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Local personalized heating in a field study—Suggestions for implementation of personalized environmental control systems in real offices

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ABSTRACT

In winter 2022/23, German legislators mandated lower indoor air temperature thresholds for public and non-residential buildings due to reduced natural gas imports from Russia. The temperature for light office work, set at 19 °C until April 2023, spurred the evaluation of local compensatory heating elements. Personalized environmental control systems (PECS) can enhance individuals' thermal satisfaction while concurrently saving energy. Using a sample of 15 university employees, the study investigated a PECS that addresses both upper and lower body parts with a heatable office chair and desk-mounted heating mats with respect to energy use, usage profiles and thermal comfort. Over three weeks, participants rated thermal comfort multiple times during the day in surveys, and temperature, humidity, and CO_2 were measured in each office. Energy consumption of the devices was monitored with socket outlet adapters. Results showed that room temperatures in the field study were often higher than the mandated 19 °C due to thermal loads such as computers and monitors and solar gains in the building. Due to predominantly neutral thermal sensation, we could not determine a significant improvement in comfort provided by local heating. High acceptance and use of local heating allow us to draw suggestions for future implementation strategies, including a modular system for individualized PECS, optimized test setups, refined measurement and survey methodologies, and approaches to mitigate inter-individual challenges.

1. Introduction

About 40 % of residential buildings in Germany rely on natural gas as the primary heating energy source. About one-third of the overall national energy consumption is attributed to the building sector [1], which aligns with the global share [2–4]. Non-residential buildings, such as schools, offices, and administrative buildings, also heavily rely on natural gas as the energy source for heating. As a consequence of the conflict between Russia and Ukraine, the amount of natural gas imported from Russia to Germany reduced markedly and ultimately stopped in 2022 [5,6]. This required changes in the heating concepts including energy efficiency measures, particularly in the building sector, while ensuring individual Thermal Comfort (TC).

In addition to short-term critical events such as the aforementioned energy shortage, German legislators have set the strategic goal for net greenhouse gas neutrality in all sectors to be achieved by 2045. By 2030, a reduction of greenhouse gas emission by 65 % compared to the 1990 baseline is to be achieved [7]. In concert with increasing renewable energy production and building insulation efforts, the building sector requires more efficient and demand-based Heating, Ventilation and Air-Conditioning (HVAC) approaches to meet ambitious climate goals. Additionally, with significantly rising energy costs, about 10 % of European citizens experience energy poverty and cannot adequately condition their indoor spaces [8–10]. One potential solution to these challenges is the implementation of Personalized Environmental Control System (PECS). Similarly, efficient PECS represent a promising approach for ensuring TC in electric vehicles while minimizing energy consumption [11].

1.1. Indoor Environmental Quality (IEQ)

TC is an important contributor to overall comfort and well-being. It is fundamentally tied to the heat exchange between the human body and its environment, influenced by factors such as air temperature, mean radiant temperature, humidity, air velocity, clothing insulation, and metabolic rate [12]. Proper thermal conditions can significantly enhance comfort, reduce stress, and improve overall well-being, which in turn boosts productivity levels and reduces the incidence of illness related to poor environmental conditions [13]. There is a notable relationship between thermally comfortable indoor environments and

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increased productivity [14–17]. Research by Wyon et al. [14] indicates that productivity significantly drops at temperatures above 26 °C. Furthermore, McCartney and Humphreys [16] have demonstrated that dissatisfaction with the thermal environment leads to decreased productivity. Moreover, allowing individuals to control their thermal environment not only enhances their TC but also their overall well-being and productivity [18,19]. Results of Zierke et al. [20], obtained using heating panels in a train mock-up, demonstrated that automated control of PECS can maintain TC without drawbacks associated with the absence of individual control, provided the correct individual settings are employed. Infrared skin and surface temperature measurements, as reviewed by Wu et al. [21], provide a method for assessing individual TC that allows for greater individualization compared to established comfort models such as Predicted Mean Vote Model (PMV) [12] and Equivalent Temperature Model (T_{eq}) [22]. Contact-less skin temperature measurements may be particularly suitable for controlling PECS. This underscores the importance and challenges of designing and maintaining thermal conditions that accommodate diverse individual preferences and functional requirements.

1.2. Situation & study setting winter 2022/23

Driven by the historical availability and cost-effectiveness of natural gas, mostly imported from Russia, the heating sector in Germany is reliant on natural gas accounting for 25 % of the total energy supply in 2018 [23]. The transition away from this dependency on fossil fuels is a major challenge in Germany's climate goals, such as climate-neutrality in the building sector by 2045. Furthermore, as a countermeasure to prevent shortages in the heating period despite the reduced gas import, a short-notice ordinance on energy saving was put in place [24]. In essence, this ordinance specified that in public buildings, such as universities, the indoor air temperature of office rooms may not exceed 19 °C in winter 2022/23 (exceptions for vulnerable groups notwithstanding).

For this reason, the mandated indoor air temperature limits were used as a context to evaluate the suitability of local heating devices as compensatory measures. The use of PECS reduces the need for large-scale heating systems, thereby decreasing reliance on natural gas. This is particularly crucial given the geopolitical risks and price volatility associated with natural gas imports, as well as the necessity to achieve stringent climate goals.

The study described in this paper focuses on the application and investigation of PECS in a university office environment. It examines the potential to reduce energy consumption while also enhancing TC for individuals. This study aims to describe the system, the data pipeline and the questionnaire procedures to facilitate investigations of PECS.

2. Personalized Environmental Control Systems

In the current building stock, HVAC systems typically condition the entire indoor air volume to create a uniform room climate. Several studies [25–29] provide comprehensive overviews of PECS, which create localized micro-climates around users, thereby improving TC while offering potential energy savings at the same time. Already existing HVAC systems would still be necessary, but would be run at more lenient set-point levels, providing only a background thermal environment. Despite the wealth of research, studies often differ in their specific combination of PECS tested, and are predominantly conducted in laboratory settings. The next section reviews important findings from the PECS literature, while also pointing to the rather heterogeneous state of the literature.

2.1. Energy Savings with PECS

Veselý and Zeiler [30] provide an overview of literature results on potential energy savings from the implementation of PECS in conjunction with energy efficiency measures. However, most existing studies focus on PECS for cooling, where Personalized Ventilation (PV) has been shown to be highly effective [31–36]. Additionally, PV is also effective in improving Indoor Air Quality (IAQ), as shown by Sekhar et al. [37],Makhoul et al. [38,39]. Hoyt et al. [40] showed significant potential energy savings of approximately 10 %/K for each degree of indoor air temperature set-point widening, based on EnergyPlus simulations. Similarly, simulation results of Ghahramani et al. [41] underscore the influence of the HVAC dead-band on potential energy savings. Hoyt et al. [42] further emphasized, through parametric simulations, that the energy consumption of efficient PECS, with energy consumption below 25 W/occupant, is nearly negligible. By widening the dead-band of HVAC to 18.3 °C to 27.8 °C, savings of 32 % to 73 % in HVAC energy consumption could be achieved, depending on the climate and type of PECS used.

Energy savings through heating PECS. According to Pasut et al. [43], heated chairs provide substantial energy savings, requiring only 16 W for heating. Heated chairs combined with leg-warmers can save up to 71 % of heating energy when the minimum room temperature is lowered to 14 °C [44]. Schmidt et al. [45] further demonstrated the potential for energy savings through the use of PECS for localized heating in vehicles. Oi et al. [46] found that in vehicle environments with an outdoor temperature of 0 °C, using a heated seat along with a foot heater achieve potential energy savings of 25 %, with the heated seat being the more energy efficient option. Zhang et al. [47] investigated a combined PECS that provided heating to the feet and hands, consuming up to 59 W while maintaining thermal acceptance at ambient temperatures as low as 18 °C. Similarly, Luo et al. [48] demonstrated that a combined low-power PECS, including a heated chair, heated wrist pad, and heated shoe insole, could maintain acceptable thermal conditions for more than 80 % of occupants at ambient temperatures down to 18 °C, with a maximum energy consumption of 23.4 W. The study also reported potential HVAC energy savings ranging from 1.5 % to 20.7 %, depending on the climatic conditions. Rugani et al. [49] indicated that a desk equipped with upward heating could achieve potential energy savings ranging between 15 % and 20 %, based on energy analyses and Computational Fluid Dynamics (CFD) analyses.

2.2. Attached and semi-detached heating PECS for office and vehicle environments

Tian et al. [50] provides an overview of PECS used for heating, emphasizing the importance of heating multiple body parts rather than a single one to achieve TC in cold environments. The review by Hooshmand et al. [51] primarily focuses on the thermal effects of radiant heating PECS. Subsequently, the most relevant studies on heating PECS for this work are reviewed, ranging from heated seats to radiant and conductive lower body heating, as well as combinations of different PECS. PV are excluded, as they require connection to an air supply system and primarily enhance inhaled air quality. Wearable PECS, which are particularly important in extreme thermal conditions, are also excluded due to focus on moderate ambient conditions and stationary PECS.

