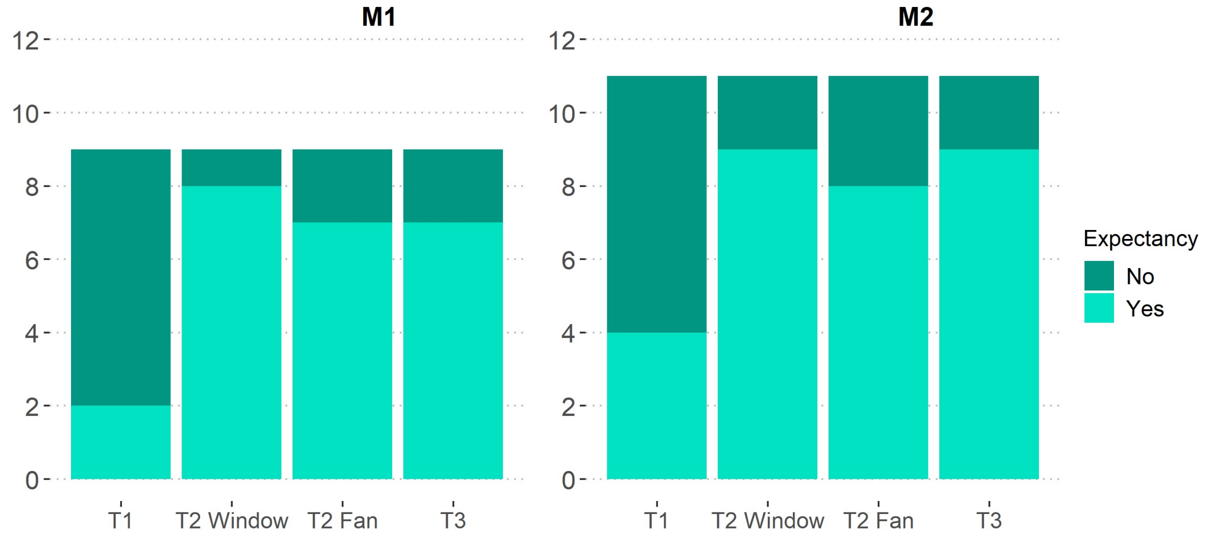

Figure 8: Level of expectancy votes for different times: T1, T2 after using the window, T2 after using the ceiling fan and T3 for M1 and M2.

5.4. Behavioural adaptation

The interactions of windows and ceiling fans was recorded by self-reported actions by participants. Figure 9 presents the number of participants who opened the window, used the ceiling fan and performed both actions during the experiment.

In the first appointment, half the participants use the ceiling fan and the other half both the ceiling fan and window. Just one person reported the opening of window as single action. In the second appointment, almost half the participants in the room with 28°C used the ceiling fan as single action while the other half performed both actions. Contrarily, by 31°C almost all participants performed both actions.

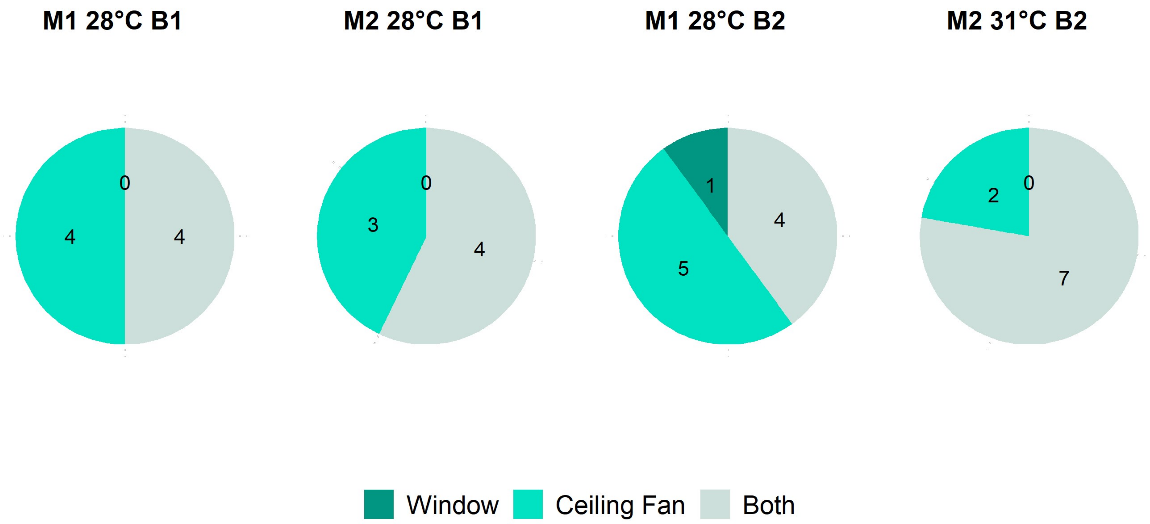

Figure 9: Number of participants who opened the window, turned on the ceiling fan and performed both actions during the day separately for M1 and M2 and temperature settings. B1: office 1; B2: office 2.

5.4.1. Performance expectations

The performance expectations of general ceiling fans and of the personal ceiling fan used in this study were analysed. Results from a reliability test and an exploratory factor analysis are shown in Table 6. Reliability test indicates internal consistency for the scale in this specific sample. Although, values lower than 0.7 indicate an unreliable scale, when measuring psychological constructs lower values can be expected due to the diversity of constructs being measured (Field *et al.* 2012). Moreover, as the number of items measuring each construct are within the recommended, a lower threshold can be expected (Hair *et al.* 2014). For this sample, results indicate good reliability of the scales, except for “importance of personalized ceiling fans” and “attitudes towards ceiling fans” in the first appointment.

KMO values indicate the sampling adequacy for each variable in the model and the complete model. As indicated by Field *et al.* (2012), values greater than 0.5 are barely acceptable, and between 0.7 and 0.8 are acceptable. All variables presented in this study present acceptable adequacy.

Table 6: Cronbach α values from reliability test and KMO values from explanatory factor analysis. GFC: general ceiling fans; PCF: personal ceiling fans. In bold: reliable scale and adequate sampling.

Cronbach α / KMO	M1		M2	
	T1	T2	T1	T2
Expectations GCF	**.729 / .617**	**.770 / .692**	**.869 / .705**	**.839 / .748**
Expectations PCF I	**.746 / .583**	**.744 / .650**	**.876 / .820**	**.899 / .659**
Expectations PCF II			**.784 / .698**	**.702 / .624**
Importance of PCF	.612 **/ .639**		**.866 / .711**	
Attitudes towards GCF	.651 **/ .540**		**.910 / .660**	

Correlations were calculated using Kendall-Tau-b- und Spearman-Rho-Coefficients for correlations between a metric (factors) and ordinal variables. In the acclimatization phase (T1), expectations of personalized ceiling fans are positively correlated to the importance of characteristics and performance of a personalized ceiling fan in both appointments (M1: r=.63, M2: r=.89, p (two-tailed) <.05).

Comparing the acclimatization phase (T1) and after using the ceiling fan (T2), expectations of general ceiling fans in T1 are significantly correlated with the expectations of ceiling fans in T2 (M1: r=.77, M2: r=.81, p (two-tailed) <.05) and the expectations of personalized ceiling fans in T2 (M1: r=.52, M2: r=.83, p (two-tailed) <.05). Similarly, attitudes towards general ceiling fans in T1 are significantly correlated with the expectations of ceiling fans in T2 (M1: r=.52, M2: r=.76, p (two-tailed) <.05).

Only in the second appointment, attitudes towards ceiling fans correlate with expectations of personalized ceiling fans in T2 (r=.74, p (two-tailed) <.01). Moreover, attitudes and expectations of ceiling fans in T1 significantly correlate with the compared expectations of personalized ceiling fans in T2 (Expectations: r= .72, p (two-tailed) <.01; Attitudes: r=.56, p (two-tailed) <.05).

Related to hypothesis 4.1, expectations of ceiling fans in the acclimatization phase correlate with expectations of general fans and personalized ceiling fans after using them, but correlation factors are higher in the second appointment in comparison to the first one. These findings could suggest that 1) expectations were fulfilled when using the ceiling fan in terms of personal control, effectivity and improvement of indoor conditions, and 2) expectations of an unknown technology, in this case an innovative personalized ceiling fan, changed and were more aligned with expectations after a second experience, when compared to the first experience. These suggestions align with the work from Auliciems (1981), suggesting that first experiences with personalized ceiling fan will shape performance expectations for a second experience with the same device.

With respect to the factor analysis results, low KMO values for attitude in the first appointment could indicate unformed attitudes before performing adaptive behaviours, showing low correlation values as well. However, for the second appointment participants could form attitudes towards the use of ceiling fans, which seem to influence performance expectations of general and personal ceiling fans. These results indicate to support hypothesis 4.2 and suggest that attitude towards a specific adaptive behaviour may be shaped and positively influenced after its implementation in a second experience. Furthermore, attitudes and expectations of personalized ceiling fans before its usage correlate with the compared expectations of personalized ceiling fans after using them, showing a positive correlation between the expected performance and expressed attitudes with the fulfilled expectations after using the device. These findings show the effect of attitudes and expectations on performance evaluation, aligned with the work of Ajzen and Fishbein (2005).

Related to hypothesis 4.3, the influence of information on perceived comfort can be discarded for this study, contrary to the work of Anderson (1973) and the study from Naddeo *et al.* (2015). As no significant difference was found between performance expectations of the ceiling fan, the effect of information on the perceived comfort – either thermal or air quality – cannot be assumed. Further analysis should rethink the way previous information was provided and a more specific link between information and its effects on perceived comfort should be proposed.

An effect of expectations on behavioural adaptation (hypothesis 3.1) is suggested by the correlation between expectations and performance importance of a personal ceiling fan for both appointments. This evidence reflects the expectancy-value theory (Wigfield and Eccles 2000), which in this case relates the expectation of using the personalized ceiling fan (likelihood) with the importance assigned to perform certain behaviour (evaluation). Besides, results suggest a methodology to assess performance expectations based on the Theory on Diffusion of Innovation (Rogers 1983) and the Theory of Planned Behaviour (Ajzen 1991) for this specific technology. Further studies may assess the effects of the expectancy-value process on the performance of adaptive behaviours and test the proposed methodology for other adaptive behaviours.

5.5. Limitations

Limitations have to be seen in the small sample and limited variance which 1) do not allow a generalization of results and the interpretations of values from the reliability test and factor analysis. Furthermore, the relationship between performance expectations and perceived comfort has not been directly assessed and could be a missing link to fulfil the gap between comfort-related behaviours and actual comfort votes. Finally, other influencing factors could be incorporated in the analysis of expectations.

6. Conclusion

This study investigated people's expectations in the built environment, their influencing factors and their impact on perceived comfort and comfort-related behaviours. The following suggestions emerge:

1) a methodology to assess thermal and performance expectations is presented, by directly asking participants about their perceived expectations and the compared expectations. Furthermore, the importance of assessing thermal expectations in a two-dimensional way (comfort and sensation) is stressed.
2) previous experiences in the current environment showed an effect on thermal expectation and performance expectations.
3) attitudes and values towards a certain technology may set performance expectations and impact on behavioural adaptation.
4) biased information given about the performance of an unknown adaptive strategy did not seem to influence later behavioural expectations.

The results suggest that occupants' expectations of indoor conditions may relax in a known environment, but significant changes in indoor temperatures are the most sensitive parameter influencing expectations. Although occupants' expectations range may vary among them, personalized adaptive behaviours tested in this study were effective enough to overcome the disparity in expectancy disconfirmation. Moreover, attitudes and performance expectations of an unknown adaptive behaviour were quickly shaped after a single usage and not by previous knowledge, which may provide guidance to promote high-comfort and energy-efficient adaptive approaches.

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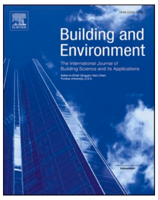

Assessing comfort in the workplace: A unified theory of behavioral and thermal expectations

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ABSTRACT

Assessing comfort and predicting occupant behavior in the workplace has been a major topic within built environmental research. Despite the vast knowledge, several studies have reported a performance gap between the predicted and the actual behaviors in buildings, together with a discrepancy between predicted and reported comfort levels of occupants within the working environment. To close these gaps, the inclusion of human behavioral and perceptual theories has been investigated to understand the drivers leading to adaptive behaviors and occupants' comfort preferences. As a result, expectations are hypothesized playing a relevant role in the perception of comfort. However, little is known about the formation of expectations towards the indoor climate and the impact on adaptive behaviors. Therefore, drawing on psychological and comfort theories, we built a research framework to study occupants' expectations in buildings and their influence on comfort-related responses and behaviors. A structural equation model was empirically tested using survey data collected from office workers in Germany. Results showed that occupant's expectations positively influenced comfort and adaptive behaviors. Cognitive mechanisms, such as attitudes, perceived control, self-efficacy, personal norms and thermal history, were needed to capture expectations of the indoor environment. The relationship between the expected interaction with a fan to modify the indoor environment and the current occupant behavior was mediated by occupants' previous experiences with fans. This paper contributes to the assessment of comfort and occupant behavior literature by developing a theoretical framework of behavioral and thermal expectations in the built environment. Findings may have implications on the design of adaptive opportunities to enhance occupant satisfaction with the workplace and to support design strategies to reduce the building energy consumption.

1. Introduction

The conceptualization, design and materialization of energy-efficient buildings while providing a comfortable, healthy indoor environment has been a major research topic in the past two decades. A large body of literature has demonstrated that occupant interactions in buildings have a significant influence on energy use [1], though their final role is still debated [2]. Therefore, the study of occupant behavior has received considerable attention and studies have focused on understanding and predicting occupant interactions with the building systems. Several occupant behavior models have been the result of these investigations [3]. Along with the study of energy-related behaviors, occupant perceptions and preferences for indoor environmental conditions have been an essential part of the assessment in building performance. A few, well-known comfort models [4,5] have provided a fruitful baseline to evaluate occupant satisfaction with the indoor environment. However, it has been frequently reported a performance gap between 1) motivations and intentions to perform an action and actual occupant behavior [6] and 2) comfort conditions provided by standards and actual comfort preferences [7].

1.1. *Occupant behavior and comfort gaps*

There have been attempts to fill the intention-behavior gap by incorporating theoretical foundations from the environmental sciences in building assessment studies. In their review, Heydarian et al. [8]

Abbreviations: SEM, Structural equation model; PCA, Principal component analysis; TPB, Theory of planned behavior; NAM, Norm activation model.

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identified the potential of interdisciplinary theory-based studies to better understand driving factors in occupant behavior and interactions in buildings. From the 135 reviewed studies, sorely a few well-known theories were implemented, namely the Theory of Planned Behavior (TPB), the Norm Activation Model (NAM) and the Value-Belief-Norm (VBN). Despite their wide applicability and validation, each theory presented inherent limitations to address the complexity of human behaviors. Schluter [9] suggests that gaps in theories open an opportunity to link theories that specify the missing processes.

To broaden and deepen the understanding of occupants' behaviors researchers showed attempts to integrate different theories by integrating various socio-psychological measures. For example, Li et al. [10] showed an integrated motivation-opportunity-ability framework (MOA), which included constructs from the TPB and NAM and explained significantly more variances of energy-saving behaviors in office buildings in the USA than both theories alone. Similarly, Guerreiro et al. [11] combined two theoretical models – the Theory of Reasoned Action and the Technology Acceptance Model – to understand the use of smart meters, being able to examine the socio-psychological factors that influence their use. Hong et al. [12] studied nine cognitive-behavioral frameworks describing human behavior using a need-action-event cognitive process to capture the stochastic and reactive nature of human behavior in a complex environment. The authors incorporated this concept into a DNAS framework ('Drivers-Needs-Actions-Systems') and proposed an ontology to study energy-related behaviors in the building indoor environment.

To fill the gap between predicted and reported comfort responses, several efforts have focused on capturing and understanding underlying mechanisms in adaptive processes of occupants in buildings, namely behavioral, physiological and psychological [13,14]. Several studies have assessed influencing factors in thermal comfort and perception, such as perceived control and self-efficacy, thermal history and adaptation, and personality traits, among others. A categorization of relevant studies is summarized in Table 1. Findings from these studies confirm the notion of thermal comfort as a social construct achieved in a cultural context, which reflects beliefs, values and aspirations towards different environments [15–17].

