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OCCUPANTS' PERSONAL COMFORT IN OFFICE ENVIROMENTS

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CONTENTS

1. INTRODUCTION

With the development of economy and contemporary living standards, people are paying increasing attention to indoor environment given that they spend the majority of the day indoors (87% of the time [1]), and that their well-being, productivity, and comfort depend on the quality of these environments.

To create steady comfortable room conditions during the longer period of time, in most cases energy demand increases and consequently, environmental problems arise. Two main questions imposes: first, how to maintain people's thermal comfort with less energy as people in buildings have various individual requirements and second, how to extend temperature range in buildings and achieve more significant energy conservation while maintaining thermal comfort for the occupants at the same time?

Nowadays, operational settings for buildings provide room conditions based on target temperature and lighting assuming occupants have identical and static comfort requirements. However, there is a limit to how much a centralized system can do to satisfy everyone with the traditional approach of providing uniformly conditions to relatively large, and often shared, office spaces in a building. Given this limitation, rather occupants are dissatisfied in office buildings than satisfied [2]. This problem is attributed to the inefficacy of the existing indoor-climate control [3] or operational strategy, resulting in over-cooled and over-warmed indoors in warm and cold climates, respectively [4]. In both cases, comfort is unachieved while the energy expense is in upsurge.

The current challenge is in providing a balance between reducing the building energy performance and improving occupants' comfort [5]. Various technologies are being developed to reduce energy consumption in building with Heating, Ventilation and Air Conditioning (HVAC) systems. They include, but are not limited to thermoelectric systems, shifting peak demand with phase change materials (PCM), variable refrigerant flow systems [6], ground-source heat pump systems, desiccant cooling, ejector systems, novel heat exchangers [7], controllers based on optimization of energy consumption, and energy efficient design of building envelope. Still, very few of them take seriously in consideration comfort of people in the room. Instrumentation of buildings with the Internet of Things (IoT) facilities to monitor operational settings such as HVAC status, energy usage, and the ambient environment is getting more and more widespread [8]. Smart new technologies to monitor human physiological parameters and comfort preferences in the combination of comfort models are a promising line of research.

Personal Comfort Systems (PCS) give an alternative or complementary solution to centralized systems by allowing a highly customizable microclimate zone in an occupant's office room without affecting others in the same space. With PCS, individuals can use personal control to provide local heating and cooling to meet their comfort requests. PCS comes in many different forms, including fans, heated and/or cooled chairs and desks, foot warmers, portable systems and thermoregulatory clothing. Currently, PCSs have been studied by many researchers in mobile vehicles, offices, and even outdoor environments. There are two main reasons for the contributions of PCSs to energy conservation, answering the questions from the beginning. The first reason is that PCSs mainly influence the practical local body parts by using a small amount of energy to keep the whole body comfortable. Thus a large amount of energy for conditioning the entire indoor space is saved [9]. The second reason is that PCSs extend the comfortable temperature range, which allows the lower set point temperature of heating systems in winter and the higher in summer. As a result, the cooling/heating loads of buildings are significantly reduced.

However, none of the existing systems and models is capable of passively and accurately estimate individual sensations to predict thermal comfort in real-time, so the use of an unobtrusive sensing device is inevitable. Diagnostic sensing devices are devices used to identify the nature or cause of a specific phenomenon by tracing certain parameters' dynamic changes. Examples of diagnostic devices are presented in this review concentrating on ones that could be used in thermal comfort assessment. These smart sensors allow for human motion detection and body/ambient temperature sensors. There are various new products that can be used to create smart building systems that dynamically adjust the indoor conditions according to the comfort of individual building occupants.

This paper reviews smart technologies (Table 1) that can monitor conditions in office building environment to calculate the occupants' thermal sensation vote (TSV) in real time and in this way affect desirable working conditions, work productivity [10] and finally, reduction of energy consumption.

Table 1 *Smart technologies for providing personal comfort*

Visual and acoustic comfort	Thermal comfort
Smart lighting and shading systems	Smart heating devices and systems
Smart lighting devices (lamp)	Smart cooling devices and systems
Sound masking devices (earphones)	Smart ventilation devices and systems
	Smart thermal systems (include comfort diagnostic devices and sensors)

Moreover, a systemic review of how indoor sensors influence in managing optimal energy saving, thermal comfort, visual comfort, and indoor air quality in the built environment was given in [11]. This paper presents the existing commercial solutions as well as research prototypes and comments on their advantages and disadvantages. Furthermore, the paper reviews diagnostic sensors and devices used as assistance in determining occupant's thermal comfort sensation and preferences.