Heated seats. Madsen and Saxhof [52] indicated that heated office chairs could maintain TC at ambient temperatures reduced by 3 °C. In laboratory conditions, Brooks and Parsons [53] demonstrated that heated vehicle seats improve TC at ambient temperatures down to 5 °C. Oi et al. [54] showed that heated seats effectively improve TC during the warm-up period of vehicles at low air temperatures below 15 °C, and Oi et al. [55] found that heating the seat cushion was more effective than heating the seat back. Deng et al. [56] showed that heated textile-covered aluminum alloy seats, set to 40 °C, improved TC at ambient temperatures of 16 °C compared to non-heated seats at 18 °C. Yang et al. [57] found that seat heating improved TC at low ambient temperatures of 14 °C, but it was insufficient to maintain TC due to cold extremities. He et al. [44] addressed this by adding legwarmers to enhance TC across more body areas. According to Shahzad et al. [58], occupants tend to prefer a warmer-than-neutral overall Thermal Sensation (TS), with heated chairs increasing "comfortable" and "very comfortable" TC votes by 20 % at an average ambient temperature of 24.1 °C. Zhang et al. [59] demonstrated that heated and cooled seats could provide acceptable thermal environments within an ambient temperature range of 15.6 °C to 28 °C. These findings are supported by Pasut et al. [60], who observed neutral TS between 16 °C and 29 °C using heated and cooled seats. This can be attributed to the heat transfer processes in the contact area [61]. At typical indoor air temperatures ranging from 21.9 °C to 25.3 °C, heated and cooled chairs can increase thermal satisfaction to 96 % [62], significantly surpassing the levels achieved by conventional HVAC and the requirements set by standards such as ANSI/ASHRAE Standard 55 [63],DIN EN ISO 7730 [64].

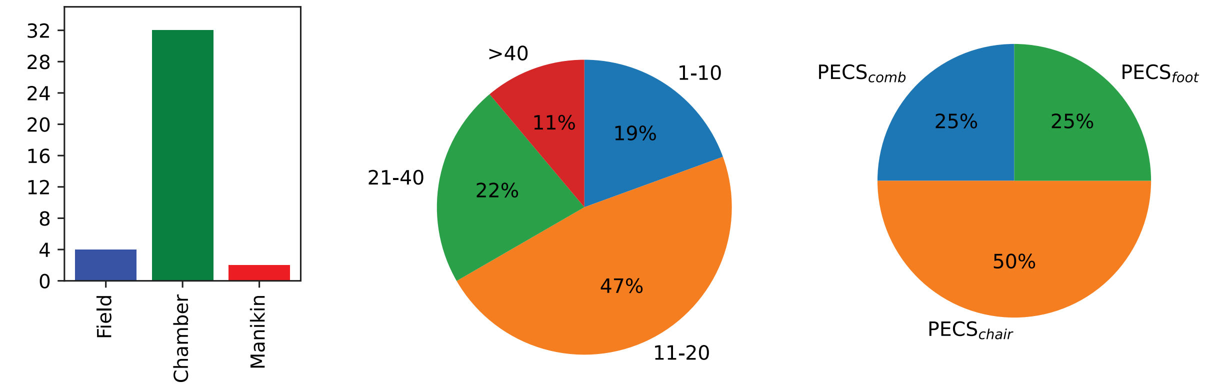
Lower body heating. Although there have been limited studies on lower body heating, traditional methods such as the Japanese "Kotatsu" demonstrate its potential for enhancing TC, with both physiological and psychological effects explored by Enomoto et al. [65]. Another traditional method is the Chinese "Huotong", a heating chair commonly used by marketplace vendors, which was studied in climate chamber and field settings by He et al. [66,67]. Additionally, the "Huoxiang", a traditional foot heater box combined with a cotton quilt to concentrate heat on the body, was evaluated in a field study by Zhou et al. [68] for its impact on TC and energy consumption. Both the "Huotong" and "Huoxiang" provide warmth through conduction, convection, and radiation, and were found to effectively improve TC in cold-humid climates. Using a thermal manikin to assess the heating effect of a lower body heating panel, Kazanci et al. [69] observed local temperature increases of up to 5 K on the front thighs and approximately 1 K for the whole body. Similarly, Foda and Sirén [70] highlighted the energy saving potential of floor heating by maintaining TC at reduced ambient temperatures of 18 °C, also using a thermal manikin for evaluation. Convective lower body heating directed at the feet can improve both local and overall TS at ambient temperatures of 12 °C to 14 °C [71]. Wang et al. [72] showed that floor heating mats efficiently improve TC at ambient temperatures between 11 °C to 13 °C and metabolic rates ranging from 1 met to 2 met. Radiant floor heating with a maximum heating power of 320 W can maintain a "neutral" or "warmer than neutral" TS for all body parts except the head at ambient temperatures of 14 °C to 16 °C [73]. At air temperatures between 13 °C to 17 °C, Li et al. [74] recommends using a foot heating pad with fluctuating heating, cycling between 40 °C and 42 °C in 60 s intervals, instead of constant heating at 41 °C. The fluctuating heating mode is more effective in preventing local overheating while maintaining Thermal Acceptance (TA) above 90 %. Wang et al. [75] demonstrated improved TS and TC at an ambient temperature of 13.5 °C using legwarmers, but recommended adding a closure above the legwarmers to enhance the heating effect. Furthermore, Zhang et al. [76] demonstrated significant energy savings in office buildings during winter through the use of five-sided enclosed foot warmers, which allowed for thermally acceptable lower ambient temperatures. In contrast, a larger, four-sided enclosed lower body heating system, as studied by Ren et al. [77], provided TC at lower ambient temperatures and appears to have fewer ergonomic limitations. However, it was less energy efficient compared to the foot warmer in [76].

Combined heating PECS. Melikov et al. [78] investigated combined radiant heating panels and recommended a half-egg-shaped back radiant heating panel placed behind the occupant, paired with heating panels below and on top of a desk. Kaczmarczyk and Ferdyn-Grygierek [79] demonstrated in a chamber study that heat mats positioned in the seat back, on the desk and under the desk can together ensure acceptable TC at temperatures of 16 °C and 18 °C for light sedentary work. This configuration required an energy demand of up to 410 W at 16 °C. In an office setting, Veselý et al. [80] found that a heated chair and desk mat significantly enhanced TC at an operative temperature of 18 °C. Schmidt et al. [45] further showed that combined heating PECS in vehicles, including heated side panels, steering wheel, and seat, achieved TC at ambient temperatures down to 15 °C. According to Yu et al. [81], a combination of heating panels, including floor heating, under-desk heating, and a hand heating pad, can achieve TC energy efficiently even at room temperatures lowered to 12 °C. A combined PECS, including PV, a heated backrest, under-desk radiant heating, and floor heating, was shown to enhance TC at reduced ambient temperatures of 20 °C compared to a reference case at 22 °C [82,83]. Su et al. [84] demonstrated that a combined PECS, including PV and radiant lower body heating, can maintain TA at 88 % in ambient temperatures of 16 °C. A combined radiant and convective heater increases TS more effectively and at a higher rate of change than single radiant or convective heaters [85]. In chamber studies involving 30 participants, Rugani et al. [86] further validated the energy efficiency of a heated desk, which heats both the lower and upper body, demonstrating that it ensures TC at a reduced ambient temperature of 17 °C. Potential enhancements in TC and IAQ through the use of a PECS, including PV and under-desk radiant heating, were demonstrated in a field study by Bauman et al. [87].

2.3. Goals of this study

As illustrated in Fig. 1, prior studies on heating PECS have primarily focused on investigating individual heating solutions tested in climate chambers, while the integration of combined heating systems in real office environments remain unexplored. The median number of participants in PECS studies typically ranges from 11 participants to 20 participants, which is also reflected in the current study. However, to further advance and establish PECS, there is a need to shift the focus towards field studies. In this context, André et al. [88] provide recommendations for the effective implementation of desk fans in open office environments. Field studies are essential for capturing real environmental conditions and addressing practical implementation challenges, which are crucial for broader adoption. Integrating PECS into real office environments requires consideration of the interrelated factors of TC, IAQ, energy consumption, efficiency, and the need for a non-obtrusive system that does not interfere with participants' usual routines.

The primary objective of this study is to investigate an implementation strategy for heating PECS in a field setting, with a focus on local and global TC, energy consumption, and minimizing disruptions to participants' usual work routines. Hereto, a combined heating PECS, including Office Chair with Seat and Back Heating (CH), On-Desk infrared Heating Plate (ODHP), and Under-Desk infrared Heating Plate (UDHP), was implemented at a single workstation in two-person offices during the short-notice announced and time-limited period of a nationally mandated maximum heating set-point of 19 °C. By allowing individualized control, the PECS enable employees to compensate for varying thermal preferences, thereby facilitating the acceptance of lower indoor temperatures. Based on the study's findings, challenges and recommendations for implementing PECS in field studies and real office environments are presented. In this regard, the present research provides a crucial foundation for future investigations of PECS in real office settings, where uncontrolled variables substantially influence system performance and user experience.