1.2. Relationship between perception and behavior

Already in 1981 Auliciems [31] revised the interaction between physiological and psychological aspects in the assessment of comfort, by addressing the relationship between comfort and behavioral adjustments through the formation of expectations. Following this line of thought, Schweiker et al. [32] studied expectations by directly assessing the congruence between people's expectations and experience of the indoor climate. They measured expectations retroactively, asking participants right after they entered a workspace if the encountered thermal conditions were in line with the expectations they had before entering the space. They found that expectations of thermal conditions have an influence on thermal responses, causing a decrease in thermal comfort when expectations are not met. However, the authors highlighted that the relationship between occupants' expectations and comfort responses is more complex.

Table 1
Summary of relevant studies assessing differences in perception of thermal comfort.

Category	Variable	Source
Short-term thermal experience	Within buildings, from home to work	[18,19]
Long-term thermal history	Dependence AC, Climate, Seasonality	[20–24]
Attitude, Beliefs, Values	Environmental attitude	[25]
Demographic and anthropomorphic characteristics	Sex, BMI, Age	[4,26,27]
Personal characteristics	Personality traits	[7]
Socioeconomic background	Social class	[19]
Perceived control	Shared/Personal control, Self-efficacy	[7,28–30]

Chappells and Shove [16] argued that it might be possible to exploit existing diversity and variety both in people's expectations and in the built environment by redefining the kind of conditions to which people become accustomed and accepting that future expectations are, in parts, shaped by contemporary experiences. As studied by Luo et al. [33], thermal comfort expectations exhibit asymmetric dynamics and advocating for greater flexibility in comfort strategies and lowering expectations can bring thermal adaptation to non-neutral indoor climatic conditions. Therefore, reviewing indoor environmental quality assessments by capturing and measuring expectations concerning adaptive opportunities may bring opportunities for occupants to cope with their individual preferences. Understanding the interaction between thermal and behavioral expectations and the effects on occupant behavior seems a possible path to enhance comfort. However, the relationship between adaptive opportunities and indoor climate expectations is still a topic to be explored further and therefore, the objective of this paper.

1.3. Objective of this study

The aim of this study is to understand the underlying relationship between comfort-related behaviors and thermal perception in office buildings. The following research questions will be examined:

- How do occupants' expectations towards the indoor environment and adaptive opportunities relate to occupants' comfort and behavior choice?
- Through which psychological and contextual factors can expectations be measured and operationalized?

To address the identified research questions and the importance of integrated theories, this study proposes an integrated framework of expectation by incorporating constructs from the Theory of Planned Behavior (TPB), the Norm Activation Model (NAM) and the Self-efficacy theory (Fig. 1). The existing psychological theories and the structure of the integrated framework as well as the research hypothesis are introduced in section 2. Based on the proposed framework, structural equation modeling (SEM) is conducted to test the proposed framework and research hypotheses. The survey design, data collection and method for data analysis are presented in section 3. Results and hypothesis testing are shown in section 4.

2. Theoretical framework and hypotheses

2.1. Psycho-physiological models and the role of expectations

As mentioned above, expectations play a relevant role in the assessment of comfort responses. In the psycho-physiological model from Auliciems [31], the relationship between comfort-related behaviors and satisfaction with the indoor environment is linked through occupant expectations: adaptive opportunities and past thermal experiences will affect thermal satisfaction in a certain environment by evaluating the mismatch between the expected conditions and the actual perception. Fig. 2 presents an overview of the model.

Although the hypothetical model of thermal responses has not been adopted in comfort studies yet, the framework by Auliciems introduces a holistic view of the influence of behavioral and technological adaptations in comfort preferences. Different integration levels for the choice of adaptive behavior are included in the model, referring not only to an effective response but also cognitive and affective components. Grabe [34] analyzed energy-relevant human interactions through the lens of expectancy-value theories, which posit that actions are motivated by the value of some goal state and an expectation that the goal can be attained

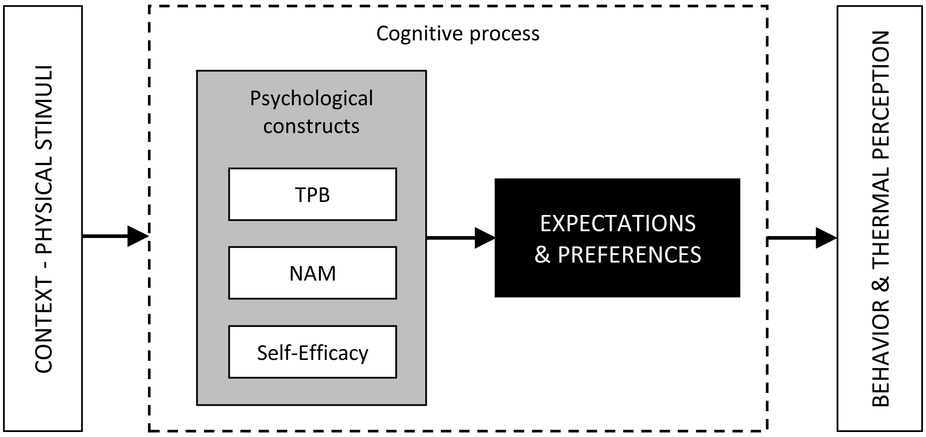

Fig. 1. Outline of integrated framework proposed in this paper.

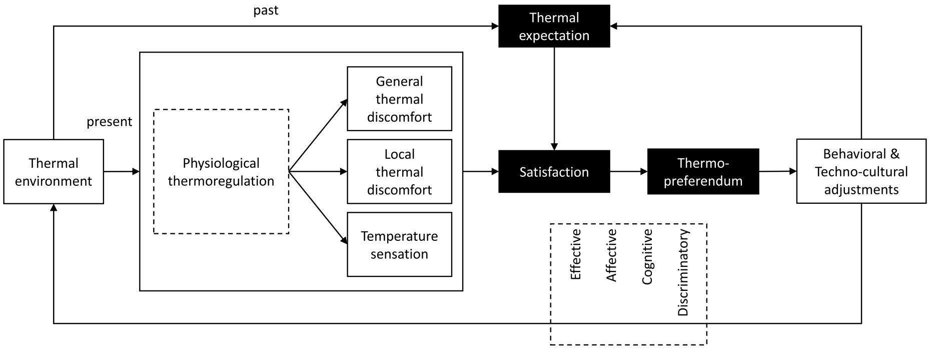

Fig. 2. Adaptation of Auliciems's model of psycho-physiological perception [31].

by acting. Therefore, the higher the expectation of the occupant to improve satisfaction (affective) and the lower the attached costs (consequences or competing needs), the higher will be the probability to execute a particular action. The work from Eccles [35] proposed that expectations and values are influenced by social cognitive variables, including ability beliefs, perceived difficulty, individual goals, self-schema and affective memories, as well as previous experiences and socialization influences. Therefore, the formation of expectations is reflected by a set of associations between a particular goal or object and related attributes to it.

2.2. *Theory of Planned Behavior - TPB*

The TPB has been demonstrated as an effective framework to predict comfort and energy-related behaviors in buildings [8]. The present study uses the TPB to strengthen the psycho-physiological model from Auliciems [31] by capturing cognitive aspects contributing to shaping expectations. The TPB was developed by Ajzen [36] and proposes that people act following their intentions and perceptions of control over the behavior, while intentions, in turn, are influenced by attitudes toward the behavior, subjective norms, and perceived behavioral control. Specific factors in the TPB were defined in the past as follows: *attitudes* are a psychological tendency that is expressed by evaluating a particular entity with some degree of favor or disfavor, referred as evaluative affect [37]. According to Krosnick [38], a higher explanatory power is achieved when attitudes refer to a particular object, rather than all objects which are associated or related; *subjective norm* refers to an individual's perception that most people who are important to this person think the behavior in question should or should not be performed by this person; *perceived control* is a belief that the individual is capable of influencing and making a difference in the events that surround their lives. Within the definition of perceived control, there is a further distinction between *perceived behavioral control*, which refers to the perceived ease or difficulty of performing the behavior, and *control belief* as the perceived presence of factors that may facilitate or impede the performance of a behavior. Some studies extended the TPB by adding *descriptive norms*, which refer to the perception of important other's opinions and behaviors, to capture the additional social influence. However, mixed findings were found for the influence of descriptive norms in the context of heating and cooling studies [39,40].

2.3. *Norm activation model - NAM*

Studies have shown that normative considerations, which imply that people prioritize collective interests over their self-interest (altruistic), play an important role in predicting and designing interventions to motivate energy-saving behaviors [41]. The NAM is one of the most influential models to explain this relationship. This model was developed by Schwartz [42] and it conceptualizes behavior as being caused by feelings of moral obligation to act in a norm concordant way, caused by activated *personal norms*. In this sense, a strong personal norm implies that an individual is intrinsically motivated to act pro-socially and enhance or preserve one's sense of self-worth. Schwartz used the term *personal norms* to signify the self-expectations for specific actions in particular situations that are constructed by an individual. Therefore, this theory will be used to enhance the proposed framework by explaining the formation of expectations.

2.4. Self-efficacy theory

Theories of behavior prediction that specify primarily intentions as determinants of behavior, such as the TPB, may lead to an intention-behavior gap, which describes the phenomenon that information about behavioral intentions and the execution of the target behavior often do not match. This gap is caused by problems in goal pursuit (e.g. volition), which can be based on internal, often self-regulatory factors, but also on external (e.g. time) factors. Empirically, certain constructs, such as self-efficacy or action control, contribute to bridging this gap by explaining other psychological processes that moderate the intention-behavior relationship [43]. The Self-efficacy theory (SET) is a subset of Bandura's Social Cognitive Theory [44]. The theory proposes that the level of expectation of personal mastery and success will lead an individual to perform or not a particular behavior. Bandura described two types of expectancies influencing behaviors: *outcome expectancy*, which is the conviction that behavior will lead to a certain outcome, and *self-efficacy expectancy*, which is the conviction of an individual of successfully executing a behavior required to produce the desired outcome. Several authors concluded that self-efficacy can result in a positive influence on energy conservation in buildings [45].

2.5. Integrated framework of expectations and research hypothesis

This study developed an integrated expectations framework to analyze the determinants of comfort and behaviors in a working environment by considering the disciplines of building science and social psychology. The approach is to investigate the integration of the model of psycho-physiological perception with well-established theories in human behavior and decision-making. The structure of the model and the hypothesis are presented in Fig. 3.

In the proposed integrated framework, thermal and behavioral expectations constitute the two main factors that influence perceived comfort and behavior, respectively. Based on the previous literature, we propose that expectations are high-level abstractions that can be inferred from other measurable variables. To capture and define expectations, constructs from the above-mentioned theories were adopted as measurable components in the model. Specific factors in the integrated expectations framework and correspondent hypothesis are described as follows.

Thermal expectations: Schweiker et al. [32] defined thermal expectation as the thermal experience predicted by occupants; the anticipated outcome, what they believe will happen. They suggested a positive association between expected conditions and reported thermal comfort:

Hypothesis 1. (H1): More positive thermal expectations of the indoor environment will be associated with greater reported thermal comfort.

However, they suggested that the integration of expectations and sensory experiences differed among participants, leading to differences in reported thermal comfort. Thus individual variables could play a role in the effect of expectations in perceptions of the indoor environment. Hawighorst et al. [28] investigated the effect of differences in personality traits on the perception of comfort. They suggested that those reporting greater self-efficacy showed a tendency towards less warm sensation (and more comfortable) despite the thermal conditions between both groups not being significantly different. Additionally, de Dear et al. [13] suggested that expectations should be regarded as a psychological state, affected by the dimension of adaptation such as perceived control. Several authors [30,46–48] investigated the effect of perceived control on thermal sensation and comfort, suggesting that higher levels of perceived control lead to higher satisfaction with the indoor environment. Recent thermal experiences - or *thermal history* [33] - shape occupants' expectations of comfort. Findings from Schweiker's work [32] suggested that the number of "expected" votes increased with the number of previous thermal experiences in a current environment. Chun et al. [49] found that there is a strong interaction and influence of occupant's experience with outdoor weather and the reported comfort with the indoor environment. Similarly, Luo et al. [33] suggested that people's perception of thermal comfort is dependent on their indoor thermal experiences, and that previous experiences can shape their ability of thermal adaptation to new environments, either increasing or decreasing occupants' thermal expectations of the indoor climate. Based on the principle of efficacy-expectancy described earlier and the effect of previous thermal experience and perceived ability for changing the environment effectively, we may hypothesize that thermal expectations can be described by self-efficacy, thermal history and perceived control:

Hypothesis 2. (H2a-c): (a) Greater reported self-efficacy will be manifested in more positive expectations of environmental conditions in the building, (b) especially among those with greater perceived control to adapt with the indoor environment. Additionally, (c) after being asked to envision working on their office room with diverse building systems to modify the indoor environment, participants feeling more comfortable in warm environments will report higher expected comfort than participants who often feel more comfortable in cold environments.

Behavioral expectations: expectations towards behavior refer to the probability to perform a certain adaptive behavior to enhance comfort in the workplace, such as turning on a fan to increase air movement or operating a shading to reduce the impact of solar radiation.

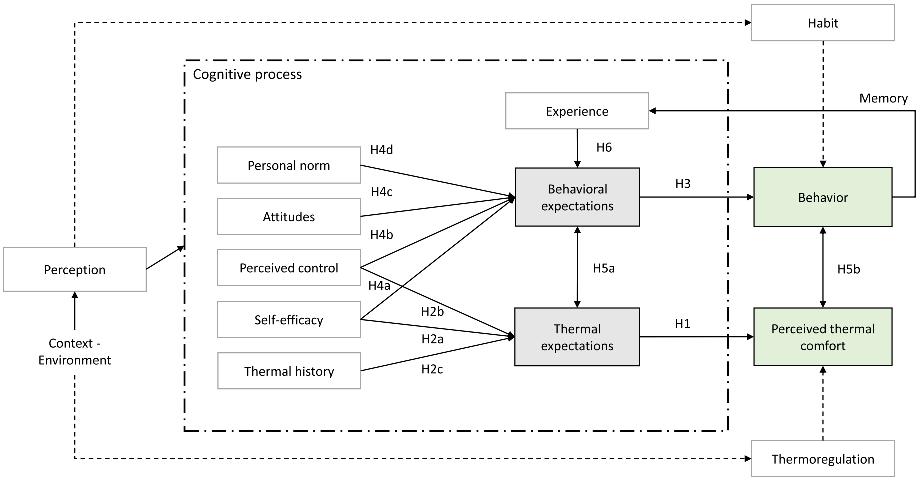

Fig. 3. Overview of the integrated expectation framework.

Hypothesis 3. (H3): More positive behavioral expectations towards a specific behavior will be associated with a higher probability to perform that action.

Hawighorst [28] studied self-efficacy to describe people's expectations towards their competencies to execute desired operations to manage their interactions and influence their thermal environment successfully. We suggest that self-efficacy will be a measurable variable to explain behavioral expectations. Additionally, several studies used the Theory of Planned Behavior as a framework to predict behavior in buildings. As reviewed by Heydarian et al. [8] several authors found that attitudes were significant predictors of intentions and behaviors towards saving energy and revealed that occupants' perceived control positively influenced both intentions and behaviors around energy conservation. Given these findings it is reasonable to predict that attitudes and perceived control will influence comfort-related behaviors as well. Therefore, we suggest that more positive evaluation of an action and the reported autonomy of the action will increase occupant's expectation to obtain the desire outcome by performing the chosen action. Additionally, the positive influence of personal norm on intention to undertake and actually perform energy conservation behaviors has been studied [8]. We suggest that personal norms impact positively in the intention to perform an action, therefore increasing the expectations to successfully perform a certain behavior. Accordingly, we tested the following hypotheses:

Hypothesis 4. (H4a-d): Higher expectations of the occupant to successfully influence their indoor environment will be manifested by participants with greater reported (a) self-efficacy and (b) perceived control than those with lower, (c) especially among participants with more positive attitudes towards the effectiveness and performance of a fan, (d) and with greater personal norms to prioritize low-intensive cooling strategies.