2. REVIEW METHODOLOGY

Elsevier's Scopus® database was the main source of existing research findings, [12]. Conducted review was focused on the two main specific application areas: 1) Smart technologies for providing personal comfort in office buildings and 2) Wearable devices as a diagnostic tool for thermal comfort assessment. Accordingly, the first primary selection was obtained with respect to the targeted keywords, *Personal Comfort* with *Office buildings* as a secondary selection within the found documents (Fig. 1). The second selection of the research work was obtained with respect to the targeted keywords *Wearable devices*, as a primary selection, with *Thermal comfort* as a secondary selection within the results (Figure 2.). All the document types were articles, review and in some specific cases conference papers written in English and published between 2016 and 2020. The subject area in both cases was limited to Engineering, Energy, Environmental Science, Social Science and Computer Science. Depending from the specific selection criteria, some articles are addressed in multiple groups based on the general paper content and specific research findings. Papers about development of personal comfort models [13] without experimental setup but data-driven [14] were not taken into account.

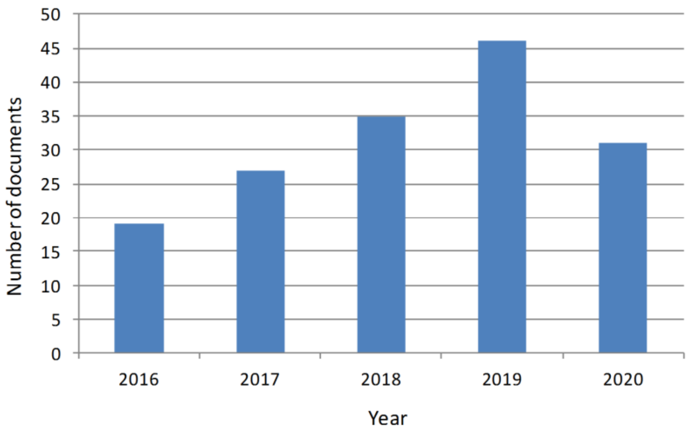

Fig. 1 Number of research studies related to investigation of personal comfort in office buildings

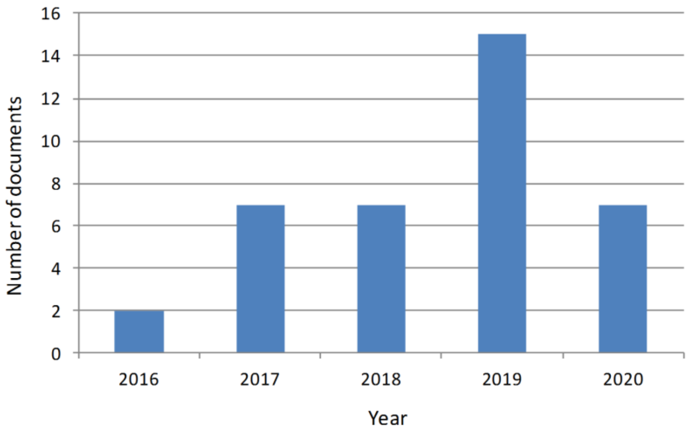

Fig. 2 Number of research studies related to investigation of wearable devices for thermal comfort assessment

This paper starts with an overview of the importance of occupant comfort in the built environment. Then it discusses different personal comfort systems (PCS) and their application in the office buildings and analyzes in terms of visual and acoustic comfort, thermal comfort, and indoor air quality and energy saving. The paper further explores and reviews the different types of diagnostic devices, explaining them in terms of how they sense the occupant thermal comfort. In the end, the paper summarises the advantages of experimental approaches and smart technologies for providing personal comfort identifying the best types of PCS and giving the guidelines for future research in the field. The methodology of the paper is given in Fig. 3.