(a) Number of Studies by Type (Field Study, Climate Chamber Study, Thermal Manikin Study).

(b) Percentage Distribution of Participant Group Sizes in Studies on PECS.

(c) Investigated PECS in Field Studies (%): Combinations (PECS$_{comb}$), Foot Warmer (PECS$_{foot}$) and Heated/Cooled Chair (PECS$_{chair}$).

Fig. 1. Overview of research on heating PECS in office and vehicle environments.

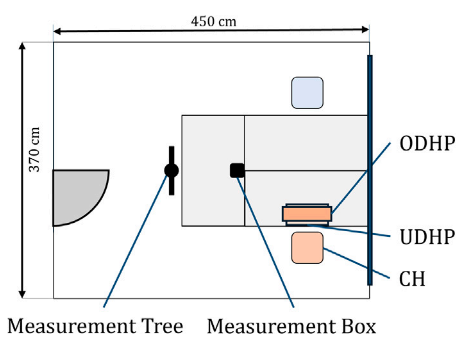


Fig. 2. Schematic representation of an exemplary office room featuring one workstation equipped with PECS (CH, UDHP, ODHP), a measurement box for continuous environmental monitoring, and a measurement tree for single-point measurements in each office room.

3. Materials and methods

3.1. Study setup

The method combined energy consumption measurements using socket outlet adapters (Shelly Plug S) with consumption metering, along with IEQ assessments through a specially developed low-cost ambient measurement box placed in each office room, which is further described by Huang et al. [89]. Additionally, occupants' perceptions are assessed through online surveys. The study participants were divided into two groups: a test group, which has access to local actuators for personal adjustment, and a control group that does not have access to such devices. The study took place in an office building at RWTH Aachen University during February and March 2023, where climate control was achieved exclusively through the use of manually operated radiators, windows, and shading systems. The study was conducted in eight offices, six of which were oriented to the northwest and two to the southeast. Each office room was a two-person office, with one workstation newly equipped with PECS, as schematically shown in Fig. 2. One participant from the test group and one from the control group typically shared the same office.

Participants. A total of 15 persons participated in the study with average morphological data described in Table 1. The sample size aligns with prior studies in the PECS research domain, as highlighted in Fig. 1, and is considered sufficient for assessing the study concept. All participants were university employees, aged between 23 years and 34 years. Despite no restrictions on clothing, the clothing insulation remained constant at approximately 0.9 clo, as calculated based on the clothing combinations reported by the participants. The typical activity of the participants was seated office work, assumed to correspond to a metabolic rate of 1.1 met [90], though activity levels could vary throughout the day. Rowe [91] observed metabolic rates in an office building predominantly ranging between 1.0 met to 1.5 met. The test and control group had the same average Body-Mass-Index (BMI) but due to preset office setups, the control over the group allocation was limited and especially the gender of the participants was unequally distributed between test and control group. As this is a field study conducted in an operational office building, the design was inherently constrained by the availability of comparable workplaces, voluntary participation, actual outdoor conditions, and workplace regulations. The study was approved by the RWTH Aachen Interfaculty Ethics Committee (ref. 03a/23).

User feedback. If the participants were more than 15 min at their workspace, they were asked to answer surveys in the time periods according to Table 2. For compatibility with work structures and in favor of acceptability, the survey frequency of the test group (group A) was higher than that of the control group (group B). The questions as well as the automated requests to fill in the survey were implemented with LimeSurvey and the CronJob plugin (https://survey-consulting.com).

Each participant was asked to complete regular digital questionnaires, predominantly focused on TC, according to the schedule outlined in Table 2. At the start of each survey, participants were asked to confirm whether they had been at their workplace for the last 15 min, report any extraordinary circumstances and describe their current clothing. Given that they were working at their desks during this period, it was assumed that their metabolic rate was consistent with typical office work. Questions on TS ("How do you feel right now?" with responses ranging from −3 "cold" to 0 "neutral" to +3 "hot"), TC ("Do you find it..." with responses from 0 "comfortable" to +4 "extremely uncomfortable"), and Thermal Preference (TP) ("How would you prefer to feel right now?" with responses from −3 "much colder" to 0 "no change" to +3 "much warmer") were formulated in accordance with DIN EN ISO 10551 [92], addressing both whole body and individual body parts. The question and response options were kept consistent across all locations. Additionally, the test group was asked about the PECS used and the usage duration and profile of the CH since the last survey. The usual surveys concluded with questions about IAQ and provided participants with the opportunity to add any additional remarks. Survey number 4 always includes an extended section for

Table 1
Average morphological data of the participants.

	count [−]	age [years]	height [m]	weight [kg]	BMI [$kg\,m^{-2}$]	male:female
Test group	7	29	1.77	75.1	23.8	3:4
Control group	8	28	1.81	78.5	23.8	7:1

Table 2
Survey times of test group A and control group B.

Survey number, Time slot:	1 8:00-9:30	2 10:30:00-12:00	3 13:00-14:30	4 15:00-15:45	5 16:15-18:00
Comfort surveys:	A	A, B	A, B	A, B	A
Performance surveys:				A, B	

Table 3
Actual ambient conditions during trials.

		All survey data		Survey data below 21 °C	
		test group A	control group B	test group A	control group B
Air temperature in °C	min:	15.9	15.8	15.9	15.8
	mean:	20.0	20.1	19.4	19.7
	max:	23.3	23.1	21.0	21.0
Relative humidity in %	min:	31.3	35.3	31.3	35.1
	mean:	45.0	46.5	45.7	46.6
	max:	54.9	60.0	54.9	60.0
CO_2 in ppm	min:	523	679	523	519
	mean:	1221	1354	1185	1296
	max:	2537	2542	2537	2542

self-evaluation, allowing participants to assess their own perception of current work tasks and performance. Additionally, each participant completes a general questionnaire once, which includes personal and background questions covering topics such as personal information, general thermal perception, health status, and experiences with PECS.

IEQ monitoring. To monitor IEQ in multiple office rooms, accurate and cost-effective sensors are required. The ambient measurement boxes, used to collect data on air temperature, relative humidity, and CO_2 levels, were installed at a height of 1.0 m on the desks in the room's center. The measurement boxes are equipped with a BME 280 sensor (Bosch, Germany) for measuring air temperature (±0.5 K) and relative humidity (±3 %), as well as two SCD 30 sensors (Sensirion, Switzerland) for measuring CO_2 levels (±(30 ppm + 3 % of the measurement value)). The operation and energy consumption of the PECS devices, including the ODHP and UDHP, were continuously monitored using socket outlet adapters with consumption metering. These were connected to an Influx database via Message Queuing Telemetry Transport (MQTT) and Node-RED, integrating with the PECS testing infrastructure presented by Metzmacher et al. [93]. Continuous monitoring and real-time transmission of the current status of connected modules, including environmental sensors and power consumption of individual PECS, enable live data processing. This system provides a robust foundation for integrating additional modules, such as comfort models and automated control systems. Since the CH is battery-powered, its usage profile and energy consumption were not measured in real-time. Instead, it was approximated based on user responses regarding CH usage and by measuring the power consumption required to charge the battery at the end of the day or when it was depleted. In each survey, participants reported on their usage and the modes of the PECS, allowing for an approximation of power consumption based on their responses and the power metering.

Additionally, the mean radiant temperature and air velocity were measured once in each office using a single measurement tree equipped with sensors from Ahlborn (Germany). This measurement tree was relocated sequentially and positioned near the fixed measurement boxes in each office (Fig. 2). This setup included a thermo-anemometer (FV A605-TA1O) for measuring air velocity and a black globe thermometer (ZA 9030-FS2) for measuring mean radiant temperature, both positioned at a height of 1.1 m. A capacitive humidity sensor and temperature sensor (FH A646-E1) were included at heights of 0.1 m and 1.1 m.

Experimental conditions. The participants were instructed to lower the radiator settings to achieve a maximum room temperature of 19 °C, in compliance with the national energy saving ordinance. While the test group was free to use local actuators to compensate for the cooler ambient conditions, the control group had no such options for local thermal adjustments. A summary of the actual ambient conditions across all surveys is provided in Table 3. While ambient conditions such as air temperature and humidity were consistent within the shared space, the localized thermal environment at the test group participant's workstation was influenced by the PECS. Differing survey schedules between the groups, along with variations in work locations and schedules, such as time spent in testing halls, home offices, or conference rooms, meant that a participant was considered present only if they completed the respective survey. This led to variations in recorded ambient conditions across both groups. Notably, the set target conditions were usually not met. To focus on colder-than-usual conditions and ensure consistency in the analysis, only surveys conducted at ambient air temperatures below 21 °C were considered. This is lower than the typical target heating temperature of 22 °C±1 °C specified by DIN EN ISO 7730 [64], enabling the analysis of user responses in sub-optimal thermal environments. On average, the ambient conditions were comparable between both groups; however, the temperatures were generally higher than planned. The indoor air temperature closely followed the outdoor conditions due to the building's lightweight construction, with indoor air temperatures typically increasing as the day progressed. This effect was most evident in unoccupied rooms. The outdoor air temperature ranged between −4.2 °C and 15.2 °C, with a mean outdoor air temperature of 4.0 °C over the entire period. Over the study period, the daily hours of sunshine varied widely from 0 h to 9.7 h, with an average of 4.1 h. The study conditions were constrained by the specified time period and the building's technical equipment, which included manual controls for radiators, window openings and shading, and local actuators available to the test group, with no other form of air conditioning. The extensive single-time measurements in each office revealed that the air temperature was on average 0.06 K (±0.33 K) higher than the mean radiant temperatures, indicating mostly uniform thermal influences and the adequacy of the continuously measured air temperature. The air temperature at 1.1 m was about 0.86 K (±0.48 K) higher than at the bottom, indicating that the vertical temperature gradient should be taken into account in future studies applying PECS. Air velocity, which was only measured

(a) Office Chair with Seat and Back Heating (CH) (b) Under-Desk infrared Heating Plate (UDHP) (c) On-Desk infrared Heating Plate (ODHP) in front of keyboard

Fig. 3. Depiction of heating devices provided to the participants.