Thermal and behavioral expectations: interactions with the building environment and systems, as well as personal adjustments are associated with perceived uncomfortable indoor conditions by occupants [50]. This feedback mechanism between environment and actions suggest that when comfort is achieved the probability to perform an action to restore comfort decreases [51,52]. Based on this adaptive principle, we may expect a negative correlation between comfort and behavior. Accordingly, we suggest that expectations to interact with the system will be negatively associated with expectations of the indoor environment:

Hypothesis 5. (H5a-b): (a) More positive expectations of environmental conditions will be associated with less anticipated need to make adjustments and interact with the systems in order to stay comfortable, (b) leading to a lower probability of a behavioral reaction and greater reported thermal comfort.

Previous experience: according to Richetin [53], most studies in the attitudinal tradition typically stop at behavior as the final chain of events to be understood and predicted. However, theoretical elaborations, especially in the field of memory and judgment, have built some meaningful hypotheses in what might determine post-behavior evaluations. Accordingly, past experiences represent a principal component of the Social Cognitive Theory. This theory suggests that these previous experiences are influencing reinforcements and expectancies no matter if the individual engages in a specific behavior or not, and exposing the reasons why the individual engages in that behavior. Therefore, we will consider previous experiences as mediators of behavior. In our model, previous experience refers to the affective memories of a person with a particular object or technology:

Hypothesis 6. (H6): After being asked to envision working on their office room with diverse building systems to modify the indoor environment, participants having experienced higher levels of effectiveness of the system will show greater probability to interact with the system than participants who experienced lower levels of effectiveness.

Habit: we have so far presented the cognitive process of thermal and behavioral expectations leading to the perception of comfort and comfort-related behaviors. There are however other components that take place in the behavior-perception process, which may interfere with the process of decision-making. Klöckner [54] studied the influence of habit on human behavior. According to his extended model of normative-decision, the existence of habits for routine behavior saves cognitive resources and allows the individual the execution of behavioral scripts. Therefore, for behaviors that are repeated often enough the influence of intentions becomes weaker and at the same time, the influence of habits grows. By assuming that strong habits weaken the relation between personal norms and behavior and increase the amount of explained variation in behavior, Klöckner integrated habit strength as a third direct predictor of behavior in his extended model. According to his model, habits are part of the evaluation stage because the process of activation is not necessarily blocked totally. Therefore, habits will be part of the integrated framework presented here and incorporated as predictors in the behavioral expectation stage.

Thermoregulation: as explained in the psycho-physiological model, the thermoregulation process affects the perception of comfort. In a review from Schweiker [4], physiological drivers leading to differences in perception of comfort are summarized, being the most influential: age, sex, body composition, metabolic rate and physiological adaptation.

Only cognitive processes of the model will be empirically tested, due to limitations of data collection. Therefore, habits and physiological processes are not included in the formulation of the hypotheses.

3. Methodology

In order to assess the above hypotheses, a nationwide survey was carried out focusing on psychological constructs influencing thermal comfort and behavior in office buildings, as described below.

3.1. Data collection and participants

Quantitative data was collected from an Internet-based survey, which targeted office employees. As the survey took place in 2020, the data collection was carried out across employees who worked in an office environment or due to the COVID-19 pandemic were at the time of the survey working from home but used to work in an office environment. The survey was distributed in August 2020 (summer season) through *respondi* - a frequently used online data collection platform by researchers. The survey platform allows not only recruiting participants but also filtering them according to specified set of quotas to address a determined target group. Of interest of this study was to obtain a representative sample for the German office employees population with respect to gender and age. Additionally to the quotas for age and gender, a recruiting criteria was to work in an office. Participants received a monetary incentive to encourage their participation in and completeness of the survey. From the 1069 invitations sent, a total of 548 questionnaires complying with the desired quotas were obtained. In the data cleaning process and quality check, questionnaires with response-time lower than 8 minutes were removed. The time was based on the average time for filling the questionnaire (25 minutes) and the minimal time recorded in the pilot testing. Responses, where the question of working in an office was missing or negative, were also removed. As a result, 430 responses were retained for the analysis. Among our sample of office employees, 35% of the participants were employees without administrative tasks, 30% were office managers, 17% were clerks, advisors or worked in the office administration and 19% did not correspond to previous categories, such as freelancer or self-employed working in an office. Most employees have been working more than 3 years at their workplaces (76%) and more than 30 h per week (82%); 39% worked in single offices and 61% in shared offices. All employees had manual access to at least one window in their workspace and 65% of the employees worked in a building with an air conditioning system. Quotas were set so that the distribution of gender (44% female and 56% male) and age (10% between 18 and 29 years old, 48% between 30 and 49 years old and 42% above 50 years old) was similar to that of the German office users population [55].

3.2. Survey structure and measures

The survey consisted of three sections. The first section included screening and quota questions (i.e., work in an office, age and gender). The second section included the measures of control variables, mainly: actual mood, characteristics of the working environment (e.g. single or shared office, story, number of windows and doors and proximity to workplace), characteristics of the job (e.g. number of working hours, years on the job, type of job), clothing level, satisfaction with the working environment - such as indoor temperature, indoor air quality, infrastructure and size of workspace, lighting, noise level -, satisfaction with the job tasks and which adaptive measures they are able to perform in their workspace. Lastly, the third section included the main measures of this study: (1) thermal expectations and behavioral expectation measures, (2) self-efficacy, perceived control, personal norms, thermal history and attitudes, (3) reported comfort and behavior. Additionally, questions to measure previous experience were included in this section.

The measurement of attitudes and perceived control was adapted from Fishbein & Ajzen [37]. In this study, a model to test interactions with a fan is presented as case study. Therefore, only questions to measure attitudes focusing on fan usage are included in the model. Questions to measure perceived control refer to it as whether or not individuals' actions are completely under their control (autonomy). Measurements of self-efficacy and personal norms were based on an available validated scale [56] and on the work from Schwartz [42], respectively. Wordings were revised to fit the context of this study. Additional questions were added to capture direct reported thermal and behavioral expectations. Previous experience refers whether or not the participant has ever interacted with each building system and how effective they are to influence their perceived comfort in the office. In this study, only questions for the fan usage were considered. All measurement items were translated and adapted to German and tested on a pilot study, in which 10 participants took part. Results of the pilot study served mainly to improve the wording of the questions and statements. For the variables shown in Tables A1, A2 and A3 respondents were asked to what extent they agree or disagree with each statement, using a seven-point Likert scale from '1 = not at all true' to '7 = completely true' (German: '1 = trifft überhaupt nicht zu'; '7 = trifft volkommen zu'). For the variable *previous experience* respondents were asked how effectively they can influence their thermal comfort in the office through the stated measures, using a scale from '1 = not at all' to '5 = very much' and with the possibility to chose 'I do not use it/does not apply' (German: '1 = gar nicht'; '5 = sehr stark'; '6 = 320 benutze ich nicht/keine Option').

Because the study was conducted during the Covid-19 pandemic and to rule out potential differences between their availability to building controls, participants were asked to envision working on an office environment were they have personal control over an energy-efficient fan and also the office has other building systems that can be accessed to modify the indoor environment (windows, blinds, air conditioning system).

3.3. Data preparation and analysis

All data preparation and analysis were conducted within the software environment R Version 3.6.3. The research hypotheses were tested through a structural equation modeling (SEM) analysis. This method of analysis has several advantages over typical multivariate analysis, as it allows all variables to be included in one model and tests for model fit and individual hypotheses [57]. Furthermore, SEM has shown advantages in built-environment studies as it allows to consider complex research questions and test multivariate models in a single study [58]. Therefore, the proposed model of expectations is tested through a SEM to 1) see if the scheme is a good model for the set of survey responses, 2) see how well it agrees with the structure of the data. In order to reduce the number of observed variables in the SEM, a principal component analysis (PCA) was conducted [59]. Furthermore, a reliability test was performed for the extracted factors. For the factor extraction, Kaiser [60] recommends retaining all factors with eigenvalues greater than 1. Kaiser's criterion is accurate when there are fewer than 30 variables and communalities after extraction are greater than 0.7 or when the sample size exceeds 250 and the average communality is greater than 0.6. Another measure of sampling adequacy is the Kaiser–Meyer–Olkin (KMO) method. The KMO statistic represents the ratio of the squared correlation between variables to the squared partial correlation between variables and varies between 0 and 1. According to the classification of Hutcheson & Sofroniou [61], values below 0.5 are not acceptable, between 0.5 and 0.7 are "mediocre", values between 0.7 and 0.8 are "good", values between 0.8 and 0.9 are "great" and values above 0.9 are "superb".

For the SEM analysis, we used the maximum likelihood estimation method for the measurement model analysis in the Lavaan test in R and the DWLS approach when binary variables for the endogenous variables (dependent variables) were incorporated in the structural model [62]. The latter uses the diagonal of the weight matrix for estimation but uses the full weight matrix to correct the standard errors and to compute the test statistic. The SEM models were represented in a path diagram in which indicators (questions) are represented by rectangles and latent factors, which are inferred from the indicators, are represented by ellipses. In this study, we adopted the second-order SEM model in which each second-order factor (i.e. thermal expectations and behavioral expectations) is a composite of several first-order factors (i.e. attitude, perceived control, thermal history and self-efficacy). In this hierarchical structure, first-order factors can be considered as the various dimensions of the second-order factors, and thus help understand which particular first-order factors contribute to the thermal expectation and behavioral expectation. Single-headed arrows connecting second-order factors and thermal comfort or behavior represent the hypothesized direct effects of one factor on each variable. The two-headed arrows represent the covariance between either second-order factors or between predicted variables.

Goodness-of-fit (GOF) indicates how well the specified model reproduces the observed covariance matrix among the indicator items. According to Hair [63], researchers should report at least one incremental index and one absolute index. Based on our sample of 430 respondents and a total of indicator variables greater than 30, evidence of good fit would include a significant χ^2 value, a CFI of at least 0.90, a SRMR of 0.08 or lower (with CFI above 0.92) and a RMSEA lower than 0.7 with CFI above 0.90. The reported values correspond to the robust test statistic.

4. Results

4.1. Factor analysis and reliability test

A principal component analysis (PCA) was conducted for the variables thermal expectations and behavioral expectations, as well as the single constructs of the model that explain the two latent variables. When necessary, the scale of the reverse-phrased items was inverted. Results from the PCA and correspondent residuals are shown in Table 2 and Table 3, respectively. Eigenvalues, percentage of variance explained and alpha values for each factor are shown in Table 4. The description of the single items and the respective loadings are shown in Table A1, Table A2 and Table A3.

Generally, the PCA results for the presented constructs have shown acceptable KMO and communalities values and significant values for the test of sphericity. An exception is the KMO value for perceived control

Table 2
Construct, number of retained items, KMO values (for individual items), Bartlett's test of sphericity and average communalities.

	Items	Rotation	KMO values	Test of sphericity	Communalities
Thermal expectations	8	Oblimin	.77 'good' (>.68)	χ^2 = 2568.14, p < .001	.74
Self-efficacy	10	None	.94 'superb' (>.92)	χ^2 (45) = 757.78, p < .001	.67
Perceived control	2	None	.5 'mediocre' (>.5)	χ^2 (1) = 131.19, p < .001	.93
Attitudes	4	Oblimin	.73 'good' (>.68)	χ^2 (6) = 688.87, p < .001	.64
Thermal history	5	Oblimin	.74 'good' (>.68)	χ^2 (10) = 304.31, p < .001	.86

Table 3
Residuals.

	Fit based upon off diagonal values	Absolute residuals > 0.05	Root means square residuals
Thermal expectations	.97	.43	.08
Self-efficacy	.99	.49	.06
Perceived control	.99	–	.07
Attitudes	.95	.83	.13
Thermal history	.99	.40	.06

Table 4
Eigenvalues, percentage of explained variance and α values for all factors.

	Eigenvalues	Percentage of variance	α value
Thermal expectations			
Factor 1	3.61	.45	.83
Factor 2	2.28	.29	.90
Self-efficacy			
Factor 1	6.75	.67	.95
Perceived control			
Factor 1	1.86	.93	.92
Attitudes			
Factor 1	2.56	.64	.81
Thermal history			
Factor 1	2.64	.53	.92
Factor 2	1.65	.33	.80

that showed a value close to the acceptable limit ($\geq$0.5). However, as the average communalities for perceived control were within the acceptable limit (>0.6), the factor was retained for further analysis. Furthermore, most residual values were within the recommended threshold (fit based upon off diagonal values should not exceed 0.95, and absolute residuals greater than 0.05 should not exceed 50%). However, the resulting residuals for attitudes showed high absolute residuals above 0.05 (almost 80%) and the root means square residuals are above 0.08. This will be taken into consideration for the analysis and interpretation of results.

Additionally, a PCA was conducted on ten items to measure behavioral expectations. Results from the Kaiser–Meyer–Olkin measure showed the sampling inadequacy for the analysis (KMO = 0.45). Therefore, a second analysis was proposed. A separate factor analysis was conducted for each behavior separately, being: window, fan, blinds, clothing and air conditioning/mechanical ventilation system. Each construct (behavior) was constituted of two items. The reliability test showed inadequate reliability of items for the window, clothing, air conditioning/mechanical ventilation system and blinds. Moreover, Bartlett's test of sphericity for the fan (p = .003) indicated that correlations between items were not sufficiently large for PCA. According to these results, no factor analysis was conducted for the construct behavioral expectations. Likewise, PCA was conducted to measure personal norm. The reliability test suggested the deletion of two items (from the original five). Therefore, a second analysis was conducted on three items. However, the fit based upon off diagonal values was lower than 0.95, showing inadequacy of the number of factors. Therefore, no factor analysis was conducted for the construct personal norms and single items were retained for further analysis.

4.2. *Structural equation model*

Two SEM models, including direct and mediating effects respectively, were tested to investigate how thermal and behavioral expectations affected thermal comfort and behaviors and, particularly, if expectations influenced behaviors through previous experience. The five obtained underlying constructs were included in the model. Behavioral expectations, personal norms and previous experience were included as single items and a separate model was analyzed for the mediation effect. All variables were standardized.

4.2.1. *Fan measurement model*

The measurement model presented in this study focuses on fan expectations. Fig. 4 shows the path analysis for the model obtained. Details of the measurement model are shown in Table A4. All model fit indices indicated a good global fit of the proposed model: χ^2 (11) = 21.55, p = .028, CFI = 0.98, RMSEA = 0.047, SRMR = 0.028. Both thermal and behavioral expectations are explained by the direct question regarding expectancy ("*I expect that the indoor climatic conditions at the office will be pleasant during the summer term.*"; "*I assume that I will turn on the fan when I am too warm.*") with high loadings – 0.76 and 0.71 respectively –, but also through the constructs analyzed in the PCA. The five constructs from the theoretical framework explain fan expectations. From a statistical perspective, the constructs share a significant proportion of variance with fan expectations. Personal norm regarding the fan explains the latent variable with high loading (0.91), followed by attitudes (0.50) and with lower loadings personal control (0.35) and self-efficacy (0.23). However, thermal expectations are explained by perceived control with high loading (0.80), followed by self-efficacy (0.51) with relatively high loading as well and thermal history (0.20) with lower loading. All relationships are significant at the level of p < .001. As we can see in the path diagram, there is a negative correlation between thermal expectations and fan expectations (estimate = −0.303, p < .001).

4.2.2. *Direct effects on comfort and behaviors*

The predicted variables thermal comfort and fan usage were included in the structural model for the fan. As the endogenous variable "fan usage" is a binary variable, the DWLS approach was implemented, which uses the diagonal of the weight matrix for estimation, but uses the full weight matrix to correct the standard errors and to compute the test statistic. Details of the selected structural model are described in Table A5. All model fit indices indicated a good global fit of the proposed model: χ^2 (23) = 43.51, p < .05, CFI = 0.95, RMSEA = 0.046, SRMR = 0.044.

As we can see in the path diagram in Fig. 5, there is a significant negative correlation between thermal expectations and fan expectations (estimate = −0.29, p < .001) and between thermal comfort and fan usage (estimate = −0.14, p = .01). Furthermore, results showed that thermal expectations and fan expectations had statistically significant effects on thermal comfort (β = 0.43, p < .001) and on fan usage (β =

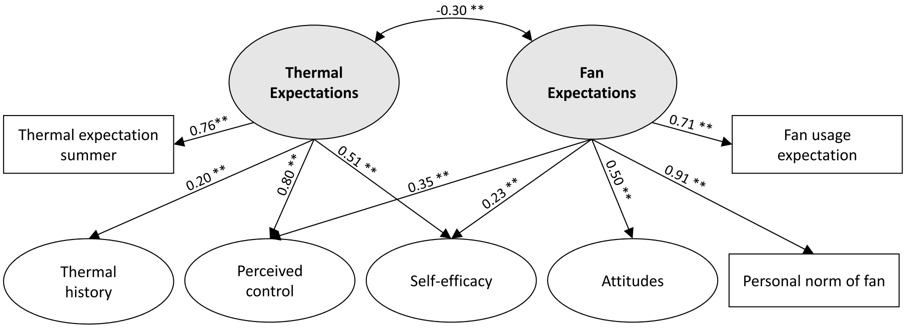

Fig. 4. Paths diagram for the measurement fan model (**p < .001; *$p \leq .05$).