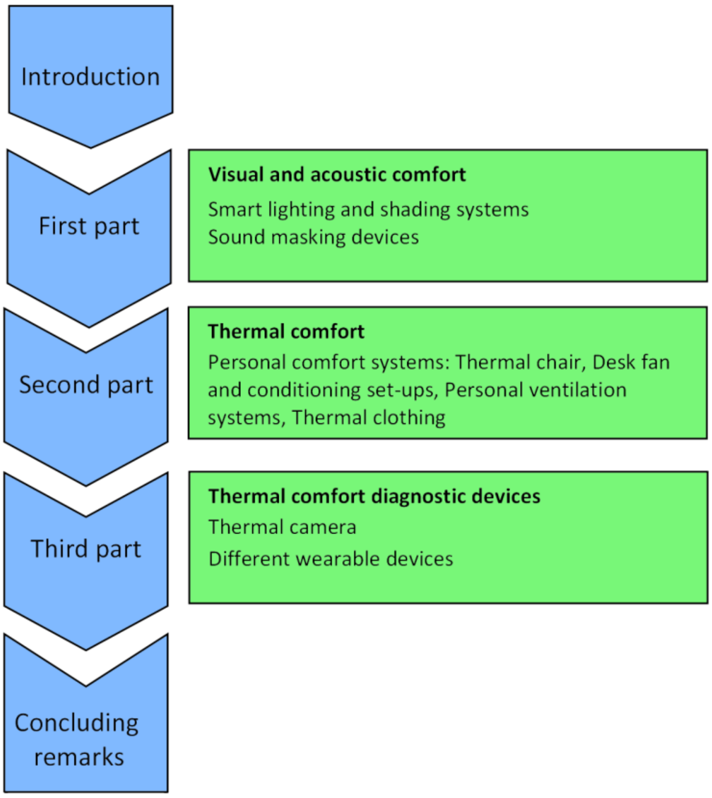

Fig. 3 Paper methodology

3. VISUAL AND ACOUSTIC COMFORT

3.1. Smart lighting and shading systems

Research literature covers a large diversity regarding effects of light (e.g. health, productivity or comfort). As per this paper, it is explored how visual comfort is achieved in office buildings, as well as how it affects occupant's comfort in their working environment in general. Visual comfort requirements vary primarily as per the individual, task they are involved in, and type of the space they work in. Therefore, providing uniform overhead monotonous/bland lighting throughout a space may not fulfil the diverse user requirements at all times. On the other hand, the correct lighting intensity plays a crucial role in determining the visual comfort and health aspects of an indoor environment, impacting factors such as occupants' emotions, visual fatigue, and visual acuity [15]. Modern systems are able to make adjustments in light intensity based on conditions such as availability of daylight and occupancy to reproduce intensities and pivot on smart sensors and actuators incorporating information and communication technologies [16]. To build such a system, personal characteristics of an occupant must be taken in consideration. For this reason, a number of studies evaluated occupants' lighting preference and the effect of their personality on interaction with lighting systems [17].

Sadeghi et al. [18] did a study on human interactions with motorized roller shades and dimmable electric lights in order to prove importance of visual comfort. The research methodology included monitoring of physical variables (occupant's interactions with shading and electric lighting) as shown in Fig. 4, as well as online surveys of occupant comfort and perception of environmental variables, their personal characteristics and attributes (non-physical variables). Four different control setups were explored ranging from manual (wall switches, remote controllers) to fully automatic.

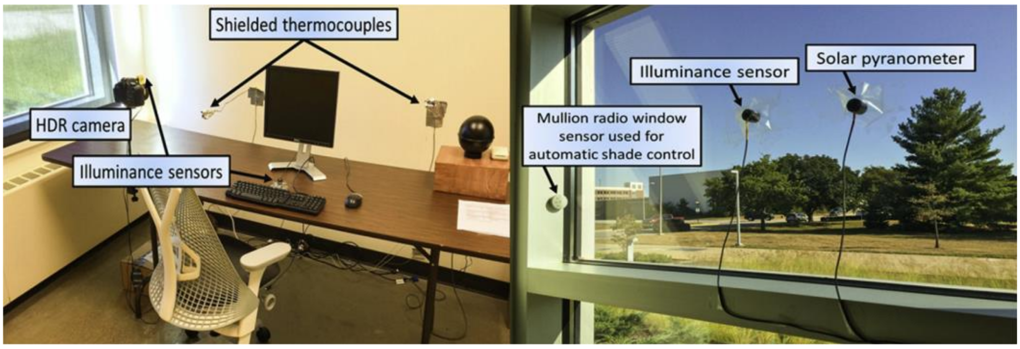

Fig. 4 Typical layout of monitoring instrumentation in each office [18]

The study revealed a strong preference for customized indoor climate, along with a relationship between occupant's perception of control and acceptability of a wider range of visual conditions. Still, the study lacks predictive models of occupant interactions with these systems, as indicated by the results.