Table 4
Specifications of local heating devices: Under-Desk infrared Heating Plate (UDHP), On-Desk infrared Heating Plate (ODHP), Office Chair with Seat and Back Heating (CH).

	size [mm^2]	power [W]	material	control
UDHP	300 x 600	40 to 150	heat-resistant fiber composite	user-controlled, stepless
ODHP	200 x 700	40 to 115	heat-resistant fiber composite	user-controlled, stepless
CH	not specified	0, 12, 16	fabric cover	user-controlled, steps 0-1-2

during the extended single-time measurements, usually remained below $0.1\,\mathrm{m\,s^{-1}}$ with an average value of $0.04\,\mathrm{m\,s^{-1}}$ ($\pm 0.03\,\mathrm{m\,s^{-1}}$). Participants did not perceive an increase in air velocity on other days compared to the comprehensive measurement day, suggesting that a low air velocity was consistently maintained. According to ANSI/ASHRAE Standard 55 [63], air velocity below $0.2\,\mathrm{m\,s^{-1}}$ can be regarded as still air, making air velocity measurements unnecessary. Consequently, the cooling effect due to air movement can be neglected.

Field study with minimal disruptions. The current study was designed to have minimal impact on the usual workflow, for which the mandated heating limit in public buildings on 19 °C lays the decisive boundary conditions. These conditions closely resemble possible implementations of PECS in office buildings without compromising occupant satisfaction through additional restrictions, while simultaneously highlighting the limitations of this study. The objective of this study is to reveal challenges in the implementation strategy of PECS in real office buildings. Given that adjustments to the central heating system would have impacted offices not participating in the study, no central interventions were implemented.

3.2. Application of PECS in this study

To compensate cold environmental conditions, the work place of each participant of the test group was equipped with commercially available ODHP, UDHP (infrared heat plate types 2070-115 and 3060-150 by thermo Flächenheizungs GmbH) and CH (Fig. 3) with characteristics specified in Table 4. This choice of PECS is based on the findings of Warthmann et al. [26], who, based on a review of prior studies, identified seat and lower body heating as well as combinations as effective compensation measures in cold thermal environments. As illustrated, the implemented PECS comprised a desk enhanced with both upward and downward heating elements as well as a heated seat, which is comparable to the seat investigated by Boudier [94], commercially available as MERA climate chair “mer98k” by Klöber GmbH. This setup directly targets the back, buttocks, legs from above, as well as the hands and arms from below, while also indirectly warming the face and feet. The UDHP is mounted in identical positions centrally under the desk at each workstation, as illustrated in Fig. 3. However, the individual impact may vary due to differences in seating posture and the distance between the table and the legs. The ODHP is typically positioned as shown in Fig. 3; however, it is designed to be movable, allowing participants to reposition or remove it from the desk if it interferes with their current tasks.

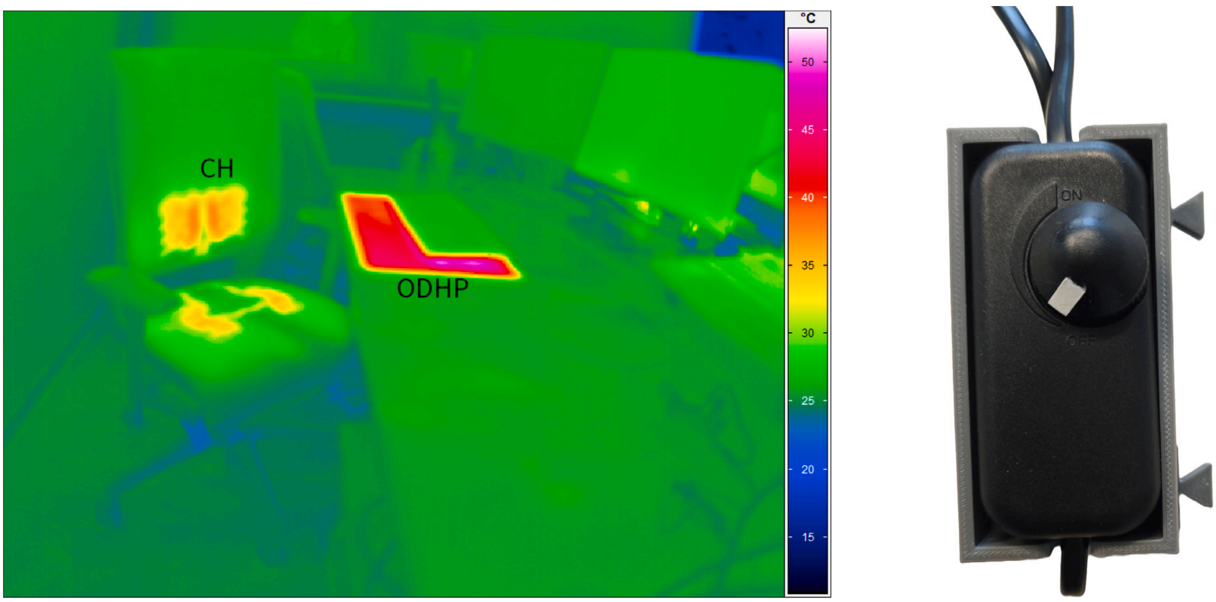
The temperature of the heating panels is mostly uniform over the entire surface, increasing locally if covered by objects such as the keyboard (Fig. 4). The seat heating element is designed to be energy efficient, targeting primarily the most sensitive body parts, as discussed in studies on improvements of heated vehicle seats [95–97].

Control of PECS. Each heating plate can be individually adjusted by the participants using a stepless dimmer, as visualized in Fig. 4, without any restrictions. The current settings are monitored by measuring the power consumption of the devices. Participants had the freedom to adjust the heating mode of the CH as needed, using two switch buttons, one for turning on or off the seat heating as well as one for setting heating level 1 or 2. Unlike the heating plates, the CH features only three settings – off, heating level one, and heating level two – and controls both the backrest and seat cushion identically.

4. Results and discussion

4.1. Questionnaire measures

The surveys were conducted online, with reminder emails sent during the available survey periods. Designed to minimize interruptions, the surveys allowed for quick responses through predefined answer schemes, such as a question about actual clothing that included six predefined combinations ranging from “shorts with shirt” to “multi-layered winter clothing”, along with an additional free-text field. While participants were free to adjust their clothing as needed, most reported clothing combinations corresponded to approximately 0.95 clo without significant changes. The office chair contributed an additional insulation. These findings suggest that participants relied more on PECS to address individual TP rather than adjusting their clothing, which exhibited minimal variation during the study — likely reflecting typical clothing habits. To better capture variations in clothing layers and further simplify the process for participants, implementing an objective measurement system would be necessary. To evaluate the statistical significance of the differences in TS and TC between the test and control groups, the Mann–Whitney U-test was employed, given its suitability for comparing non-normally distributed data between two independent groups. The survey responses are linked with the corresponding measurement data from each specific office, with incomplete and erroneous entries, such as surveys not fully answered or those lacking indoor climate measurements at the time of the survey, removed.



(a) Temperature distribution of the heating PECS Office Chair with Seat and Back Heating (CH) and On-Desk infrared Heating Plate (ODHP)

(b) Manual controller for the ODHP and UDHP

Fig. 4. Infrared image of a workstation equipped with PECS and a photo of the manual controller for the heating panels.

Response rate. The tasks of the participants were not recorded and were likely to vary between persons, with some spending more time in their offices and others partially in meeting rooms or off-site. Over the entire study period, participants in the test group completed surveys on 29 days when the corresponding control group participant (from the same room) did not. Conversely, on only 12 days, control group participants completed surveys while the corresponding test group participant did not on the same day. This discrepancy could originate from different working habits or varying motivations related to their assigned roles in the study.