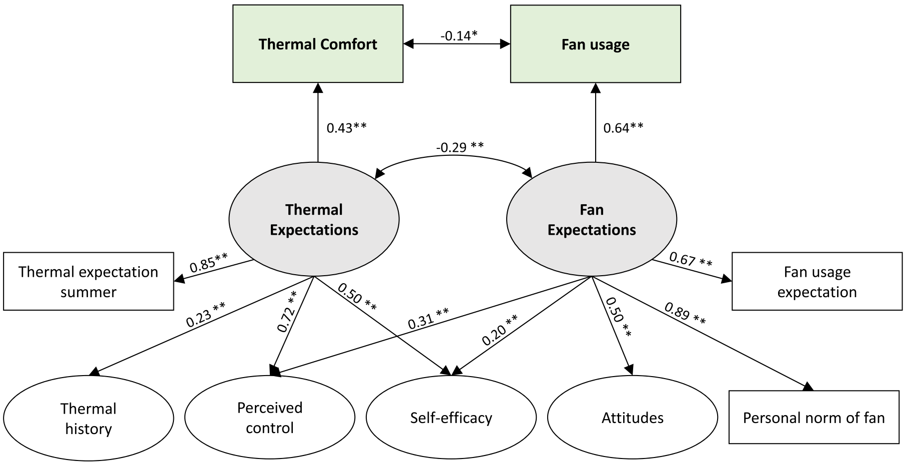

Fig. 5. Paths diagram for the structural fan model with direct effects (**p < .001; *$p \leq .05$).

0.64, p < .001), respectively. The results reported the R^2 of behavior as 41% and of thermal comfort of 19%.

To account for possible effects of sex and age on the outcome variable, they were included as control variables in the fan model. Results showed that neither sex nor age were significantly associated with thermal comfort (Sex: $\beta = 0.10$, p = .31, Age: $\beta = -0.06$, p = .39) or with behavior (Sex: $\beta = 0.11$, p = .37, Age: $\beta = -0.13$, p = .15). The potential influence of employees working in a building with air conditioning system was also tested in the model. The building type was not significantly associated neither with thermal comfort ($\beta = 0.02$, p = .83) nor behavior ($\beta = -0.21$, p = .11).

4.2.3. *Mediation effects on comfort and behaviors*

Following the theoretical approach of the proposed model, a mediation effect of previous experience with fans was included in the model. A summary of the indirect effect is presented in Table 5. The added path for mediation (FE: $\beta = 0.46$, p < .001) was significant, indicating that behavioral expectations affected behavior. As we can see in the path diagram in Fig. 6, results also suggested a statistically significant effects of fan effectiveness ($\beta = 0.28$, p < .001) and behavioral expectation ($\beta = 0.49$, p < .001) on behavior. The model fit indices indicated a good global fit of the model: χ^2 (30) = 46.72, p = .03, CFI = 0.97, RMSEA = 0.043, SRMR = 0.055. Details of the structural model are described in Table A6. However, only 306 participants reported experience with fans and were able to rate them according to their effectiveness, lowering the sample size of the model. The results reported the R^2 of behavior as 45% and of thermal comfort of 18%.

5. Discussion

5.1. *Measurement of constructs - PCA*

The principal component analysis and reliability test for *thermal expectations* distinguish the two subscales from the questionnaire:

Table 5
Summary of indirect effects test.

Indirect effect tested	Path A		Path B		Path C′		Indirect effect		
	(X → M)		(M → Y)		(X → Y)		95% CI		
	β	p	β	p	β	p	Lower	Point	Upper
BE → FE → FB	0.46	.00	0.28	.00	0.49	.00	0.06	0.13	0.19**

Note: Path A = relationship between independent variable (IV) and mediator; Path B = relationship between mediator and dependent variable (DV), controlling for IV. Path C’ = direct effect of IV on DV, controlling for mediator. Lower = lower bound of confidence interval; Point = point estimate; Upper = upper bound of confidence interval. BE = Behavioral expectation; FE = Fan effectiveness; FB = Fan behavior; Indirect effect is significant if confidence interval does not include zero. Indirect effects estimated using 5,000 bootstrap samples. **p < .01. ***p < .001.

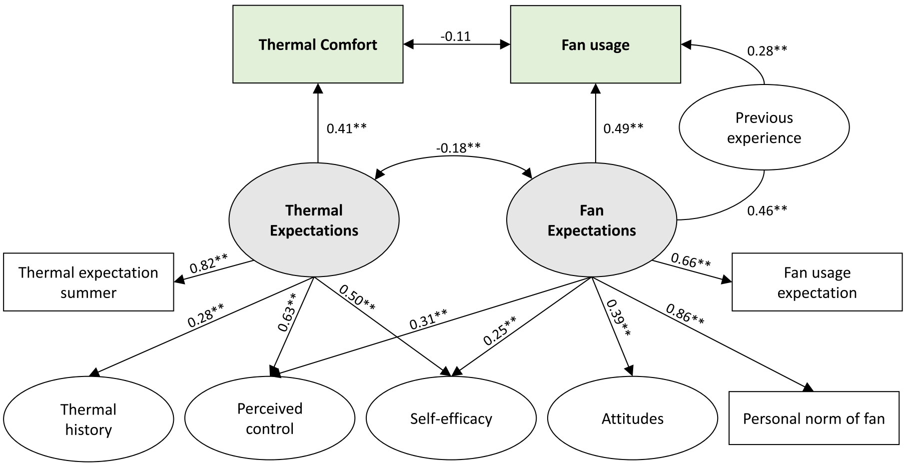

Fig. 6. Paths diagram for the structural fan model 2 with direct and indirect effects (**p < .001; *$p \leq .05$).

thermal expectations in summer and thermal expectations in winter. The elimination of two items suggests that those questions referring to "evaluation of indoor climatic conditions at end of the day" during wintertime may not be applicable during the winter season, in comparison to the summer season. One possible explanation could be the influence of the season (summer) in which the study was conducted, being difficult for participants to recall winter conditions. Another possible explanation could be related to the rather stable indoor conditions provided by heating systems, if compared to free-running buildings, leading to insignificant changes in the perception of indoor temperature and air quality in wintertime.

The unique factor representing *self-efficacy* suggests that all items fit onto a single theoretical construct. As an operational definition, that means they are one dimension. Likewise, the unique factor representing *perceived control* seems to reveal that two items of the initial questionnaire measure a single theoretical construct: perceived control of climatic conditions at the office. The other items may fail to measure perceived control in other contexts, such as control of life situations and environment. The analysis of *attitudes* seems to reveal that the initial questionnaire measures attitudes towards ceiling fans, fitting all items onto a single theoretical construct. The deletion of three items can be interpreted as they refer to general attitudes towards environmental protection and energy-efficient solutions, and cannot be grouped to object-oriented attitudes, in this case, the fan usage [38]. However, the large number of residuals observed in this factor may suggest that new items should be added and tested to the proposed scale.

The analysis of *thermal history* can be interpreted as two subcomponents of thermal history: person's temperature type or - as mostly used in the literature – 'thermal experience' but referred to as "cold type" and general thermal preference. The high correlation between factors may express an interrelationship between them. On a theoretical level, we may expect a fairly strong relationship between thermal preferences and thermal experiences, supported by previous studies [64]. The deletion of the four items can be interpreted as 1) that item 1 may have not been adequately formulated, due to the generalization of "being always warm", 2) the adaptive behaviors for cooling/warming up may have not been adequate to capture thermal experiences correctly (items 2, 3 and 9). Both analyses of *behavioral expectations* and personal norms seem to reveal that all behaviors cannot be summarized in a unique construct. These findings may be interpreted as those behaviors are independent of each other. A reason that may support this explanation might be because all actions could not be performed simultaneously, the adaptive measures may not have been all available in the workplace or the effectiveness rated by occupants was not the same for all the adaptive actions.

5.2. Model and testing of hypothesis - SEM

This study examined the extent to which expectations of indoor environmental conditions and of the adaptive opportunities in an office environment were associated with reported thermal comfort and reported behavior and how existing motivations and individual features - thermal history, personal norms, attitudes, perceived control and self-efficacy - might explain the formation of those expectations. We also examined the extent to which occupants' previous experience might mediate the influence of individuals' expectations on their behaviors. Understanding expectations was an important phenomenon, as they can influence occupants' perceptions of indoor climate conditions and their intended behaviors, especially when analysing occupants' comfort in free-running buildings.

Our study expands the psycho-physiological model from Auliciems [31] to assess the relationship between adaptive opportunities, comfort and associated expectations by incorporating socio-psychological concepts of well-established theories. Results indicate that the model fit indices of the two proposed models - the direct effect model and the mediating effect model (previous experience) - are both acceptable. However, the mediating effect model explains slightly more variances in comfort behaviors and the hypothesized mediating effects of behavioral expectation to fan usage via previous experience are also significant. Therefore, the mediating effect model is retained for discussion.

Results from the SEM indicate that both hypotheses referring to the formation of expectations (H2 and H4) can be confirmed: attitudes, personal norm, fan expectation, perceived control and self-efficacy contribute to explain behavioral expectations; perceived control, thermal history and self-efficacy explain thermal expectations. Personal norms are directed to the behavior itself (fan operation), which may explain the high loading to behavioral expectation. Likewise, perceived control was directed to the control of the indoor climate, leading to a higher loading on thermal expectations but explaining - with a lower loading - expectations to control the environment as well (behavioral expectations). The relatively weak relationship of self-efficacy and behavioral expectation can be interpreted as the target questions for self-efficacy aimed to capture general aspects of a person's nature and not specifically related to an action. A higher contribution of self-efficacy to thermal expectations can be observed, supporting previous findings [28], where occupants with greater self-efficacy reported higher thermal comfort with the indoor conditions. As suggested by previous work [32], perceived comfort is influenced by previous thermal experiences. This can have a significant impact on the acceptability of thermal conditions in naturally ventilated buildings, as studied by de Vecchi et al. [65].

The theoretical expectations model was tested for fan expectations and thermal expectations. As thermal comfort and fan usage were predicted by thermal expectations and fan expectations, respectively, the positive direct effects described by hypotheses H1 and H3 can be confirmed. These results support findings from the study of Schweiker et al. [32], in which they suggested a congruence between expectations and perceived comfort, and contribute to their work by capturing expectations through other measurable socio-psychological individual variables. Based on our findings in this study, the influence of expectations on comfort and behavior suggests that 1) the design of adaptive measures in offices can focus on targeting adaptive measures for occupants according to their personality traits and psychological state, and 2) the communication of adaptive possibilities can target occupants' comfort and satisfaction.

The mediation effects proposed by the expectations framework was supported by the SEM for fan expectations. Fan experience has a significant positive effect on fan expectations to predict fan usage, supporting the principles of Social Cognitive Theory [44] and therefore confirming hypothesis H6. This indirect effect suggests that if an individual rated the adaptive action - in this case using a fan - more effectively, occupant's expectations will increase the probability to successfully perform that action to restore comfort. Results suggest that it might be useful to address occupants' expectations of building systems and operations by increasing occupants' positive experiences with those adaptive opportunities in the building.

In the SEM model, a negative correlation can be observed between fan and thermal expectations, suggesting that no action is expected to be taken when the expected thermal conditions are met. Likewise, comfort and behaviors are negatively correlated. These results support the adaptive principle and therefore confirm hypotheses H5. However, the low correlation coefficients between the latter may suggest that behaviors are not merely motivated by thermal drivers but rather triggered by other psycho-physiological factors, as suggested by the model of expectations.

Future studies need to continue to apply the framework of occupant expectations to show the applicability and potential of the model. The resulting fan model should be tested with a higher sample size, as in this study a low number of participants had experience with either a ceiling or desk fan (~ 40%). Moreover, the model needs to be evaluated on different data-sets to test other cultural backgrounds and climatic conditions. As the current study was developed in a German office context, where the use of ceiling fans is not of common practice, applying the model to other countries may deliver different results. As previous experiences with the fan mediate the relationship between expectations and behavior, a more frequent use of fans in office context may increase the interaction with the device. In our fan model, occupants' comfort level and behaviors were not affected by differences in existent building cooling strategies - air conditioning system vs. free-running building. A significant influence of building type might be found in locations with higher frequency of hot days or warmer daily temperatures and higher number of air conditioned office buildings. Finally, future work could test the influence of expectations in other adaptive behaviors, the role of habit in action choice as well as the effect of physiological aspects in the model assessment.

5.3. Practical implications

The findings of this study imply that addressing and better understanding occupants' expectations of building environmental conditions and control strategies might be useful to increase occupant satisfaction with the indoor environment. Previous research [32] reported a complex formation of expectations of indoor environmental conditions. Our findings indicate that psychological constructs can be useful to address comfort expectations. In this respect, the integrated framework may have policy implications in the building design and operation phase. Behavioral interventions designed to enhance comfort in the workplace can focus on the constraining factors identified with the integrated framework. For instance, information and guidelines on the building operation could be given to occupants describing available adaptive possibilities to the indoor climatic conditions, building systems operation and consequences of occupants' actions in terms of comfort, energy and social constraints. Characterizing better occupant's aspirations and expectations of the indoor environment may support the design of building systems and their integration with communication and feedback tools. Furthermore, targeting occupants' expectations of control strategies may have a direct impact on reducing energy consumption due to a congruence in expected and current behavior. Within a context of climate change, passive cooling strategies may gain a significant role on reducing energy use. Rising positive expectations of alternative energy-efficient technologies may have a significant impact on their acceptance and sustainable use of provided building control strategies.

5.4. Limitations

Even though the negative impact of the SARS-COV-2-pandemic during the summer months in 2020 on the working and life situation in Germany decreased significantly, it may have affected the contextual circumstances in which the respondents have answered the questionnaire. Although participants were asked to envision their working environment to answer the questionnaire, some participants might have been working from home, where indoor environmental conditions and building control possibilities may vary from those encountered at the office. Their current home experience may have influenced the expected comfort level reported in the questionnaire, which may not match the one usually expected in the working environment. Similarly, the reported behavior from home may differ from the expected interactions at the office. Furthermore, while the scenario and questionnaire approach were appropriate for this study for reasons explained, thermal and behavioral expectations as indicated in surveys may not translate into actual comfort or behavior. Due to the pandemic, we were not able to measure the extent to which the hypothetical reported behavior and comfort level may have corresponded to actual perceptions of indoor environmental quality and building interactions. We suggest to conduct additional studies in laboratories or in situ to examine that consistency. As concluded by Heydarian et al. [8] research could gain further confidence through integrated survey-based and monitoring studies to generalize the application of behavioral theories.

6. Conclusions

This study aimed at understanding underlying cognitive processes that lead to perceived comfort and adaptive behaviors. We proposed an integrated framework of expectations that integrates constructs from the TPB, the NAM and the Self-efficacy theory to define measurable dimensions of expectations under a psycho-physiological model of comfort and behavior. Within this study it was found that expectations were important drivers of comfort and behavior and cognitive processes are needed to explain expectations of the indoor environment and comfort-related behaviors. Findings from this study showed that previous experiences with buildings systems, such as fans, mediated the relationship between the occupants' expected behavior to adapt to the indoor climatic conditions and their actual behavior. The proposed theoretical framework of behavioral and thermal expectations of the built environment is a contribution to the assessment of comfort and occupant behavior literature. Additionally, findings may have implications on the design of adaptive opportunities to enhance occupant satisfaction with the workplace and to support design strategies to reduce the building energy consumption. Further research should focus on how occupant expectations can be modified and challenged to tailor the acceptance of new energy-efficient technologies within a changing and dynamic climatic scenario.

Institutional review

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the data protection officer of the Karlsruhe Institute of Technology (Date of approval: 31.07.2020).