Godithi et al. [15] did thorough literature research on advances for thermal and visual comfort controls. As for the personal lighting, they argued that the efficient coordination of task lighting with ambient light and daylight can provide adequate visual comfort for different tasks while reducing energy use. These systems employ distributed sensor nodes to implement occupancy and daylight control while incorporating control feedback from the occupants.

However, these suggestions are made according to research review and do not have a base in practice experiment.

Van Duijnhoven et al. [19] took a step further and proposed a new non-obtrusive method to obtain personal lighting conditions using location-bound measurement instruments, known as location-bound estimations (LBE). Measurements at reference locations allow estimations of lighting conditions at other locations inside the building. The LBE method is promising but needs to be further investigated to determine its applicability on individual.

Xavier et al. [16] built and presented a smart lighting system that can shift the light intensities according to the visual comfort by mobile application or directly from the server. The wireless communication technology used in the research work is ZigBee (IEEE 802.15.4). Similar to [16], Kumar et al. [20] proposed the lighting system that can provide three different control modes (Manual, Automatic and Hybrid). However, the user selection cannot be implemented directly on the hardware; there are backend devices and controls which make it possible. Moreover, systems that require occupant engagement are invasive in terms that occupant looses focus from actual working task. A system should sense the occupant preferences and set the conditions itself.

Despenic et al. [21] tried to model users' preference profiles in terms of visual comfort based on their control behaviour and preference information according to the four group modes: Activeness, Tolerance, Dominance, Preference. The results of their study pointed valuable conclusions for the smart lighting systems. Illuminance measurement in shared or open space offices is not realistically possible, since adjusting the light of the user depends largely on the brightness of the space of his colleague. Therefore, it is not possible to determine occupant preferences regarding the brightness of the space. Moreover, verbal agreements reflecting the preference of multiple users are unknown to the researcher. Furthermore, people could have different preference depending on different aspects (e.g. weather conditions, the time of the day, colleagues' presence, compensation for high room brightness due to high wall luminance, etc).

3.2. Sound masking devices

The main goal of achieving acoustic comfort conditions is the reduction of possible parameters that can provoke discomfort to occupants. The sound insulation and the sound absorption coefficients of the construction and decoration materials are considered, as they can reduce drastically the noise levels from the outdoor and indoor environment [22]. Moreover, the geometry and type of area are of great interest, as the sound wave reflectance on indoor surfaces can lead to intense discomfort conditions for the occupants. In this respect, it is clear that the reduction of any possible sound that can be characterized as noise by the occupants is essential, as it can have a great impact on their concentration's and productivity level. As neutral level of acoustics in case of office buildings (ISO13779) defined the sound pressure range from 30 to 40 dB [23]. The parameter of acoustic comfort should not be overlooked as the discomfort causes are great. Based on Pellerin and Candas analysis, the discomfort caused by a 1 °C temperature change is similar to the one caused by a 2.6 dB change [24]. As for the office room areas, external noise in general can be minimized by external elements and building design and the internal noise can be minimized by using sound internal arrangement, office layout and absorbing materials. Currently, for the office work spaces there are no sound masking devices that we are aware of, other than simple earphones used by occupants, mostly in shared rooms.