Responses on overall TS. As demonstrated in Fig. 5, the TS of the participants during the trial period was predominantly neutral. Notably, the reference group mostly (about 75 %) rated the environmental conditions as neutral. The test group also rated the ambient conditions as neutral (about 60 %), but showed more deviation in both colder and warmer directions. From the analyzed data, no significant differences were observed. In particular, during the first survey, which was only active for the test group, more than 40 % of the responses indicated a preference for slightly warmer conditions. However, PECS were often not in use, possibly because participants had just arrived at the workplace and had only a short acclimatization time of 15 min, but frequently turned them on immediately after completing the surveys. This emphasizes the need for automatic control of PECS, as the local heating devices were turned off by default. Automatic control should anticipate and adjust for the delayed TS response, ensuring optimal comfort without requiring user intervention.

In the last survey (only available for the test group), about 30 % of the responses rated TS as slightly cool, while approximately 15 % rated it as slightly warm. Implementing a longer adaptation period after changes in conditions could further help mitigate these effects. This more sensitive evaluation of the thermal environment by the test group could be attributed to several factors:

- Higher expectations: The presence of additional PECS may have raised expectations for ideal thermal conditions, leading to a more critical assessment.
- Thermal asymmetries: Increased thermal asymmetries between body locations heated by the PECS and those not affected by it might have created a less uniform thermal experience.
- Perceived control: The ability to control local heating might have made participants more aware of and sensitive to any deviation from their preferred condition.
- Placebo effect: Being aware of their participation in an experimental group might have influenced the participants' perception and evaluation of TC, potentially making them more sensitive to slight variations.

The relatively high deviation from neutral TS during the first and last surveys, which were conducted exclusively for the test group, contributed to the unequal distribution of TS responses between the test and control groups. This underscores the importance of maintaining equal survey schedules for both groups and highlights the need for alternative approaches to minimize user interruptions, such as event based scheduling. These divergent TS ratings between the two groups highlight the standard challenges posed in field studies. It is important to address the risks of varying sensitivity and attention among participants. Simplified surveys could help address this issue, but e.g. pre-allocating answers based on general TS or a neutral TS might lead to ambiguous results. Less engaged participants might opt for the easiest path with the fewest required inputs, while more engaged participants might provide more critical evaluations. Therefore, it is crucial to ensure a balanced effort in completing the survey, regardless of the answers and individual motivation. To achieve this, it is important to keep the surveys as short as possible while still obtaining all necessary information. This requires a comprehensive definition of the study objectives in advance, and the survey interval should be adjusted accordingly. Furthermore, especially in field studies, it is crucial to motivate all participants to complete the surveys conscientiously. This can be achieved through clear and open communication that emphasizes the value of their contributions, such as the potential benefits for future measures, without distorting the results.

Responses on local TS and TC. Examining the local assessment of TS and TC reveals the impact of the PECS. The PECS effectively warmed the hands and lower body parts (legs) of the test group (Fig. 6) , with a small-to-moderate effect according to Cliff's delta ($\delta = 0.23$ for hands, $\delta = 0.32$ for legs). The average TS values were 0.1 for the hands and 0.4 for the legs, which were statistically significantly warmer than those of the control group ($p < 0.05$), where the average TS

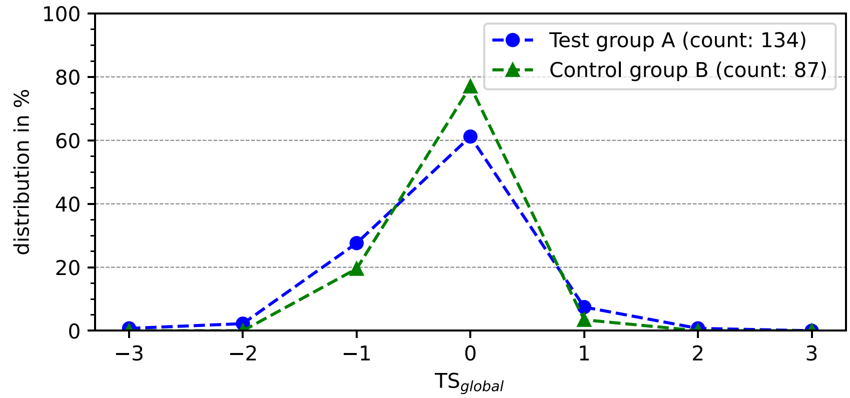
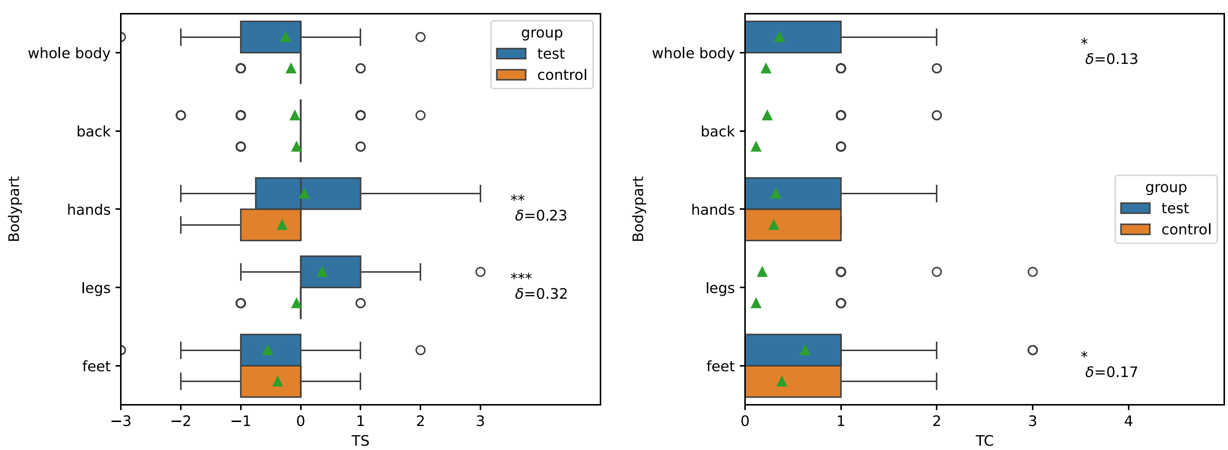


Fig. 5. Percentage distribution of Thermal Sensation (TS) responses from the test and control groups across all surveys, as scheduled in Table 2, for air temperatures below 21 °C.



(a) Thermal Sensation (TS) distribution

(b) Thermal Comfort (TC) distribution

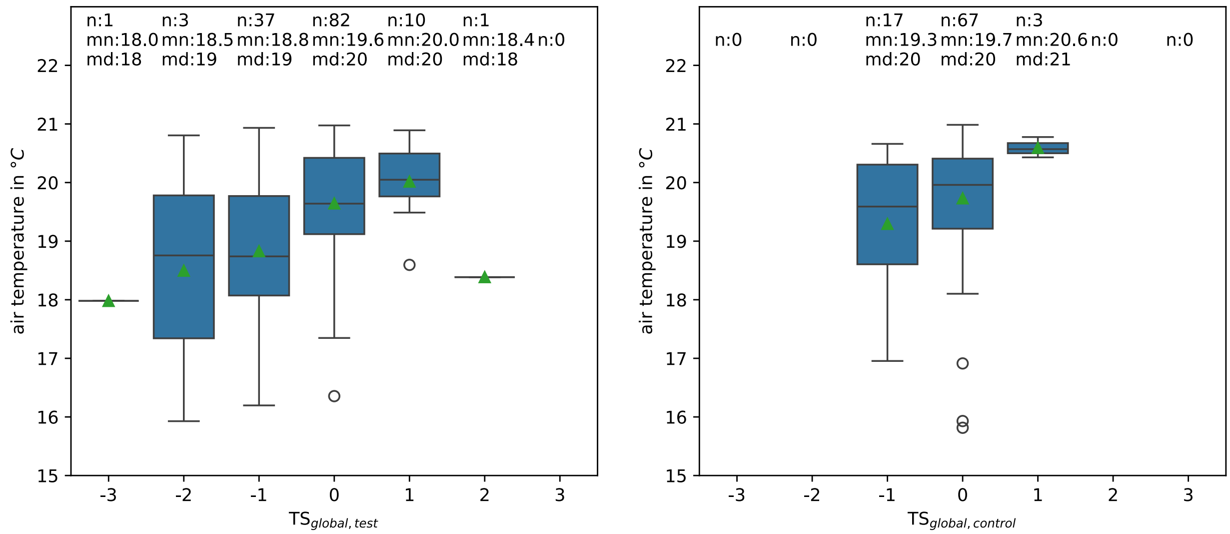
Fig. 6. Distribution of the TS and TC responses for the test and control group, visualized using box plots. The arithmetic means (mn) are indicated by green triangles, and the medians (md) by black lines. Pairwise comparisons were performed using the Mann–Whitney U-test, with statistically significant differences indicated as follows: $*$ $p < .05$, $**$ $p < .01$, $***$ $p < .001$. When significant differences are observed, Cliff's delta (δ) is also reported.

values were −0.3 for the hands and −0.1 for the legs. However, the applied UDHP seems insufficient for warming the feet, as no statistically significant effect on TS was observed. This insufficiency contributed to higher levels of thermal discomfort in the test group, which were statistically significantly worse, with average TC value of 0.6 compared to the control group ($p < 0.05$), with average TC value of 0.4. The more neutrally rated thermal environment by the control group than expected can be attributed to warmer-than-planned indoor conditions, a cooler TP compared to the test group, and thermal adaptation to the anticipated colder conditions. The results highlight the potential of PECS to address inter-individual differences and individual TP. Consequently, both groups assessed these colder ambient conditions as mostly thermally acceptable (TC between 0 to 1). This indicates that PECS contributed to more effectively realizing the policy to limit indoor heating while maintaining acceptable TC.