Informed consent

Informed consent was obtained from all subjects involved in the study.

CRediT authorship contribution statement

Romina Rissetto: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Riklef Rambow:** Writing – review & editing, Supervision. **Marcel Schweiker:** Methodology, Supervision, Writing – review & editing, Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

This appendix presents the translation into English of the questionnaires used for the study presented in this paper. Note that the questionnaire applied in this study was in German and the here presented translations were not validated (the German version is available from the authors per request). The instructions given were: "Bitte wählen Sie die Option, die am ehesten auf Sie zutrifft." ("Please select the option that most closely applies to you."). Sentences in the tables written in italics indicate removed items after factor extraction and reliability test.

Table A1

Main variables and associated survey questions for thermal expectations and thermal history (N = 449). Sentences in the table written in italics indicate removed items after factor extraction and reliability test. Factor loadings over .40 appear in bold.

Construct	Item description	M (SD)	Factor 1	Factor 2
Thermal expectations	I expect that the indoor climatic conditions at the office will be pleasant during the summer term.	3.96 (2.01)	**0.87**	0.08
	I expect that the indoor climatic conditions at the office will be pleasant during the winter term.	5.16 (1.53)	−0.01	**0.91**
	I expect that the indoor climatic conditions will be unpleasant at the end of the working day during the summer term.	3.44 (2.08)	**0.87**	−0.12
	I expect that the indoor climatic conditions will be pleasant at the end of the working day during the winter term.			
	I expect that the indoor air quality at the office will be good during the summer term.	4.13 (1.90)	**0.85**	0.13
	I expect that the indoor air quality at the office will be good during the winter term.	4.91 (1.55)	0.14	**0.81**
	I expect that the indoor air quality will not be good at the end of the working day during the summer term.	3.50 (2.09)	**0.80**	−0.10
	I expect that the indoor air quality will be good at the end of the working day during the winter term.			
	I assume that I will not be too warm at the office even if it is very hot outside.	3.51 (2.09)	**0.84**	0.02
	I assume that I will not be too cold at the office even if it is very cold outside.	5.25 (1.63)	−0.08	**0.86**
Thermal history	I often have the feeling that I freeze faster than others.	2.79 (2.08)	**0.94**	0.
	I am always warm.			
	When on mild spring days some people still walk outside with their coat, I already feel comfortable in light clothing.			
	I feel that I have to wear more/warmer clothes than others in order not to freeze.	2.94 (1.89)	**0.93**	0.
	I feel cold very often.	2.78 (1.83)	**0.93**	0.
	In general, I feel more comfortable in countries with a hot climate.	3.87(1.96)	0.	**0.94**
	In general, I feel more comfortable in countries with a cold climate.	4.10(1.93)	0.	**0.87**
	In the warm season, I regularly need to have some refreshment or things to cool down, such as a cold shower.			
	In the cold season, I really need things to warm me up, like a hot water bottle, wool socks or a hot shower.			

Table A2
Main variables and associated survey questions for self-efficacy perceived control and attitudes. Sentences in the table written in italics indicate removed items after factor extraction and reliability test. Factor loadings over .40 appear in bold.

Construct	Item description	M (SD)	Factor
Self-efficacy	When resistance arises, I find ways and means to assert myself.	5.21 (1.23)	**0.77**
	I always succeed in solving difficult problems when I put my mind to it.	5.47 (1.12)	**0.79**
	I have no difficulty in realizing my intentions and goals.	5.17 (1.26)	**0.79**
	In unexpected situations I always know how to behave.	5.00 (1.27)	**0.81**
	Even in the case of surprising events, I believe that I can cope with them well.	5.41 (1.15)	**0.84**
	I face difficulties calmly because I can always trust my abilities	5.28 (1,21)	**0.82**
	No matter what happens, I will be fine.	5.49 (1.14)	**0.86**
	I can find a solution to any problem.	5.35 (1.21)	**0.80**
	When a new thing comes my way, I know how to deal with it.	5.26 (1.21)	**0.86**
	When a problem arises, I can cope with it by myself.	5.36 (1.10)	**0.85**
Perceived control	*Basically, I feel like I have my life under control.*		
	If I wanted to, I could change my life from the ground up.		
	I don't think I'm in a position to really change things.		
	In the office I can influence how warm or how cold I feel	4.77 (1.76)	**0.96**
	I feel that I can influence my environment through my actions.		
	Ultimately, others decide how my life goes.		
	I think that I can control the indoor climate in the office myself.	4.76 (1.77)	**0.96**
Attitudes	*I find opening a window a reasonable approach to improve the room temperature in the office.*		
	I find using fans a reasonable approach to improve the room temperature in the office.	4.91 (1.82)	**0.64**
	If I could choose, I would use an energy-efficient cooling strategy.		
	If I could choose, I would prefer to use a ceiling fan instead of turning on the air conditioning system.	3.97 (2.03)	**0.80**
	Using a ceiling fan is more sustainable than turning on the air conditioning system.	4.79 (1.74)	**0.85**
	Using a ceiling fan is an energy-saving cooling strategy.	4.68 (1.72)	**0.90**
	It is very important to me to protect the environment.		

Table A3
Main variables and associated survey questions for behavioral expectations, personal norm and previous experience. No factor extraction was done for these constructs. Variables were analyzed and tested separately.

Construct	Item description	M (SD)
Behavioral expectations	I assume that I will open the window if I am too hot.	5.31 (1.79)
	I assume that I will turn on the fan when I am too warm.	4.98 (2.03)
	I assume that I will take off a piece of clothing when I am too warm.	4.51 (1.99)
	I assume that I will turn on the air conditioning/mechanical ventilation system if I am too hot.	4.39 (2.40)
	I assume that I will operate the blinds when I am too warm.	5.27 (2.00)
Personal norm	It is very important to me to open a window in the office when I am too warm.	5.62 (1.64)
	It is very important to me to turn on the fan in the office when I am too warm.	5.12 (1.94)
	It is very important to me to take off a piece of clothing in the office when I am too warm.	4.80 (1.95)
	It is very important to me to operate the blinds in the office when I am too warm.	5.67 (1.59)
	It is very important to me to turn on the air conditioning/mechanical ventilation system in the office when I am too warm.	5.22 (1.94)
Previous experience	Open a window	4.19 (1.06)
	Open a door.	3.52 (1.32)
	Operate the blinds.	3.81 (1.33)
	Turn on a desk fan.	3.41 (1.49)
	Turn on a ceiling fan.	2.10 (1.52)
	Take off a piece of clothing.	3.69 (1.23)
	Drink a cold/hot beverage.	4.14 (0.99)
	Switching on/off or turn up/down the heating.	4.05 (1.21)
	Switching on/off or turn up/down the air conditioning system.	3.16 (1.68)
	Leaving the building (outside).	3.55 (1.28)

Table A4
Estimates, standard errors, z- and significance values of latent variables for selected measurement model.

	Estimate	Std.Error	z-Value	P(>|z|)
Thermal expectation				
Thermal expectation summer	0.76	0.06	13.63	.00
Self-efficacy	0.51	0.06	9.11	.00
Personal control	0.80	0.06	12.50	.00
Thermal history	0.20	0.06	3.71	.00
Fan expectation				
Fan usage expectation	0.71	0.05	14.10	.00
Self-efficacy	0.23	0.05	4.19	.00
Personal control	0.35	0.06	6.06	.00
Personal norm Fan	0.91	0.05	17.97	.00
Attitudes	0.50	0.05	10.05	.00
Covariance				
Thermal expectation ↔ Fan expectation	-0.30	0.07	−4.65	.00

Table A5
Estimates, standard errors, z- and significance values of latent variables for selected structural model with. direct effects.

	Estimate	Std.Error	z-Value	P(>|z|)
Thermal expectation				
Thermal expectation summer	0.85	0.07	12.29	.00
Self-efficacy	0.50	0.52	9.64	.00
Personal control	0.72	0.07	10.84	.00
Thermal history	0.23	0.05	4.20	.00
Fan expectation				
Fan usage expectation	0.67	0.08	8.78	.00
Self-efficacy	0.20	0.05	3.86	.00
Personal control	0.31	0.06	5.43	.00
Personal norm fan	0.89	0.08	10.89	.00
Attitudes	0.50	0.06	8.94	.00
Covariance				
Thermal expectation ↔ Fan expectation	-0.29	0.06	−4.71	.00
Thermal comfort ↔ Fan usage	-0.14	0.06	−2.53	.01
Regressions				
Thermal expectation → Thermal comfort	0.43	0.06	7.88	.00
Fan expectation → Fan usage	0.64	0.05	12.25	.00

Table A6
Estimates, standard errors, z- and significance values of latent variables for selected structural model with direct and mediation effects.

	Estimate	Std.Error	z-Value	P(>|z|)
Thermal expectation				
Thermal expectation summer	0.82	0.06	14.65	.00
Self-efficacy	0.50	0.07	7.15	.00
Personal control	0.63	0.07	9.46	.00
Thermal history	0.28	0.07	4.06	.00
Fan expectation				
Fan usage expectation	0.66	0.06	10.71	.00
Self-efficacy	0.25	0.07	3.54	.00
Personal control	0.31	0.07	4.36	.00
Personal norm fan	0.86	0.06	14.78	.00
Attitudes	0.39	0.06	6.30	.00
Covariance				
Thermal expectation ↔ Fan expectation	−0.18	0.09	−2.17	.03
Thermal Comfort ↔ Fan usage	−0.11	0.07	−1.73	.08
Regressions				
Thermal expectation → Thermal comfort	0.41	0.06	6.57	.00
Fan expectation → Fan usage	0.49	0.08	6.04	.00
Fan expectation → Previous experience	0.46	0.07	6.99	.00
Previous experience → Fan usage	0.28	0.07	3.93	.00

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Article

Exploring Information and Comfort Expectations Related to the Use of a Personal Ceiling Fan

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Abstract: Rising global temperatures have increased the need for research into human adaptability and comfort in buildings. To reduce comfort-related energy demands, low-energy-consumption alternatives for space cooling, such as personal environmental control systems (PECS), are being investigated. The implementation of PECS in office buildings is still underway, and little is known about how occupants' expectations can influence their satisfaction with PECS and indoor environmental quality. This study examines the influence of tailored information and occupants' comfort expectations on their thermal perceptions and satisfaction with a personal ceiling fan. Seventy-six participants completed an online questionnaire and attended a half-day session at 30 °C in a climate chamber in Germany. A manipulation technique to activate personal norms was used to test the influence of information on expectations. Results indicated higher reported thermal comfort in participants with more positive thermal expectations, regardless of their expectations of the building systems. These effects were largely moderated by personal norms, indicating the importance of activating normative motivations to increase thermal comfort. Occupants with negative expectations improved their perceptions of the fan when making personal adjustments to stay comfortable. However, this effect was not moderated by personal norms. Practical implications focus on manipulating occupants' comfort expectations, e.g., by providing occupants with normative messages and individual control, to achieve greater comfort and acceptance of personal building controls in naturally ventilated buildings.

Keywords: psychological adaptation; adaptive behaviors; personal ceiling fan; personal norms; test chamber; thermal perception; thermal comfort

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1. Introduction

The global climate emergency has led to a push to deliver habitable indoor spaces, resulting in a growing demand for space cooling. A compounding increase in the use of air conditioning is expected, which will sharply escalate global carbon dioxide emissions. By better understanding how humans perceive and adapt to their thermal built environment, it may be possible to reduce the comfort-related energy demands of buildings. The literature on adaptive thermal comfort has gained particular attention over the past twenty years [1]. According to the theory of adaptive thermal comfort [2], three mechanisms take place in the adaptive processes of occupants in buildings—namely behavioral, physiological, and psychological mechanisms. Although many efforts have been made to understand the different factors that influence human adaptation, there is still a gap between predicted and actual occupant comfort and behavior observed in field studies [1,3].

The concept of comfort expectations has been studied as a relevant dimension of psychological adaptation to the environment [2]. According to the expectation hypothesis, an expectation (or anticipatory attitude) affects people's attitude towards thermal comfort attainment. Thus, the expectation of specific thermal conditions is certainly a major aspect of subjective assessment and satisfaction [4,5]. Some empirical evidence from China [6] suggested that long-term thermal experiences can raise thermal comfort expectations and that it is easier and quicker to enhance an individual's thermal expectations but harder to lower them. Accordingly, occupants in air-conditioned buildings are quicker to complain whenever the indoor temperature slightly strays from the usual set point because they have come to expect thermal constancy [7].

Relaxing comfort expectations could be an alternative path to promote resilience in buildings. A strategy to transform expectations could be achieved by widening occupants' thermal acceptability through adaptive behaviors, especially in free-running and green buildings [8,9]. Adding adaptive capacity in buildings, that is, the ability to implement effective adaptation strategies, is strongly related to control strategies [10]. Luo et al. [11] suggested the implementation of personal environmental control systems (PECS) as an adaptive strategy. PECS have the advantage of controlling the localized environment at the occupant's workstation according to their preferences rather than conditioning an entire room. Thus, PECS have the potential not only to save energy but also to improve comfort by addressing intra- and interpersonal differences among occupants [12,13]. Personal fans have been widely implemented as a type of PECS, as the cooling effect of air movement increases the thermal comfort and acceptability range of occupants in moderately warm thermal conditions [14–16].

By giving occupants the responsibility of managing certain aspects of the building, more information needs to be provided related to the passive features and building control systems in order to pursue an energy-efficient approach [17]. On the one hand, this might reduce the gap between how designers expect occupants to use a building and how they actually do. On the other hand, information feedback has been shown to help occupants save energy. For example, Schweiker et al. [18] found that participants receiving training and information about passive strategies were more likely to apply such methods and to reduce high-energy-consumption devices, such as AC-units. Day et al. [19] found that individuals who reported effective training and therefore understood how to operate the building controls were significantly more likely to be satisfied with their office environment when compared to individuals who did not receive any kind of training. Brown et al. [20] found a positive relationship between knowledge of a building's systems and higher use of personal control.

Research Gap and Scientific Contribution

Although several experimental and field studies have shown the potential of providing effective information and increasing occupants' knowledge to promote energy-saving behaviors [21,22] and increase occupant satisfaction [23,24], little work has examined how tailored information may influence the interaction between comfort expectations and satisfaction with PECS in naturally ventilated buildings. Thus, this study aims to understand whether information and knowledge can manipulate occupants with different positive or negative expectations about PECS and some aspects of the indoor environmental quality (IEQ), as such expectations could, in turn, influence occupants' satisfaction with the building controls and their perception of the indoor environment. The following research questions will be examined:

- To what extent do occupants' different expectations of the indoor environment and adaptive possibilities influence their a) thermal and indoor air quality perception and b) their satisfaction with a type of PECS?
- To what extent can tailored information to activate normative motivations be used to manipulate thermal and indoor air quality perception and satisfaction with a type of PECS of occupants with different expectations?

To address the identified research questions, this study investigates the relationship between occupants with different expectations of their built environment and their satisfaction with their indoor environment, as well as how expectations of a type of PECS can be manipulated to achieve greater satisfaction with the device. The existing definitions, relevant studies in the literature, and the research hypotheses are presented in Section 2. An experimental study and an online survey were conducted to test the research hypotheses. The study design and methods for data collection and analysis are presented in Section 3. The results and related hypotheses are discussed in Section 4.

This work contributes to the research on the acceptance of a type of PECS to increase its prominence and implementation in buildings and adds knowledge to the adaptive comfort literature by deepening the concept of comfort expectations in naturally ventilated buildings. The application of a theory-based definition of comfort expectation in a case study and the relationship between occupant expectations and their acceptance of a personal control device constitute the novelty of this paper.

2. Literature Review, Definitions and Hypotheses

2.1. Thermal and Behavioral Expectations

Evidence indicates occupants' expectations of indoor building environments influence their perceptions of climatic conditions, and unmet expectations of building performance can lead to dissatisfaction with indoor conditions. To better understand the mismatch between the occupants' predicted thermal perceptions of indoor environments and reported satisfaction, expectations in prior studies have been conceptualized in different ways. Fanger et al. [25] introduced an expectancy factor that relates expectations to past experiences, such as habituation to warm environments and exposure to air-conditioned buildings. Schweiker et al. [26] investigated how observed expectations affect occupants' thermal comfort levels and found a significant influence of thermal memory on expected comfort. Comfort expectations have mainly been analyzed in relation to perceived control [6,8,27], thermal experience and exposure [28–31], and thermal memory [32].