4. THERMAL COMFORT

Personal comfort systems (PCS) or task ambient conditioning systems [25] are typically space conditioning systems, installed in office buildings. Various forms of PCS have been studied in laboratory and field studies, such as radiant or convective heaters, and temperature-controlled surfaces on desk and chairs, or desk and ceiling fans. Local thermal conditioning promises to increase the comfort of occupants while lowering the energy consumed by central HVAC [26] (unlike the private office approach) because it is inherently more efficient to heat and cool the individual occupants directly than to condition the entire ambient space [27]. The occupants control PCS systems freely or there is smart automatic control strategy of the thermal conditions in the small regions surrounding them without affecting the thermal environment and comfort of other occupants. Some researchers investigated is this possible by traditional personal heating device and some went beyond and upgraded them. For example, Huotong [28, 29] a kind of traditional personal heating device with the complex heat transfer process, which combines conduction, convection, and radiation, was retrofitted so it could maintain people's comfort even when the temperature was lower than 10°C. However, the feet of subjects were still in cool condition at 9 and 12°C. Same effect is occurred when using traditional cooling devices. The microzones, in general, can keep occupants comfortable over a wider temperature set point. Still, reducing building energy consumption is not guaranteed unless the devices in charge of thermal microzones creation are more energy-efficient than the building systems. Creating a thermally comfortable microzone is a challenge and below are described some studies that are done on this topic, which include thermal chairs, cooling and conditioning systems, robots and thermoregulatory clothing.

4.1. Thermal chair

Deng et al. [30] carried out a series of experiments on heating thermoelectric chairs with 36 participants who tested it and gave subjective thermal responses. The authors reported thermal sensation and comfort of the subjects at 16°C were significantly higher than at 18°C. Although there was an improvement in occupants' thermal satisfaction, occupants' sensation of body exterminates was not investigated.

He [9] studied the effect of chair heating assisted by leg-warmers at 14°C, 16°C, and 18°C. He found that the combination of heating chairs and leg-warmers performed better on improving overall sensation and comfort and that independent chair heating could not eliminate the cold discomfort of different body extremities such as feet. Occupants' subjective responses were recorded and analyzed, showing the improvement of comfort at lower temperatures (more than 80% of subjects voted on the acceptable side even at 14°C). Also, the authors emphasized that the combination of heating chairs and leg-warmers could generate a 71.0% of the total heating energy. However, there were only two subjects in the room each time. The occupant number may be not the same as that in the real environment. Therefore, further studies in real environments are still needed to validate the results of this study.

Yang et al. [31] investigated the effects of a chair with heatable backrest and seat cushions (Fig. 5) which means that the chair could be used in cold conditions only. The experiments were carried out at 14°C, 16°C, and 18°C in a climate chamber in the climate chamber at Tsinghua University in Beijing, China, during the winter. The results revealed that compared to the well-insulated chair, the additional active heating has no significant advantage for the overall thermal comfort at 16°C and 18°C and has only a limited effect on improving overall thermal sensation and comfort at 14°C. However, the amount of electricity was not recorded in detail; thus, energy consumption cannot be presented quantitatively.