Ambient air temperature related to TS. For controlling PECS, an automatic control based on ensuring neutral TS is a promising approach. By grouping the answers based on the TS vote, the corresponding average air temperature and typical temperature range for each vote can be determined. The results, as shown in Fig. 7, indicate that heating PECS result in slightly lower air temperatures for each TS vote (considering both arithmetic mean and median values), although these differences were not statistically significant. While the minimal air temperature of the control group was slightly lower than that of the test group (Table 3), test group participants were more frequently exposed to ambient temperatures below 18 °C compared to the control group. For the test group, the median air temperature corresponding to a TS of −1 is 18.7 °C, for TS of 0 is 19.6 °C and for TS of 1 is 20 °C. In contrast, the results for the control group are consistently higher, with median air temperatures of 19.6 °C for TS of −1, 20 °C for TS of 0 and 20.6 °C for TS of 1.

Combined PECS. In this study, a PECS for both lower and upper body regions was implemented. Most studies focus on single PECS devices and demonstrate potential TC improvements. However, a more detailed examination of adequate combinations of PECS in real-world settings is necessary to ensure individual TC in an energy efficient way. The results indicate a need for efficient heating of the feet (tendency towards a slightly cool evaluation), while maintaining a neutral TS at the head region (evaluated as neutral) to avoid local overheating. Additionally, PECS, including targeted heating of the feet through radiant heating, must be ergonomically designed to accommodate varying working habits such as standing and seated positions. To address this, PECS designs should be adjustable in both position and direction to meet individual needs while remaining as unobtrusive as possible to avoid disrupting the user's typical work activities. Exss et al. [98] investigated studies on PECS, focusing on their relationship to the user by differentiating between embodiment and background as well as between high-tech and low-tech, to elaborate their impact on users' perception. This analysis supports the incorporation of post-phenomenological mediation categories in PECS design decisions.

For the upper body, PV could be an energy efficient solution to balance local thermal differences, serving as an effective PECS during



(a) Test group

(b) Control group

Fig. 7. Box plots of corresponding air temperatures for TS votes, with the count (n), arithmetic mean (mn) (green triangles) and median (md) (black lines) indicated.

summer conditions while simultaneously improving IAQ. The design of combined systems must consider possible cumulative effects of PECS and require a user-friendly control interface, which needs to be individualized in future implementations. However, it should be noted that these results are based on cool to neutral thermal environments, with most answers corresponding to a neutral TS. These results need to be verified or corrected in studies conducted under broader environmental conditions with a larger number of participants.

Sample size. A larger sample size and more data points, especially in colder indoor climates, are necessary for more robust conclusions. The sample size should be sufficient to account for variability in responses and environmental conditions. A guideline for such studies would be to have at least 30 participants per group, which can be adjusted based on preliminary findings or pilot studies. Lan and Lian [99],Lei et al. [100, 101] recommend conducting a power analysis, as it often indicates that small sample sizes are adequate if the study design is well-defined and thoroughly prepared. According to these studies, studies on PECS with around 16 participants could be sufficient. However a slightly higher number of participants than calculated is recommended to account for individual variations. In the case of small sample sizes, a within-subjects design could be beneficial, as individual differences have less pronounced effects on the results. Differences between investigated conditions are more easily visible since participants are part of both groups, reducing variability between the groups, so that a within-subjects design is often advantageous [100,101]. Additionally, since each participant serves as their own control, fewer participants are required. For small sample sizes, further restrictions on participant groups could be considered depending on the study objectives.

Monitoring and user feedback. The survey module is implemented independently of the measurement data, which is advantageous for repeatability and familiarizing participants with the survey schedule. However, this approach led to feedback that the questions were repetitive and the survey reminders intrusive. A demand-based implementation based on live measurements could reduce the number of surveys to those scenarios with higher potential benefits for the study's objectives. Further modules for field studies are required, such as feedback or reminders based on measurement data, for instance, to prompt participants to open windows when IEQ deteriorates, or if possible, to control the HVAC system based on the measured data and user profiles.

4.2. Environmental conditions and monitoring

Ambient parameters such as air velocity, humidity, and temperature have a significant effect on TS and TC, and are crucial for accurately assessing thermal conditions. Additional IAQ factors, such as CO_2 concentrations, further characterize the ambient environment and are recommended for measurement to explore potential interrelations between IAQ, TS, and TC, as well as possible positive side-effects of PECS, such as improved ventilation behavior. In this context, Gauthier et al. [102] identified a potential relationship between CO_2 concentration and TS, though statistical significance could not be confirmed due to the small sample size. As shown in Table 3, the indoor air temperature was predominantly above 19 °C when surveys were answered, with both median and average temperatures at 20 °C. To focus solely on times where the environment was considered "cool" to "neutral", only data from surveys conducted at air temperatures below 21 °C were evaluated. This resulted in average air temperatures of 19.4 °C for the test group and 19.7 °C for the control group.

Air temperature and CO_2 curves. As illustrated in Fig. 8, indoor air temperatures start to rise at the beginning of the participants' workday. The absence of temperature control which would have allowed for a stricter enforcement of the 19 °C limit becomes more critical in the afternoon, when indoor temperatures typically rise to 20 °C and higher. This increase can be attributed to heat sources such as occupants, electronic devices, and active radiators within the room, as well as solar radiation. This temperature rise coincides with a decrease in relative humidity. A longer trial period during colder weather would have been beneficial to assess colder indoor conditions; however, unlike in climate chamber studies, such conditions cannot be guaranteed in a field study. Aligning with the temperature increase, the CO_2 levels also rise on average. Despite advice to ventilate regularly, the usual ventilation behavior in winter does not appear sufficient to maintain CO_2 levels below or around 1000 ppm. During nearly two-thirds of the study period, the CO_2 level indicated a low or moderate IAQ. By afternoon, the prevailing CO_2 levels typically indicate moderate IAQ. This highlights the need for additional measures to ensure a healthy indoor environment. Since the test and control groups share the rooms, potential improvements from PECS cannot be validated in this study, emphasizing the importance of addressing this issue in future research. Although the PECS in this study lacked fresh air supply, and no significant differences in CO_2 concentration were observed, these measurements remain valuable for

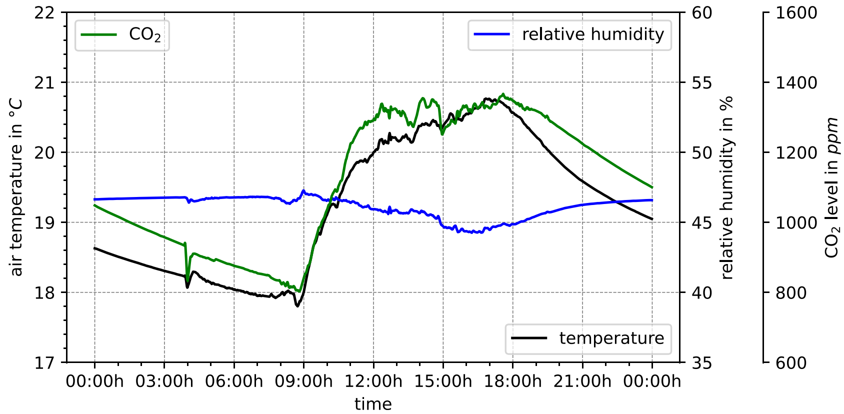


Fig. 8. Average air temperature in °C, relative humidity in % and CO_2 levels in ppm over a typical 24-hour period, based on sensor data from all office rooms.

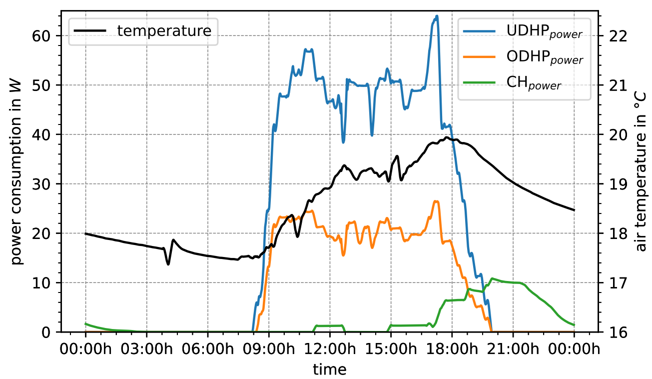


Fig. 9. Average air temperature in °C and power consumption in W of an average day for office 41.

understanding the broader environmental context. Furthermore, these measurements provide a baseline for future studies involving different PECS or other systems directly affecting IAQ.