Despite the mentioned efforts in the literature, there is a lack of evidence-based and theory-driven characterization of the psychological adaptive concept of expectation [1]. In a recent study, the authors of reference [33] proposed a framework to operationalize expectations through cognitive mechanisms from well-established psychological and comfort theories (i.e., self-efficacy, perceived control, thermal history, and personal norms and attitudes). The model was tested through a nationwide survey, and it was concluded that expectations are key drivers of comfort and comfort-related behaviors. Based on the psycho-physiological model of Auliciems [34] and the adaptive theory, the framework established that expectations can be distinguished by thermal and behavioral expectations, which can be defined as follows:

- Thermal expectations: the thermal experience foreseen by occupants; the anticipated result, their perception of what will occur.
- Behavioral expectations: the likelihood of engaging in a specific behavior to adapt to the thermal environment to improve their comfort.

The results of the study [33] showed that the more the positive thermal expectations of the indoor environment were, the greater the associated reported thermal comfort was. Similarly, a positive relationship was found between more positive behavioral expectations toward a specific behavior and the probability of performing that action. A negative correlation was found between thermal and behavioral expectations, supporting the adaptive principle. The theoretical framework was empirically tested by asking the survey respondents to envision a working space with defined adaptive opportunities, but participants' actual comfort votes and adaptive actions were not captured in real-time and under the actual thermal conditions and building settings. Although the relationship between thermal and behavioral expectations was evaluated, the combined effect of positive–negative thermal and behavioral expectations on participants' thermal comfort and behavior responses was not investigated. It would be meaningful to classify different types of thermal and behavioral expectations for groups of participants with similar cognitive mechanisms, as this may give insights into how different groups of occupants may be targeted according to their shared expectations.

2.2. Provided Information and Building Interactions

In addition to individual differences in preferences and expectations for thermal comfort, variations in occupants' behaviors may result from their inadequate understandings of the building controls and purpose design of the building [35] or from missing knowledge or feedback regarding the effect of occupant actions (e.g., [36,37]). Studies on feedback and feedforward information revealed that the decisions made by occupants can be manipulated by providing feedback about the consequences of their previous actions [38] or feedforward information advising occupants prior to their actions [21,39,40]. Only a few studies have analyzed the impact of feedback and feedforward information on the decision process of occupants with respect to their building interactions and their change in comfort level after such decisions.

Meinke et al. [41] concluded that participants tended to interact more rationally with their built environment when receiving information about the consequences of different cooling strategies on comfort and energy consumption. They also found that when occupants were more aware of their control options, it led to increased perceived control and, consequently, higher comfort. Brown et al. [20] found that occupants' knowledge of the building, i.e., awareness and understanding of the building's environmental features and control systems, was positively related to the use of personal control in green buildings. More recently, Arpan et al. [42] investigated the effect of information on building occupants' expectations of sustainable buildings. They concluded that potential building occupants who are informed about the common features of sustainable buildings and how they function may have more positive a priori expectations about the thermal and indoor air quality conditions in the building. Accordingly, it could be hypothesized that providing information about the benefits and operation of PECS could create positive expectations towards the device and, consequently, satisfaction with it.

2.3. Normative Motivations

Additional results from the above-mentioned study [33] showed that behavioral expectations were partially explained by personal norms: participants with greater motivations towards passive cooling strategies (stronger personal norms) will express higher expectations to successfully modify their indoor environment. Changes in user expectations may be reflected in expectations of building systems and occupant behavior [43]. Research conducted in intervention studies suggests that normative motivations, i.e., people who prioritize collective interests over their personal ones, have a significant impact on anticipating and designing interventions to encourage energy-saving behavior [39]. Accordingly, when activating personal norms, occupants' behavior is driven by feelings of moral obligation to act in a norm-concordant manner. In this sense, occupants with strong personal norms suggest that they are intrinsically motivated to act pro-socially—following normative considerations—and increase their sense of self-worth. For example, Hameed et al. [44] studied patterns of adoption of low-carbon practices and concluded that normative motivations were key drivers for the purchase of energy-saving air conditioners in Pakistan. Similarly, Gerhardsson et al. [45] found that lighting behaviors, such as improving lighting technology, were driven by normative goals, while Wall et al. [46] found that environmentally motivated participants who were motivated to save energy were more tolerant of the poor performance of energy-efficient energy lamps than less environmentally motivated participants. By activating personal norms, individuals tend to act according to those norms and are more willing to make concessions to meet their standards of behavior, especially those who are more environmentally engaged [47].

A theoretical foundation prominently used in psychology to analyze behavioral change and promote pro-environmental behaviors is the goal-framing theory [48]. According to this theory, goals determine or "frame" what people pay attention to, what knowledge and attitudes become most cognitively accessible, how people evaluate different aspects of the situation, and what alternatives are being considered. A "goal-frame" is the way in which people process information and act on it. If people change their goals, they will also perceive the situation differently. When it is activated or "focalized", a goal is a combination of a motive and an activated knowledge structure. There are three types of frames: gain, hedonistic, and normative frames. The latter two will be considered for the present study. Hedonistic frames activate subgoals that promise to improve how one feels in a particular situation. Their time horizon is very short, and people in this frame are sensitive to what changes their pleasure and mood. For example, feeling warm in a room may decrease a person's thermal comfort. The normative frames of "act appropriately" activate goals related to what is appropriate, and people in this frame are sensitive to what should be done according to their self or others, including, for example, turning off the thermostat when the windows are open even if the person does not pay the bill simply because it is the right thing to do.

In an experimental study, Li et al. [24] used social normative messages to investigate intended occupant interactions with a PECS, showing a positive influence of feedforward information on the intended use of a personal desk fan. Thus, informing individuals with strong pro-environmental norms about PECS features designed to protect the environment should activate their normative goals and subsequently motivate them to act—or perceive the situation—in a manner that is congruent with those personal norms. Accordingly, it might be expected that some occupants would have more positive expectations of PECS and be more tolerant of indoor conditions when these overarching personal goals are activated.

2.4. Hypotheses

The review of the state of the art has shown that there is a lack of studies assessing the effect of occupants' expectations and normative motivations on their satisfaction with thermal and indoor air quality conditions and personal controls in buildings. Based on the state of the art in combination with the definitions presented, a preliminary framework for the assessment of expectancy was developed (Figure 1), which summarizes results from a previous study on thermal and behavioral expectations [33] and proposes a new investigation to assess the effect of expectancy groups on thermal satisfactions and satisfaction with PECS tailored by normative motivations.

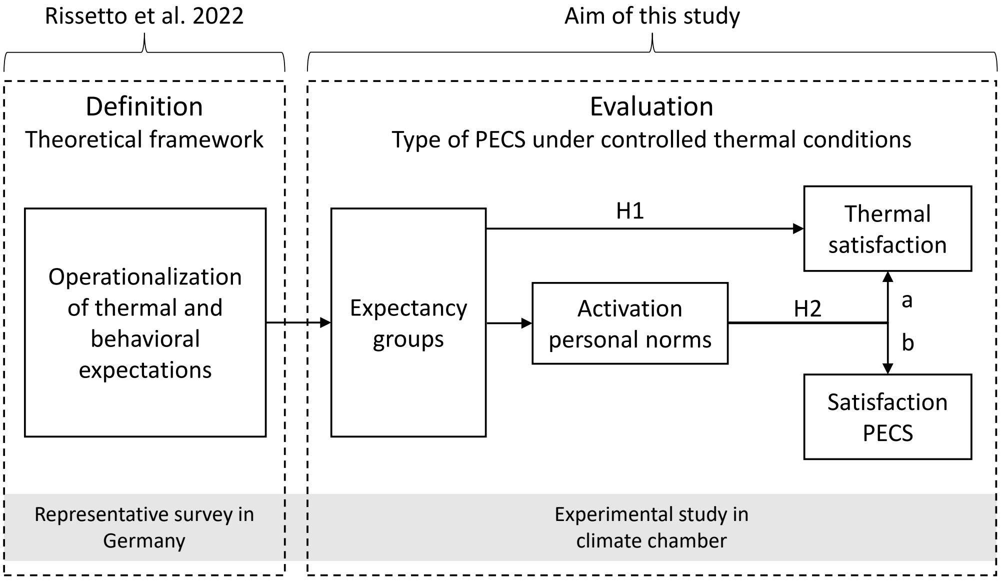

Figure 1. Proposed framework to assess occupants' expectancy, personal norms, and satisfaction with thermal conditions and a type of PECS, together with an existing theoretical framework [33]. H1, H2a and H2b are the investigated hypotheses.

Based on the above-stated research questions, the following hypotheses will be investigated:

- H1: A person with more positive expectations about the thermal conditions in the room and towards a type of PECS will find the climatic conditions more acceptable, expressing higher thermal satisfaction than a person with more negative expectations.
- H2: By activating normative motivations through tailored information, expectations can be influenced in a positive direction so that (a) participants with more positive expectations will express higher thermal satisfaction and (b) participants with more negative expectations will show a change in expectations after using the PECS.

3. Methods

In order to assess the proposed hypotheses, an experimental study in a laboratory setting and an online survey were conducted. First, participants were asked to complete an online questionnaire prior to attending a half-day session at the LOBSTER test chamber in Karlsruhe, Germany [49]. The latter consists of two identical office rooms, each with two operable windows and blinds facing north. The surface of the test facility (except for the glass facade) is activated with a capillary tube system, which allows set point temperature of each surface to be changed individually. For this study, each room was equipped with a personal ceiling fan. The sessions took place over 15 working days in August 2021. All procedures were approved by the data protection officer and the ethics committee of the Karlsruhe Institute of Technology and were conducted in accordance with the Declaration of Helsinki. The study is described as follows.

3.1. Recruitment and Participation

Participants were recruited primarily through the local newspaper and university websites. Participants had to be non-smokers and be German or have a good command of the German language to ensure that they understood and were capable of answering the provided questionnaires. They received monetary compensation for participating in the survey and the test chamber session. A total of 76 participants (35 male and 41 female), aged 18–34 and 50–70 years, took part in the half-day experiment and completed the online questionnaire. The aim of including those age groups was to increase the probability of participation and control the sample, as there was a higher probability that individuals of those groups were able to participate in the experiment during working hours and have higher motivation to receive a monetary compensation (e.g., students or retired participants). For the session in the LOBSTER, participants were asked to wear long pants, a shirt, and closed shoes. Clothing data were collected in the initial questionnaire, and the clothing level was estimated based on self-reported clothing items in the questionnaire and converted to clo values based on ISO 7730 [50]. An average value of 0.44 clo (SD = 0.12) was calculated with an additional value of 0.10 clo to account for the insulation provided by the desk chair. The participants were not allowed to change their clothing level (e.g., by taking off their sweater or shoes) during the test.

3.2. Pre-Test: Online Questionnaire

Participants completed an online background questionnaire one week before the LOBSTER session. The focus of the questionnaire was to assess participants' psychological constructs that represent expectations about the indoor environment and PECS, as well as related topics, such as sustainability or passive climate control strategies in buildings. The questions were based on the expectancy framework proposed by Rissetto et al. [33]. The questionnaires were sent via Limesurvey [51]. The purpose of this pre-test was to obtain the long-term attitudes of the participants without the possible influence of the controlled environment and the experience with the personal ceiling fan in the test chamber.

The survey consisted of three parts. The first section included an anonymous ID code to allow a comparison with the results of the session in the test chamber (see Section 3.3) and the measures of control variables, mainly current mood, experience with and evaluation of fans, experience working in an office environment (e.g., use of air conditioning and the use of building controls to adjust to climatic conditions). The second section included the main measures of this study: (1) measures of thermal expectations and behavioral expectations, (2) self-efficacy, perceived control, personal norms, thermal history, and attitudes, and (3) reported comfort and behavior. Finally, the third section included temperature type and sensitivity to indoor air quality and humidity, as well as expectations of ceiling fans. The last item was included to analyze the effect of information on a possible change in fan expectations (related to H2b).

3.3. Session in the LOBSTER

The same participants participated in a half-day session (either morning or afternoon) in the test chamber. Each session lasted three and a half hours, and a single participant occupied each room. Figure 2 describes the complete schedule before and during one session in the chamber. For the first 10 min, the study and the schedule were explained to the participants in the hallway. During the first half hour (acclimation phase), they entered the respective room and adapted to the climatic conditions. Both groups experienced warm indoor thermal conditions, so the walls' surface temperature was set to 30 °C. Participants were not able to modify the indoor environmental conditions of the rooms. During the next three hours, they engaged in personal activities, such as reading their own material or working on the computers provided. Meanwhile, they had the opportunity to perform different adaptive measures to restore their comfort with the thermal environment: (1) turning on the ceiling fan, (2) tilting the window(s), or (3) drinking water or another beverage.

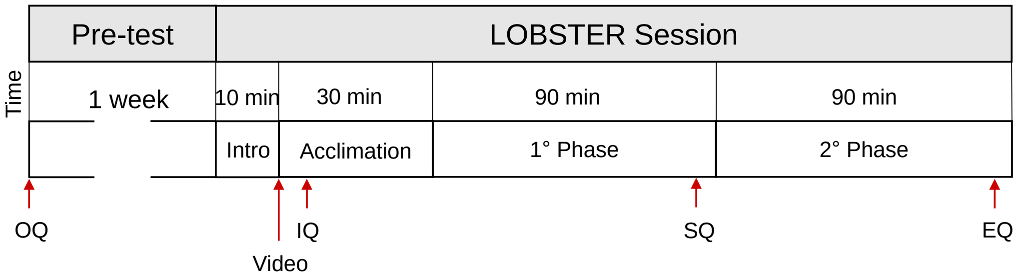

Figure 2. Timeline of surveys and experimental conditions before and during the session in the LOBSTER. OQ: online questionnaire. IQ: initial questionnaire; SQ: status questionnaire; EQ: end questionnaire.

Figure 3 shows the workstation, the personal ceiling fan, and the corresponding sensor equipment. The participants were seated 50 cm away from the center of the personal ceiling fan and 1.50 m from the windows. The personal ceiling fan corresponds to a type of PECS as it is workstation-related, i.e., each occupant owns a device, and can be individually controlled by the occupant. The axial fan had a small rotating area, and it was integrated into an acoustic panel to improve the acoustics in the room. The integrated ceiling fan had an adjustable grille to direct the airflow to the head of the participants, which in this study was directed towards the side of the participant's head. The influence of different airflow directions was previously tested for this personal fan [52], and no significant difference was found between top, back, frontal and side airflow. The air velocity of the ceiling fan could be adjusted by the participants using a remote control. Further descriptions of the ceiling fan can be found in Rissetto et al. [52].

Participants completed various questionnaires during their stay via a web interface based on pre-set schedules (Figure 2). The focus was to collect information mainly on their perception of and satisfaction with the IEQ and the personal ceiling fan. As the questions were asked in the German language, most of the questions and corresponding scales were based on the German index "INKA: Instrument für Nutzerbefragungen zum Komfort am Arbeitsplatz" to assess comfort in office buildings [53], which is based on the questionnaire of ASHRAE 55 [54]. The questionnaires were divided into three blocks according to different experimental phases: an initial questionnaire (IQ) at the beginning of the acclimation phase (first 30 min of the experiment), an intermediate questionnaire

(SQ) at the end of the first hour and a half after the acclimation phase (phase 1), and a final questionnaire (EQ) asked 10 min prior the end of the second phase of the experimental part of the session (phase 2). Participants were exposed to the same thermal conditions in phases 1 and 2, but each phase indicated the appearance of the comfort questionnaires at different points in time (SQ and EQ) to evaluate the comfort votes during the length of the study. To analyze a possible change in fan expectations, participants were asked about their experiences with fans and their expectations and preferences with the personal ceiling fan and PECS in general to examine whether the expectations reported in the background questionnaire (Section 3.2) changed after using the personal device and having received the targeted information (see Section 3.3.2). Table 1 summarizes the key variables collected on the questionnaires relevant to this paper.