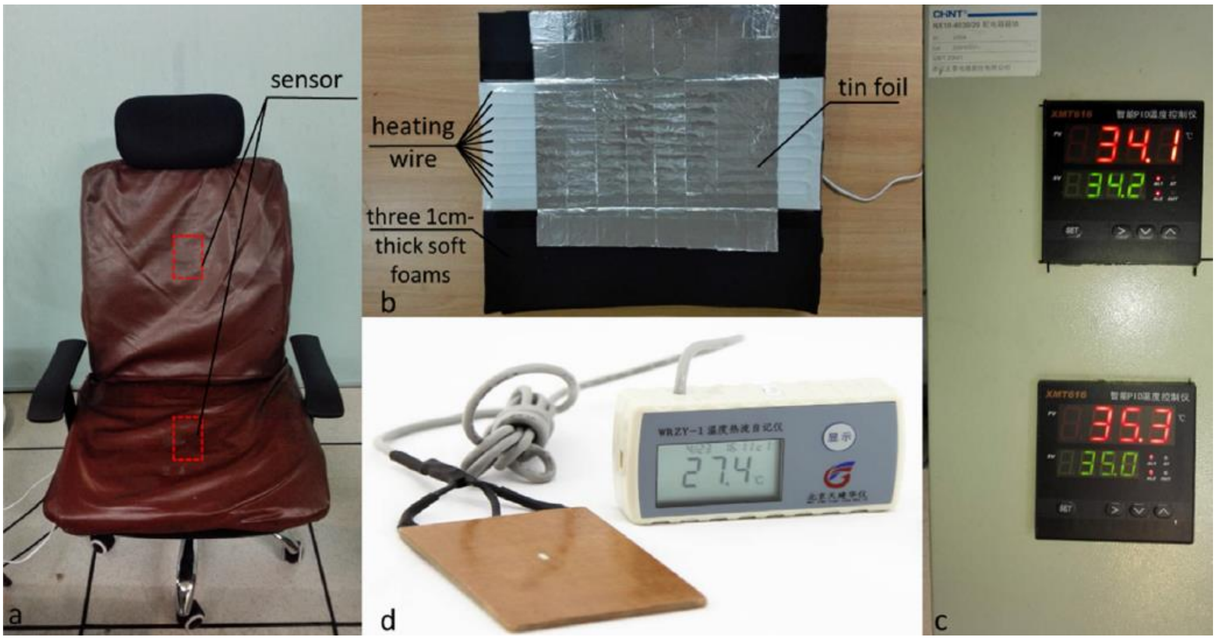

Fig. 5 Pictures of the devices used in the measurement. (a) The chair with backrest and seat heating cushions; (b) structure inside the heating cushions; (c) control panel, where the red numbers are tested temperatures and the green numbers are set temperatures; and (d) self-recording sensor which records temperature and heat flow [31]

In their work Shahzad et al. [32] designed, produced and tested a prototype of an office chair equipped with separate user temperature control over the seat and the back on 45 respondents who used the chair and filled out a survey questionnaire. The chair seat and the backrest areas were incorporated with heating element pads covered by the chair fabric. Each pad uses up to 30 W. Hence, the thermal chair energy consumption is relatively low when compared to typical personal heaters, which are about 1–1.5 kW, showing good potential for energy savings in buildings, particularly during cold winter where the device could be used. This group of authors continued their work [33] and made a model simulation of a building with thermal chairs in Building Energy Simulation (BES) software, IES Virtual Environment. Furthermore, they equipped the chair with separate user temperature control over the seat and the back of the chair. The results showed a heating energy demand reduction of 27% in January and 25.4% in February. Moreover, occupants reported 20% higher comfort and a 35% higher satisfaction level by using the chair during their working hours. On the downside, areas such as the face and legs regions cannot be improved by the current design; therefore, further work is necessary to redistribute the heat to other areas of the user.

Veselý [34] tested the effectiveness of a personalized heating system consisting of a heated chair, a heated desk mat, and a heated floor mat. The heaters were tested separately and in combination as user-controlled. The system significantly improved thermal comfort at 18°C, while the heated chair was found to be the most effective heater. A hand skin temperature was used as a feedback signal to compare user interaction with automated control. The goal was to determine, whether an automated control can substitute the user interaction and the authors concluded that the automatic control mode could provide the same level of thermal comfort as user control. Still, the authors did not state clearly what happens with the energy consumption in buildings while using this system.

Kim et al. [35] upgraded thermal chairs with wireless communication via embedded sensors and data reporting capabilities for cooling and heating season, respectively. The authors concluded that in the case of the PCS-chair microzone, the energy costs of maintaining occupant comfort are far smaller than if the whole zone were kept at a comfortable level. The results showed much higher comfort satisfaction (96%) than typically achieved in buildings. Although the study has some useful findings of occupant comfort and behaviour that the intelligence built on PCS data turn into actionable feedback for HVAC controls, it still lacks prediction models to be valuable for occupants' indoor environment.

Investigated thermal chairs and their characteristics are given summarised in Table 2.

Table 2 *Investigated thermal chairs and their characteristics*

Thermal chair Characteristics	Impact on energy consumption	Reported comfort and TSV	Reference paper
heating thermoelectric chairs	Not investigated	reported thermal sensation and comfort of the subjects at 16°C were significantly higher than at 18°C	[30]
heating chairs combined with leg-warmers	- heating chairs could only save 61.0% of the total energy at most to meet the 80% acceptable requirement - combination of heating chairs and leg-warmers, reduced 71.0% of total heating energy	Occupant reported that heating chairs and leg-warmers performed better on improving overall sensation than heating chair alone: improvement of comfort at lower temperatures (more than 80% of subjects voted on the acceptable side even at 14℃)	[9]
chair with heatable backrest and seat cushions	speculate that actual energy consumption was low	no significant advantage for the overall thermal comfort	[31]
chair incorporated with heating element pads covered by the chair fabric	heating energy demand reduction of 27% in January and 25.4% in February	occupants reported 20% higher comfort and a 35% higher satisfaction level	[32]
heating system consisting of a heated chair, a heated desk mat, and a heated floor mat	Not investigated	a heated chair and a heated desk mat improve thermal comfort at 18°C	[34]
thermal chairs with wireless communication via embedded sensors and data reporting capabilities for cooling and heating season	Not investigated	results showed that thermal chairs produce much higher comfort satisfaction (96%) than typically achieved in buildings	[35]