Extending the measurement period prior to the study could have helped determine the expected daily temperature curve, identify underlying causes and suggest potential improvements such as adapted survey timings, stricter thermostat regulations and ventilation practices. Implementing these improvements could involve automatic notifications triggered by expected temperature profiles as well as based on real-time environmental conditions. For future studies, it is recommended to conduct a thorough preliminary investigation that closely mirrors the actual study conditions. This should include an assessment of typical on-site conditions and feasible interventions to ensure the collection of statistically significant data.

In an office room with a northern orientation, the average air temperature remained mostly within the planned thermal range, with a maximum average air temperature below 20 °C and a usual air temperature below 19.5 °C until about 4 pm (Fig. 9). In this room, the PECS were used consistently throughout the workday, indicating their acceptance as an effective countermeasure to cold thermal indoor environments. This was the only room that consistently maintained the desired temperature range.

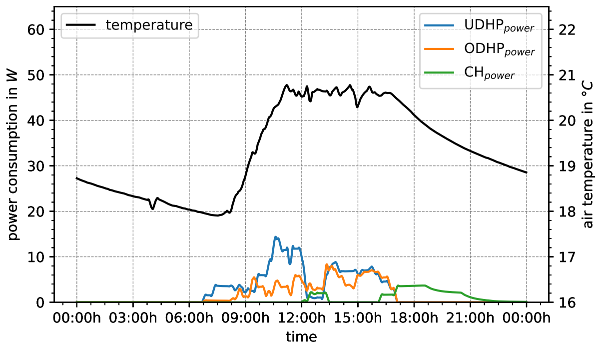
4.3. Energy consumption and control

PECS usage. The use of the heating PECS varied significantly among individuals, as exemplified in Fig. 10. For instance, office 24 exhibited notably higher energy consumption from the PECS, with occasional use at higher settings, including peaks of 175 W for the UDHP, resulting in an average energy consumption of 30 W to 50 W throughout the day. In contrast, office 21 demonstrated typically lower energy consumption, with each PECS averaging below 15 W, despite frequent use during survey responses. The lower energy consumption can be attributed to the devices being set to lower power levels and turned off when participants left their workstations. The indoor conditions in office 21 were not significantly colder than those in office 24, suggesting that the observed differences in PECS usage likely result from inter-individual factors, such as gender, BMI, and general TP. This highlights the potential of PECS to accommodate individual preferences and underscores the importance of further investigating these inter-individual differences in larger participant groups.

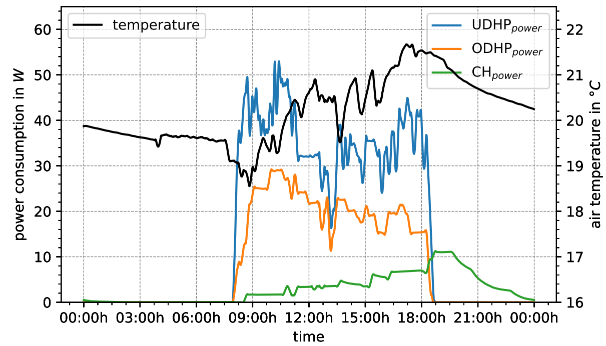
PECS combinations. If PECS were in use, the most preferred combination according to participant response was the simultaneous use of all three devices (Fig. 11), which was employed during approximately every second survey. Not included in this figure is the fact that during 25 surveys, no PECS was active at all. When PECS were used, the UDHP was part of the combination in 87 % of the surveys. This preference can be attributed to the effective heating of the lower body, despite the feet, which aligns with participants' preference for a warmer lower body (Fig. 6). Additionally, due to its primarily radiant heating, the UDHP did not lead to an overly hot TS. Moreover, no ergonomic issues are expected since it was mounted directly below the table without contacting the participants.

In contrast, the ODHP was rarely used as the sole heating device, although the TS at the arms and hands were occasionally evaluated as too cold. Positioned on the desk, the ODHP could be disruptive during work, potentially leading to improper placement or deactivation due to ergonomic concerns. Furthermore, heat transfer by conduction could make it feel locally too warm and rising warm air to the face could be annoying. This aligns with the fact that the TS of the head was neutrally rated and earlier studies confirm a cooler TP in the face region.

Power consumption of PECS. Averaging the data across all considered office rooms throughout the trial period reveals typical daily temperatures and power consumption, as illustrated in Fig. 12. The data analysis indicates the highest energy demand was associated with heating the lower body using the UDHP, while the lowest energy demand was for the CH. Although the UDHP was effective in warming the lower body, particularly the legs, it was inadequate for effectively heating the feet. A more targeted heating strategy for the lower body compartments appears necessary for both energy efficiency and TC. According to Fig. 13, the UDHP was used more frequently than the CH, and its median power consumption (56 W) was significantly higher than that of both the ODHP (32 W) and the CH (12 W). This difference in energy consumption can be attributed to different prevailing heat transfer mechanisms. The ODHP primarily heats the arms and hands via thermal conduction, which may lead to lower power settings due to potentially too-warm local TS. Occasionally, the ODHP was not



(a) Office 21



(b) Office 24

Fig. 10. Average power consumption in W and air temperature in °C of an average day for two offices.

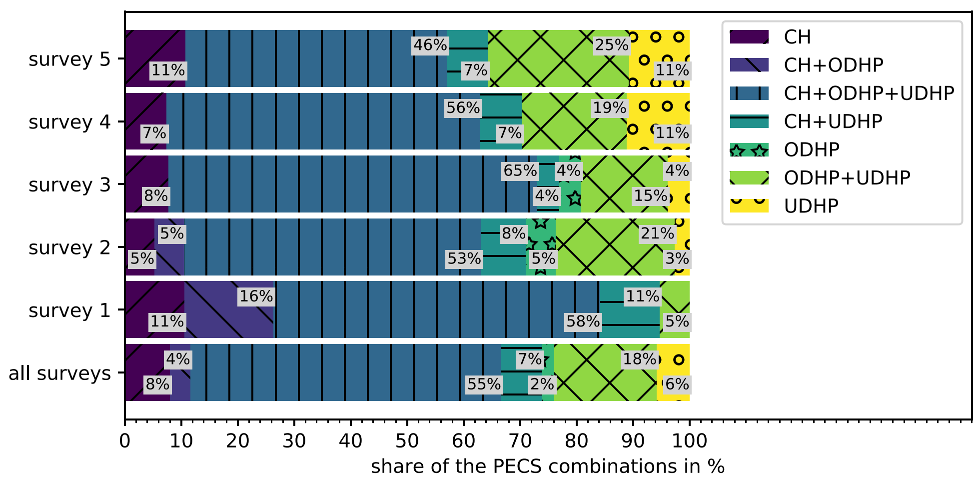


Fig. 11. Percentage distribution of PECS combinations used across surveys, conducted at different times throughout the day, with survey 1 taking place at the start of the workday and survey 5 at the end.

utilized when thermal environment was cold, as the ODHP interfered with current working activities, such as correcting exams. This observation underscores the need for further ergonomic enhancements of the ODHP. Ideally, these would be integrated into the desk and partially adjustable to accommodate various working activities. The CH proved to be the most energy efficient heating device, primarily heating the local body compartments back and buttocks through thermal conduction. Since the CH operates in direct contact with the human body, its heating energy is applied very effectively. In contrast, the ODHP and UDHP also heat the surrounding environment, which reduces their overall efficiency and contributes to higher overall power consumption. Further improvements to these PECS could focus on optimizing TC with lower power consumption by minimizing heat losses, and more precisely targeting colder or thermally sensitive body parts.

By reducing the target heating temperature from 22 °C to 19.4 °C, approximately $1.4\,\mathrm{kW\,h\,d^{-1}}$ could be saved, based on the following assumptions specific to this study:

- Average heating energy consumption of $110\,\mathrm{kW\,h\,m^{-2}\,a^{-1}}$ for office buildings built between 2009 to 2016 [103]
- Assumed area per person of $9\,\mathrm{m^2}$
- An average heating period of $180\,\mathrm{d\,a^{-1}}$
- Energy savings of 10 % per kelvin temperature reduction [42,104]

Under these assumptions, when the PECS is used for $8\,\mathrm{h\,d^{-1}}$, net energy savings remain achievable if the target heating temperature is reduced by at least 1.5 °C, as observed during this field study. However, the actual energy savings will depend on factors such as the building type, local climate conditions, and the efficient integration of PECS into the existing HVAC system. Furthermore, personalized control can enhance these savings, as individuals with cooler TP tend to use PECS less frequently. In average, the heating demand for PECS was $38.5\,\mathrm{W\,K^{-1}}$, if the offices would have been heated on a constant air temperature of 22 °C without PECS.