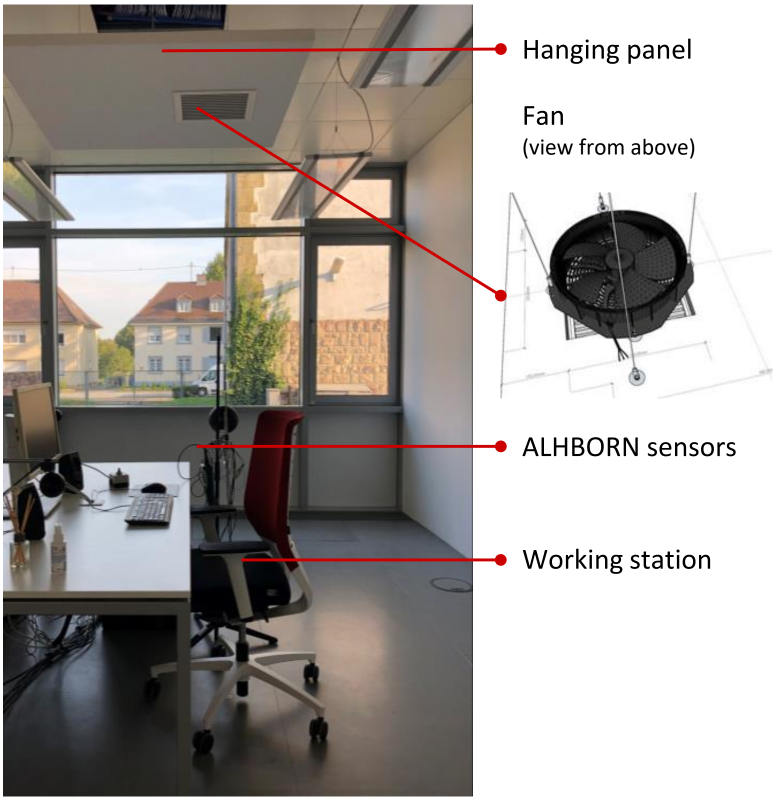

Figure 3. Setup of ceiling fan, sitting position, and sensors in the office room in the test chamber.

Indoor and outdoor parameters were collected from sensors through the building management system (BMS). Air temperature (Mean = 29.7 °C, SD = 0.6), globe temperature (Mean = 29.6 °C, SD = 0.6), relative humidity (Mean = 41.9%, SD = 4.5), and air velocity (Mean = 0.13 m/s, SD = 0.1) were collected with AHLBORN comfort meters placed at the height of 1.10 m and 0.25 m away from the participant's head. The corresponding resolutions are 0.01 °C, 0.01 °C, 0.1%, and 0.001 m/s; the accuracies are ±0.2 K, ±(0.30 K + 0.005 × T), ±2.0%, and ±(3% reading + 0.01), respectively. Interactions with the remote control and with the windows were recorded by the BMS. The fan speed chosen by participants through the remote control was recorded as a continuous variable between 0 and 100%. At the end of the sessions, participants were asked about their drink consumption. Physiological data were also collected, including heart rate (EcgMove 4: r = 12 bit, input range CM = 560 mV, DM = +/−5 mV) and skin temperature (iButton DS1921H: r = 0.125 °C, a = +/− 1 °C). The resulting analysis of the physiological data was not included in this paper. All data were recorded at 1 min intervals.

Table 1. The main information obtained by the questionnaires. All answers are integer values. Note: the provided questionnaires were in German; the English translations in the table were not used in the study and are presented only for understanding purposes. The German version is available from the authors per request.

Measure	**Description of Item**	**Response Categories**	**Mean (SD)**
Thermal sensation [a]	"Wie fühlen Sie sich jetzt gerade?" (*How do you feel right now?*)	−3 (cold) to +3 (hot)	4.79 (0.55)
Thermal comfort [a]	"Empfinden Sie dies als. . . " (*Right now, do you find this environment...?*)	1 (extremely uncomfortable) to 5 (comfortable)	3.87 (0.55)
Thermal preference [a]	"Wie hätten Sie es jetzt gerade lieber?" (*Right now, would you prefer to be...?*)	1 (much cooler) to 7 (much warmer)	3.29 (0.54)
Thermal acceptability [a]	"Wie empfinden Sie diese Temperaturbedingungen jetzt gerade?" (*Right now, do you find the thermal environment...?*)	1 (clearly unacceptable) to 4 (clearly acceptable)	3.47 (0.55)
Indoor air quality perception [a]	"Wie nehmen Sie die Raumluftqualität im Büro wahr?" (*How do you perceive the indoor air quality in the office?*)	1 (very good) to 7 (very bad)	4.26 (1.02)
Fan satisfaction [b]	To maintain comfortable indoor temperatures, the ceiling fan is more effective than I expected; To maintain comfortable indoor temperatures, the ceiling fan is more effective than I expected; If I could choose, I would rather use a ceiling fan than open the windows; I have control over the personal ceiling fan; The ceiling fan is easy to operate; The ceiling fan fits well with the floor plan and furnishings of the office; I can understand the advantages of the ceiling fan; The ceiling fan is quiet; Being able to adjust the air velocity myself is an advantage of the ceiling fan; Improving the indoor climate is a benefit of using the ceiling fan; If I could choose, I would use the fan as an energy-saving cooling strategy; If I could choose, I would use a ceiling fan instead of turning on an air conditioner; I consider myself capable of operating the personal ceiling fan; I should avoid opening the window when it is very warm outside.	1 (strongly disagree) to 7 (strongly agree)	8.24 (0.76) [6.05, 9.40] [d]
Fan expectations [c]	Same as before, but slightly modified and adapted in the form of *"I expect that ..."*	1 (strongly disagree) to 7 (strongly agree)	4.53 (2.11) [1.52, 8.83] [d]

[a] Measured in IQ, SQ, and EQ during the LOBSTER session. [b] Measured in EQ during the LOBSTER session. Scale reliability: 0.70. [c] Measured in background questionnaire (pre-test). Scale reliability: 0.93. [d] Unstandardized values resulting from principal component analysis (PCA) conducted with all presented questions (see Section 3.4.1).

3.3.1. Classification of Expectancy Groups

Participants were divided into groups to investigate the influence of different "levels" of expectancy on occupant satisfaction (related to H1). The clustering process was adapted from a previous study [55] following these steps:

- Using a training dataset, the cluster structure was calculated to explain a selected threshold of 80% of the variance using the k-means method [56].
- As the k-means method requires the number of clusters as an input, the elbow method was applied to calculate the optimal number of clusters.
- A test dataset was fitted to the obtained cluster structure using a support vector machine (SVM) method [57], which is a class of supervised learning algorithms that train the classifier function using labeled data.

A pre-analysis of the data from the nationwide survey to assess comfort expectations [33], explained in Section 2.1, was used as the training dataset to define the cluster structure. An expectancy value was obtained for each participant by assigning two scores: one for thermal expectations and one for behavioral expectations. The scores were obtained by principal component analysis (PCA). The obtained expectancy value was used to define the cluster centers using the k-means algorithm. The results from the elbow method showed an optimal number of three clusters. The corresponding label (cluster) was assigned to each point of the training dataset.

Prior to the LOBSTER session, the new scores for expectancy values were obtained for each participant using the data from the online survey explained in Section 3.2 (test data). With the labeled data, the SVM linear classifier was used to fit the participants' scores from the test data into the defined cluster structure. Figure 4 shows the results of the SVM. The different colors represent the three clusters. We can interpret the cluster classification as follows: participants in cluster 1 had positive fan expectations and negative thermal expectations; participants in cluster 2 had positive thermal and fan expectations; participants in cluster 3 had near-neutral thermal expectations and negative fan expectations.

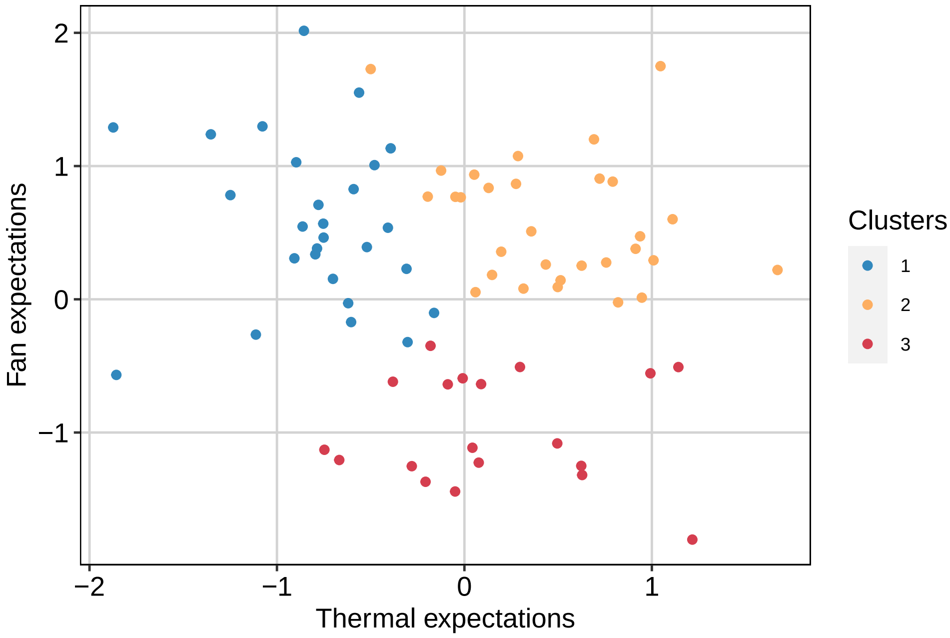

Figure 4. Classification groups for thermal and behavioral expectations based on the SVM method.

This clustering process was carried out before the session in the LOBSTER to similarly distribute participants according to daytime (morning/afternoon) and information groups (Section 3.3.2).

3.3.2. Manipulation Technique

The experimental study used a manipulation technique to test the effect of information on occupants' expectations and satisfaction (H2). The main goal of the manipulation technique is to activate hedonistic frames in all participants and to test whether normative frames predominate over hedonistic frames according to the different information provided. To activate the hedonistic frames, the office rooms were set to warm conditions, which can act as a stimulus for subjects to perform an action to restore thermal comfort (hedonistic motivation). Previous studies investigating the cooling effect of air movement under controlled conditions in test rooms [58,59] found that thermal comfort can be achieved at an indoor temperature set point of 30 °C if a personally controlled fan was provided. For this study, a setpoint of 30 °C was selected to trigger warm discomfort and encourage the use of the personal fans to achieve thermal comfort without compromising health and productivity issues that may affect occupants' satisfaction in the room. To fulfill the hedonistic frames, i.e., to restore thermal comfort, participants were provided with adjustment options, such as turning on the ceiling fan, opening the window, and drinking a beverage. Questions about the fulfillment of hedonistic frames were asked in the final questionnaire (EQ).

Participants watched a video (see Figure 2 in Section 3.3) that provided information about sustainability and energy efficiency in buildings to activate the normative frames. Two different videos were created. The control group was shown a shorter video containing general information about sustainability, climate change, and political energy targets in Germany, as well as the aim of the study. The experimental group was shown a longer video (https://www.youtube.com/watch?v=JJdQMij2kT0, accessed on 14 January 2024) that had the same initial content as the control group but included additional information about benefits and scientific explanations on how ceiling fans work.

The inclusion of general information is to set a "baseline" of information for all participants. The distinction between videos (additional information on personal ceiling fans) is intended to increase motivation to use the low-energy-consumption device in opposition to other non-energy-efficient strategies, such as opening the windows when it is too warm outside. Accordingly, participants were divided into the experimental group (long video) and the control group (short video). Both groups received instructions with a standardized text on how to operate the adaptive strategies: turning on and adjusting the air velocity of the ceiling fan, opening the tilt windows, and recording beverage intake in liters. Different adaptive opportunities to counteract thermal discomfort were given based on the work from Meinke et al. [41] to evaluate the influence of the provided information about the potential change in comfort and energy consumption of the personal ceiling fan on the experimental group. Participants were similarly distributed according to their cluster group of expectations described in the previous section.

During the session, participants were also asked to rate the educational video. All questions had a 7-point Likert scale ranging from strongly disagree (1) to strongly agree (7).

3.4. Data Analysis

All data preparation and analysis were performed in the software environment R (Version 4.1.3) [60]. The following subsections describe the assumptions and methods used for data analysis.

3.4.1. Sample Size and Checks on Random Assignment

The sample size was calculated using G*Power 3.1.9.7 [61]. Since the sample size was less than the required to achieve a small effect size, a large effect size was necessary (>0.8). For a t-test between two independent group means with an α value of 0.05, a power $(1 - \beta)$ of 0.95, and an effect size of 0.8, the required sample size was 74 participants.

Before testing the hypotheses, we verified the equivalence of the participant groups in the two research conditions using t-tests and Chi-square analyses (see Appendix A for results of these equivalence tests). Table A1 shows the distribution of participants from the different clusters according to their demographics and other characteristics, as well as the experimental conditions. Body mass index was categorized into two groups according to the WHO classification [62]: BMI < 25 kg/m^2 = normal and BMI > 25 kg/m^2 = overweight. The results showed that BMI and previous experience in working in an office were significantly different between clusters. Accordingly, we controlled for those variables by entering them as covariates in the tests of H1–H2. Table A2 shows the distribution of participants from the different clusters according to their actual mood, video rating, and fan use (air velocity and duration of fan turned on). None of the variables were significantly different between groups.

Additionally, we verified differences in indoor climate perception between the expectation clusters. To capture changes in the reported thermal comfort between the acclimation phase and the rest of the experimental phase, a mean value for comfort votes was taken for the whole test. Results of the Kruskal–Wallis tests showed that participants in cluster 2 were significantly more comfortable with the thermal conditions during the whole test compared to the other two groups (H(2) = 6.65, $p < 0.05$, $\eta^2 = 0.06$). A post hoc analysis was performed using the Dunn test to determine which levels of the independent variable differed from each other. The pairwise comparison test showed that cluster 2 is significantly different from cluster 1 ($p < 0.05$) but not from cluster 3 ($p = 0.089$). In addition, no differences were found for thermal sensation, preference, and acceptability and indoor air quality perception between groups. Therefore, only thermal comfort was kept for further analysis as the dependent variable to test the proposed hypotheses.

To evaluate changes in participants' fan expectations and evaluation, questions related to the expectations of personal ceiling fans from the background questionnaire (Section 3.2) and the last questionnaire from the LOBSTER session were analyzed. Firstly, a principal component analysis (PCA) was conducted on 13 questions from the background questionnaire. The weights from the background questionnaire were calculated to obtain the scores for the equivalent questions in the LOBSTER session. A single component was obtained for fan expectations (pre-test) and fulfilled expectations (LOBSTER session). To obtain a value representing the change between fan expectations (before the session) and evaluation (after the session), the difference between the two variables was calculated. The resulting variable was called "fan evaluation" (M = 3.71, SD = 2.25).

3.4.2. Hypotheses Testing: Statistical Tests

To test the hypothesis that groups of occupants with different types of thermal and behavioral expectations will express different thermal satisfaction (H1), a regression analysis was conducted. The single-answer options for measuring participants' evaluation of the temperature could not be assumed to be equidistant but needed to be considered as ordered categorical data [63]. Therefore, an ordinal model was selected to test the relationship between these ordinal response variables and one or more independent variables using the *clm* (cumulative link model) function from the R package ordinal [64]. The independent variable was the expectancy group (cluster), which was treated as categorical (1, 2, or 3). The hypothesis that the effect of information on participants' thermal satisfaction would be particularly strong among participants with more positive expectations of the indoor air quality and thermal conditions and the use of the personal ceiling fan (H2a) was tested with a conditional process analysis [65] using Hayes' PROCESS model 1 of moderation for R with cluster as the multicategorical variable. To test for possible changes in the expectations of participants with negative expectations after providing information (H2b), an additional process analysis was conducted with fan evaluation as the dependent variable. Similar to the evaluation approach for thermal comfort, fan evaluation was considered ordered categorical data.

4. Results

A series of predictive models were run to examine the above-mentioned hypotheses. H1 predicted that greater reported thermal comfort would be reported by participants with more positive thermal and behavioral expectations. To test this hypothesis, the total effect model was examined by testing the simple effect of the independent variable and control variables on the outcome variable. H1 was supported, as belonging to cluster 2 (the group with more positive thermal and behavioral expectations) was associated with significantly greater reported thermal comfort (Table 2). The coefficient in the model indicates a positive relationship: the more positive the thermal and behavioral expectations, the higher comfort participants in this group reported. A likelihood ratio test was performed with an ANOVA test. The results showed that the model that includes the expectation groups as a variable is significantly better than an intercept-only baseline model ($\chi^2 < 0.05$). Control variables of BMI and previous experience in working in an office did not significantly influence thermal comfort.