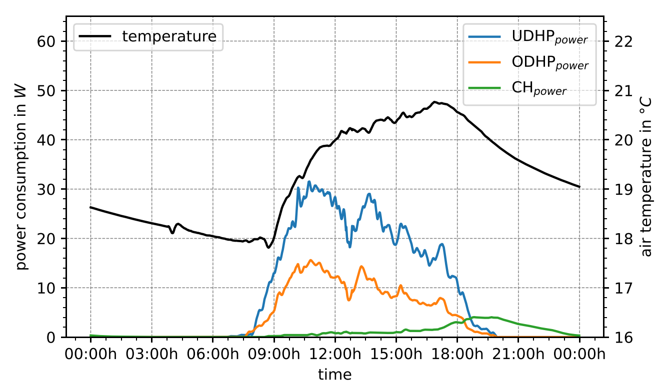
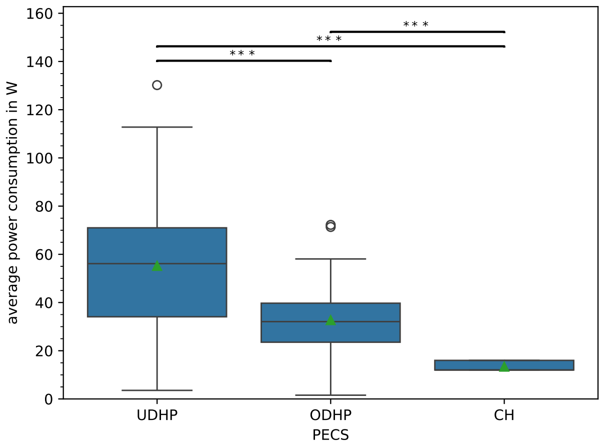
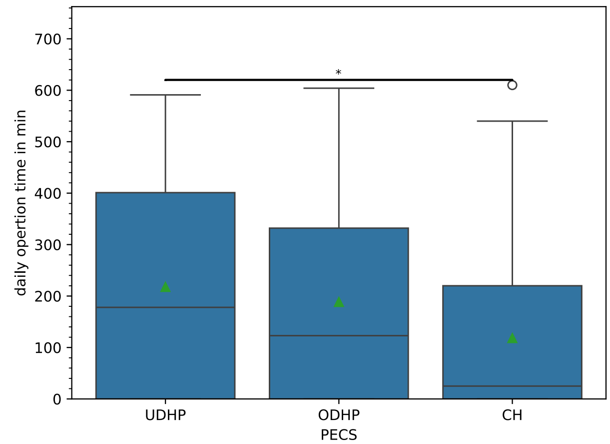


Fig. 12. Average power consumption in W and air temperature in °C of an average day.

Control of PECS. The heating elements for the back and buttocks are not separately controlled, meaning that differing TS between these body parts cannot be addressed. Combined with the limitation of only



(a) Power consumption of the PECS



(b) Daily operation time

Fig. 13. Box plots illustrating the range of average power consumption (when active) of the PECS, as well as the average daily operation time. The arithmetic means (mn) are indicated by green triangles, and the medians (md) by black lines. Pairwise comparisons were performed using the Mann–Whitney U-test, with statistical significance indicated as follows: $* \ p < .05$, $*** \ p < .001$.

two heating modes, the available control of the CH seems insufficient to accommodate all TP. On some occasions, heating mode 2 was locally too warm or resulted in a sensation of heat accumulation due to a lack of simultaneous ventilation, while heating mode 1 was not able to provide enough heat as needed. This can lead to feelings of local overheating, causing the entire device to be disabled. Although the aggregated control simplifies the actions required, it leads to difficulties in addressing varying individual TP. As shown in Fig. 13, the CH had a significantly lower operation time compared to the UDHP, highlighting the advantages of the integrated presence detection. The CH was the only device with an automatic shutdown feature when the user left the workstation. Extending presence detection to all PECS could further enhance energy saving potential. For live tracking of the CH, an additional module could be implemented to send the set heat modes and power consumption to the database in real-time. This would enable the individualization of control modes or the implementation of alternative control strategies. To control the heating mode remotely, such a module would be essential for the implementation of control strategies based on measurement data and user feedback, thereby reducing the required user input.

4.4. Limitations

Some limitations constrained the results of this study. The investigated building is a lightweight construction with HVAC limited to manually operated windows, radiators, and shading systems, and it is lacking thermal ambient measurement devices for continuous measurement. Consequently, measurement systems needed to be installed and it was not possible to centrally control the indoor climate. The study was based on the federally mandated heating set-point of 19 °C for indoor air temperature in winter. Participants were instructed to lower the radiator settings in accordance with the regulations; however, it was not possible to ensure and enforce these lower air temperatures. Increasing air temperatures during the day due to thermal loads and solar radiation led to higher-than-planned indoor air temperatures, averaging 20 °C.

The study is also limited by the small number of participants, with a total of 15 participants distributed between test and control groups, which was not sufficient to obtain generalizable results. Additionally, differences in gender distribution and survey frequency may have influenced the outcomes. A larger sample size, possibly determined through power analyses, would be necessary. Additionally, a within-subjects design would be feasible if a longer test period during cold outdoor conditions is investigated. However, this was not achievable due to the actual outdoor conditions and the study concept, which was constrained by the short-noticed and time-limited ordinance on energy saving in public buildings. Given that the findings are based on a small sample size of 15 people over a three-week period, it is essential to conduct a larger study with a greater sample size and colder thermal conditions, particularly in buildings and rooms with lower temperatures and predefined variations, to validate these results and achieve more generalizable results.

Participants of the test group appeared to evaluate the thermal environment more sensitively than those in the control group. This increased sensitivity may result from individual differences, higher expectations due to control over additional PECS and the awareness of participating in an experimental group. To address this issue, it is important to motivate both test and control groups equally. This can be achieved through better communication of the value of their contributions. Additionally, simplifying the surveys or reducing the survey interval – such as only conducting surveys when ambient conditions are promising for obtaining valuable responses – could help ensure more consistent and reliable data.

5. Conclusions

The current study presented the results of a field study involving the implementation of a Personalized Environmental Control System (PECS), including an Office Chair with Seat and Back Heating (CH), Under-Desk infrared Heating Plate (UDHP) and On-Desk infrared Heating Plate (ODHP), which target the lower and upper body parts as well as the contact areas back and buttocks. The study was conducted in a university building with two-person offices, where one workstation in each office was newly equipped with PECS while the other served as a reference. The participants were free to control the PECS as needed. However, due to higher-than-planned air temperatures (19 °C), the thermal conditions investigated did not allow for a thorough evaluation of the compensation effects using PECS. As the PECS were widely used and even some limitations constrained the results, we can still draw some suggestions for future implementation strategies of PECS in the field:

- The usual ventilation behavior was insufficient to maintain low CO_2 levels throughout a typical working day, with CO_2 concentrations exceeding 1000 ppm during approximately two-thirds of the measurement period. Implementing notifications or automated controls based on measured environmental parameters, such as CO_2 levels, could be beneficial for maintaining healthy IAQ. Additionally, alternative PECS, such as PV, may be necessary to maintain good IAQ. Future studies should evaluate the combined effects of these systems on both IAQ, TC, and energy consumption to develop integrated and efficient solutions.

- Use and effect of the PECS including CH, ODHP and UDHP:
  - Acceptance of PECS is high when occupants have control over the system and are not disrupted during their regular activities. Minimizing interruptions during the study further contributed to higher user satisfaction.
  - The PECS statistically significant improved the TS of the lower body and hands. In the test group, the average lower body TS increased by 0.5, while the hands TS increased by 0.4 compared to the control group. However, the PECS was insufficient for the feet, highlighting the need for additional PECS modules to prevent discomfort from thermal asymmetries and to ensure TC across all body parts, particularly the feet.
  - The CH was the most energy-efficient PECS, with the lowest energy consumption (median: 12 W), which was significantly lower compared to the ODHP (median: 32 W) and UDHP (median: 56 W). This lower energy demand is partly attributable to the CH's lower maximum power demand, as detailed in Table 4, further highlighting its energy efficiency by design.
  - Variations in individual usage patterns of PECS indicate the need for individualized control of PECS to meet diverse user preferences.

CRediT authorship contribution statement

Alexander Warthmann: Conceptualization of this study, Methodology, Data curation, Analysis, Writing – original draft. **Marc Syndicus:** Data curation, Project administration, Writing – original draft, Analysis. **Jérôme Frisch:** Writing – review & editing. **Christoph van Treeck:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Glossary

BMI: Body-Mass-Index
CFD: Computational Fluid Dynamics
CH: Office Chair with Seat and Back Heating
HVAC: Heating, Ventilation and Air-Conditioning
IAQ: Indoor Air Quality
IEQ: Indoor Environmental Quality
MQTT: Message Queuing Telemetry Transport
ODHP: On-Desk infrared Heating Plate
PECS: Personalized Environmental Control System
PMV: Predicted Mean Vote Model
PV: Personalized Ventilation
TA: Thermal Acceptance
TC: Thermal Comfort
T_{eq}: Equivalent Temperature Model
TP: Thermal Preference
TS: Thermal Sensation
UDHP: Under-Desk infrared Heating Plate