Table 2. Results of the ordinal regression analysis to test the effect of expectancy cluster on thermal comfort.

	Estimate	Std. Error	z-Value	*p*-Value
Cluster 2 [a]	1.65	0.67	2.45	0.015 *
Cluster 3 [a]	0.076	0.66	0.11	0.909
BMI (overweight)	−0.42	0.56	−0.76	0.449
Experience (yes)	−0.91	0.60	−1.50	0.133

* $p < 0.05$; [a] Results against cluster 1.

H2a predicted that the effect of the expectancy cluster on thermal comfort would be especially strong among participants with greater existing personal norms to protect the environment and save energy, as activated by tailored information (long video). This hypothesis was supported (see Figure 5 for coefficients and *p*-values), as the moderation model was significant (F (5, 70) = 3.08, $p < 0.05$, $R^2 = 0.18$). Tailored information to activate personal norms (the long video) seems to have prompted higher reported thermal comfort in participants from cluster 2 compared to those from clusters 1 and 3. Those participants who did not receive tailored information (the short video) expressed similar reported thermal comfort regardless of their expectancy cluster, indicating no effect of video on the relationship between expectancy and thermal comfort.

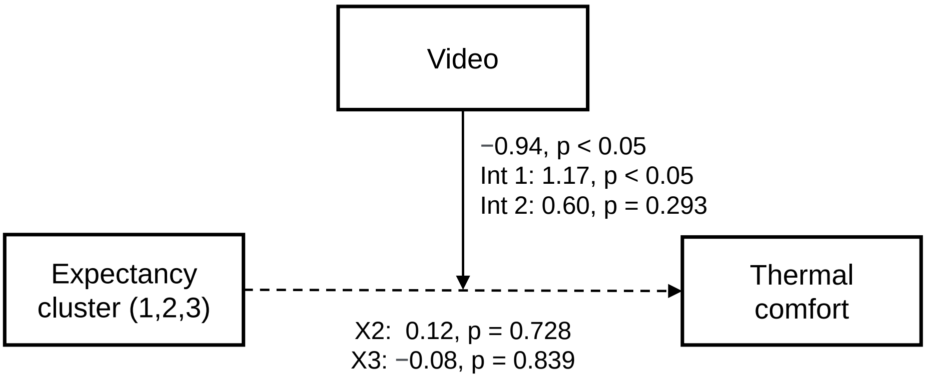

Figure 5. Model of moderating effects of video on thermal satisfaction. Unstandardized coefficients are shown. Dotted lines indicate nonsignificant relationships. Short video condition coded as 0; long video condition coded as 1. Expectancy cluster coded as dummy variables for multicategorical variables. Video significantly moderates the effect of cluster 2 on thermal comfort (Int 1).

Although data from the test of the total effect model for H1 (Table 2) identified a significant effect of expectancy cluster on reported thermal comfort, this effect was nonsignificant in the moderation model that included video (tailored information). Note that tests of direct effects (the path from expectancy cluster to thermal comfort shown in

Figure 5) reflect the influence of a predictor variable on an outcome variable while holding any moderation variables constant; this is in contrast to the total effect model, which only estimates the effect of expectancy cluster and the control variables on thermal comfort. Such findings indicate that the effect of expectancy cluster on reported thermal comfort is significant depending on the value of video. Additionally, the moderation model that included the effect of video explained higher variance ($R^2 = 0.18$) than the total effect model ($R^2 = 0.09$).

H2b predicted that by activating personal norms (the long video), the change in reported satisfaction with the personal fan would be greater among those participants with more negative expectations. This hypothesis was not supported (see Figure 6 for coefficients and p-values), as the moderation effect was not significant for any of the expectancy clusters. However, the expectancy cluster had a significant effect on reported fan satisfaction, and the model was significant ($F(5, 70) = 2.78$, $p < 0.05$, $R^2 = 0.17$). The negative coefficients indicate that those participants from clusters 2 and 3 may express a lower change in reported fan satisfaction compared to those from cluster 1.

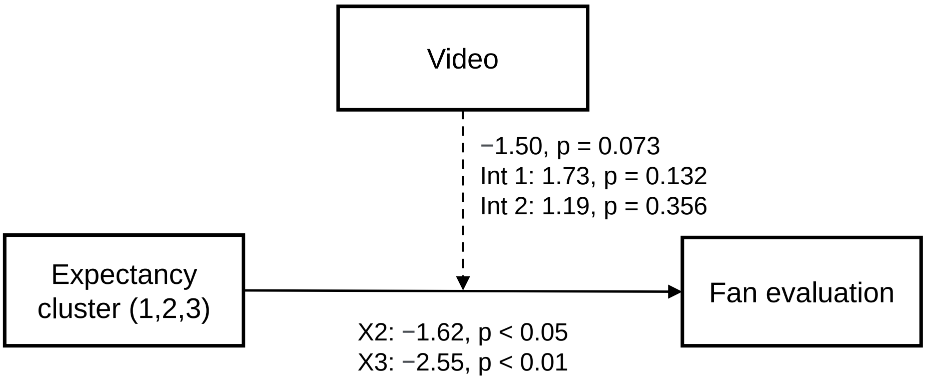

Figure 6. Model of moderating effects of video on changes in fan satisfaction. Unstandardized coefficients shown. Dotted lines indicate non-significant relationships. Short video condition coded as 0; long video condition coded as 1. Expectancy cluster coded as dummy variables for multicategorical variables. Video did not significantly moderate the effect of expectancy cluster on fan satisfaction.

5. Discussion

Previous studies have examined the effect of expectations on occupants' thermal and overall satisfaction [2,66,67], indicating cultural, geographical, and building-type differences [6]. By combining occupants' expectations of indoor thermal conditions and expectations towards building control opportunities, the current study proposed to distinguish occupants according to their expectancy levels. Thus, the relationship between participants' comfort expectations, described as thermal and behavioral expectations, and their thermal comfort in a simulated work environment was tested (H1). The study found that reported thermal comfort was greater among those participants with more positive thermal and behavioral expectations (cluster 2) and significantly differed from participants with negative thermal expectations (cluster 1) but not from the cluster expecting neutral thermal conditions and having negative behavioral expectations (cluster 3). These results may reflect the assimilation effect given by the coherence between expected and experienced indoor conditions that lead to greater thermal satisfaction [7,68]. Additionally, these findings reflect the higher importance of thermal expectations in predicting comfort compared to the effect of behavioral expectations. This could be associated with the modest expectations of occupants towards building controls in naturally ventilated buildings, which is the building type mostly found in the city where this study took place. Usually, occupants in naturally ventilated buildings do not associate their discomfort with the thermal environment provided by the building, as they may be more in contact with the outdoor conditions (e.g., by opening the window), and therefore do not expect their comfort to change due to the building's performance but through their actions [31].

Due to significant BMI differences between cluster groups, this variable was included in the model. However, BMI did not significantly influence participants' thermal perception. These results may contradict the general tendency in the literature that BMI differences exist [13,69]. However, BMI classification has recently been criticized as inaccurate and misleading [70]. Because BMI is based only on height and weight and does not take into account other body characteristics such as body fat content, muscle mass, and body composition, it is possible that some of the participants were misclassified without taking into account factors that affect human thermoregulation. Further research on the thermoregulatory process considering actual measurements of body composition should be carried out.

These first results reinforce Brown and Coles' [20] statement that expectations play an important role in shaping occupant comfort and indoor environmental behavior. However, this main effect seems best explained by the moderating role of normative motivations. The activation of personal norms was found to significantly moderate the influence of expectancy on reporter thermal comfort (H2a). Those who watched a video with detailed information about sustainable buildings and the benefits of the personal fan reported greater thermal comfort than those who watched a video with general information about the study. Although the test of H1 identified a significant influence of expectancy cluster on reporter thermal comfort, when the variable video was added to the model, that effect became non-significant. This finding suggests that the positive association between the expectancy and thermal comfort identified in the test of H1 could be largely explained by the activation of personal norms elicited among participants with more positive expectations. Additionally, greater variance in thermal comfort was explained by the moderation model that included video as compared to that explained by the total effect model, which isolated the effect of comfort expectations. Accordingly, we suggest that future studies examine the potential influence of other social-psychological constructs, such as personal norms, on perceptions of IEQ, along with additional attempts to identify which types of occupants are likely to feel more comfortable based on their social–psychological characteristics to shape their comfort expectations.

We anticipated, but did not find, a moderation effect of active personal norms on the influence of expectancy on changes in fan evaluation (H2b). An explanation for this lack of influence could be that hedonic goals were a priority for all participants rather than their normative motivations [48]. Given the moderately warm indoor temperatures, participants' comfort needs (i.e., the need to restore comfort due to the warm thermal sensation) may have become more relevant, and the potential influence of the video may not have been strong enough to rate the fan according to normative principles but rather according to its effectiveness to restore comfort (prioritizing hedonic goals). Although the moderation effect of the video was not significant in the model, there was a significant effect of expectancy on changes in fan evaluation. Greater changes in fan evaluation after participation in the experimental session (i.e., fulfilled expectations) were observed for participants with negative thermal expectations compared to participants with positive thermal expectations. These findings indicated that individually controlling the fan to increase thermal comfort may have effectively induced a change towards a more positive fan evaluation, especially in participants with lower comfort expectations. However, these results do not eliminate the possible effect of tailored information on fan evaluations and behavioral interactions, which may vary depending on the way the information is delivered. For instance, Schweiker et al. [18] found that participants who participated in a workshop were more likely to change their behavior than those who only received an information brochure. Future studies could investigate other ways of providing information to investigate whether the association of occupants' different expectations with actual normative behaviors, specifically with PECS, could be moderated by personal norms. As studied by Li et al. [24], normative messaging in personal environmental control systems could not only enhance thermal comfort but induce a higher probability of using personal devices, such as personal fans, to restore comfort.

5.1. Practical Implications

The findings of this study suggest that it may be useful to address and attempt to influence occupants' expectations of indoor thermal conditions and building operations. This is particularly relevant to the implementation of PECS in buildings as positive expectations of the indoor environment and the use of PECS may have implications for reducing energy consumption while increasing occupant satisfaction in buildings. The positive effect of information on higher tolerance of the expected indoor environment conditions, together with the provision of personal, low-intensive cooling strategies, could support the acceptance and use of PECS, such as personal ceiling fans, to ensure occupant satisfaction with the thermal environment in naturally ventilated buildings.

5.2. Limitations

This study was conducted in a laboratory setting, an unfamiliar environment to the participants. We therefore could not measure the extent to which expectations influence on-site perceptions of the thermal environment in a familiar environment, where occupants may have different expectations of the climatic conditions, as suggested by Schweiker et al. [26]. We suggest that future studies investigate such a relationship. In the present study, normative messaging was tested on the evaluation of and satisfaction with one adaptive strategy that was available for all participants. The possible effect of personal norms may be different if (1) multiple adaptive strategies with different normative impacts (e.g., low-energy-consumption strategies vs. the use of air conditioning) have been tested simultaneously, giving participants multiple adaptive possibilities, and (2) the actual behaviors have been tested in addition to the adaptive strategy's evaluation. Furthermore, the influence of information and expectancy group was examined for the personal ceiling fan for a constant temperature condition and a German sample. We suggest that additional studies be conducted with other types of PECS, different thermal conditions, and a variety of samples to examine whether the type of adaptive strategy, climatic conditions, or relevant cultural differences influence the effect of information on thermal comfort. Finally, we suggest that future studies examine the extent to which more information about the features of PECS and other types of manipulation techniques influence real-time, on-site IEQ perceptions and behaviors.

6. Conclusions

This study investigated the effect of occupants' expectations on their satisfaction with the thermal environment and a personal ceiling fan as influenced by the activation of normative goals. Our results indicate that building occupants who have more positive expectations about indoor thermal conditions may express higher levels of thermal comfort than those with more negative comfort expectations, regardless of their expectations of the building systems. Our findings also indicate that comfort expectations can be influenced by the activation of personal norms. By activating normative motivations, occupants may perceive indoor conditions as more comfortable. Those expectations should be associated with the expected satisfaction and fulfilled expectations of adaptive actions in order to stay comfortable in a building. To the extent that thermal expectations are negative, occupants might improve their perceptions of personal building controls (such as a personal ceiling fan) when making personal adjustments in order to stay comfortable. Our findings suggest that building designers could focus and manipulate occupants' comfort expectations, e.g., by providing occupants with normative messages and individual control, to achieve greater comfort and acceptance of personal building controls, such as PECS, in naturally ventilated buildings.

Author Contributions: Conceptualization, R.R. and M.S.; methodology, R.R. and M.S.; software, R.R.; validation, R.R.; formal analysis, R.R.; investigation, R.R.; resources, R.R.; writing—original draft preparation, R.R.; writing—review and editing, R.R. and M.S.; visualization, R.R.; supervision, M.S.; project administration, R.R.; funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the data protection officer of the Karlsruhe Institute of Technology (date of approval: 10 June 2021). Note: the Ethics Committee of the Karlsruhe Institute of Technology began assigning application numbers for applications in 2023. Therefore, there is no approval number for this study. However, the approval letter is available from the authors upon request.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy restrictions.

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Abbreviations

The following abbreviations are used in this manuscript:

BMI	Body mass index
BMS	Building management system
EQ	End questionnaire
IEQ	Indoor environmental quality
Int	Intercept
IQ	Initial questionnaire
LOBSTER	Laboratory for Occupant Behavior, Satisfaction, Thermal comfort, and Environmental Research
OQ	Online questionnaire
PCA	Principal component analysis
PECS	Personal environmental control system
SD	Standard deviation
SQ	Start questionnaire
SVM	Support vector machine
WHO	World Health Organization

Appendix A. Additional Tables

Table A1. Participant demographics and other characteristics, as well as experimental conditions according to expectation clusters and results of tests of equivalence of research conditions.

	Cluster 1	**Cluster 2**	**Cluster 3**	**Full Sample**	**Test of Independence**		
	N	*N*	*N*	*N*	χ^2	**df**	***p*-Value**
Sex					0.15	2	0.928
Female	13	13	9	35			
Female	14	17	10	41			

Table A1. *Cont.*

	Cluster 1	Cluster 2	Cluster 3	Full Sample	Test of Independence		
	N	*N*	*N*	*N*	χ^2	df	*p*-Value
Age					0.15	2	0.929
Young	18	19	13	50			
Elderly	9	11	6	26			
BMI					6.12 *	2	0.047
Normal	12	20	15	47			
Overweight	15	10	4	29			
Daytime					0.47	2	0.079
Morning	12	16	9	37			
Afternoon	15	14	10	39			
Office					4.67	2	0.097
1	9	18	11	38			
2	18	12	8	38			
Video					0.52	2	0.771
Short	15	14	9	38			
Long	12	16	10	38			
Experience with fans					5.13	2	0.077
Yes	2	4	6	12			
No	25	26	13	64			
Experience with ceiling fans					2.05	2	0.359
Yes	7	8	2	17			
No	29	22	17	59			
Previous worked in office					7.25 *	2	0.027
Yes	9	3	8	20			
No	18	27	11	56			

* $p < 0.05$.

Table A2. Participants' votes and fan use according to expectation clusters and results of tests of equivalence of research conditions.

	Cluster 1 M (SD)	Cluster 2 M (SD)	Cluster 3 M (SD)	Test of Independence χ^2	df	*p*-Value
Actual mood [a]	3.04 (1.02)	2.57 (1.14)	3.21 (1.13)	4.53	2	0.104
Air velocity level [%]	55.48 (21.44)	46.52 (29.62)	48.92 (25.10)	2.29	2	0.318
Duration fan on [min]	127.99 (5.69)	123.35 (19.50)	124.00 (24.87)	2.90	2	0.235
Video rating 1 [b]	0.21 (0.89)	−0.21 (1.14)	0.04 (1.23)	3.28	2	0.194
Video rating 2 [b]	0.03 (0.99)	−0.04 (1.02)	0.02 (1.04)	0.12	2	0.940

[a] Integer values. Scale ranged from 1 (very bad) to 7 (very good): "*How is your mood right now?*". [b] Unstandarized values resulting from PCA conducted with seven questions. Two components resulted from the analysis.

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