In general, thermal chairs produce much higher comfort satisfaction than typically achieved in buildings, and their energy consumption is relatively low when compared to typical personal heaters. Moreover, thermal chairs provide not only personalized comfort solutions but also offer individualized feedback that can improve comfort analytics and control decisions in buildings. Nonetheless, there is a list of limitations accrued in real building experiments. The first limitation is connected to battery life which decreases over time, requiring more frequent charging. Many chair users left the charging cable connected to the battery all the time, presenting potential trip hazards and damage to the charger (e.g., broken plug). A larger capacity battery or batteries with a longer life, or low power continuous wireless charging are a better alternative. Another issue is the ergonomic problem. In most studies, occupants expressed feeling uncomfortable due to the ergonomic nature of the chair equipped with and various sensors and heating pads. Moreover, thermal chairs alone do not resolve extremities discomfort as they influence only the middle part of the human body. In the end, clothing ensembles, humidity, air velocity, and metabolic rate of the occupants were not adequately considered in developed prototypes of thermal chairs.

4.2. Desk fan and conditioning set-ups

The most commonly used devices for cooling and expanding the comfortable range of ambient temperatures in an office environment during the cooling period are desk fans. Elevated air movement by electric fans is a cost-effective cooling method for both energy-saving and thermal comfort improvement. Recent studies proposed different fan positioning, but the desk fans proved to be the most effective and the least energy-consuming ones.

Shetty [36], [37] collected occupants' desk fan usage preferences via wireless sensor and actuator network (WSAN) in two shared offices along with indoor and outdoor environmental conditions as well as user presence information from July to November 2017. Each user was provided with a commercially available desk fan integrated with a wireless sensing and actuating node. The WSAN enabled the occupants to control their fans. Random forests method achieved the best performance with the average test set accuracy of 97.73% for classifying fan state with 95.42% accuracy for instances where a user is present, and the fan speed was estimated with average RMSE of 15.83 of the fan setting. The same as He et al. [38], Shetty proved desk fans to be more effective working under free-control mode rather than under fixed air velocity mode. The subjects in their experiments considered the hot-humid environment more comfortable when they were allowed to control the desk fan freely. On the contrary, Zhai et al. [39] tested twenty-three subjects in summer under a set of air speed set points and found that ceiling fans were very effective for providing comfort in warm temperatures and high humidity (up to the 30°C and 60% RH). However, this study was not compared to research of desk fans so there is no reason why ceiling fans would be better than desk fans. Still, their results showed that availability of air movement is more important than providing control over it and that airflow is preferred by people when it is directed against the upper parts of the body (e.g., face, head, chest) while a transverse flow improves thermal comfort. It is also learned that males prefer higher air speeds than females at the same temperature and RH conditions.

On the other hand, He et al. [40] did a series of tests on the influence of desk fans on personal comfort with subjects having access to controlling indoor temperature and not having the control. They found that desk fans significantly reduced the warm sensation in warm environments, but the subjects still adjusted the indoor environment when they had access to control the indoor temperature. Meaning, when people have various available approaches for adapting to their ambient environments, they will choose the most effective one to keep them comfortable [41]. In other studies, using air conditioners was considered to be more effective than personal cooling devices such as fans. Liu et al. [42] and Xu et al. [43] dealt with improving commercially available desk fan with the camera-based indoor tracking system and air-conditioning system combined with mechanical ventilation, respectively. Those authors proposed a calibrated mapping algorithm to automatically adjust the fan input power to generate the desired airspeed. The results showed energy cost saving, personal thermal satisfaction improvement, and more efficient operation of the power grid contribution. The study's limitations were that the models of room energy dynamics and ACMV are obtained based on the simplified model with the measured data. Furthermore, there is a need to develop an on-line optimization method involving real-time feedback. Moreover, the experiment included only four human subjects to demonstrate the performance of the proposed method as a proof of concept; thus, it should be evaluated in a large-scale filed test with many occupants.

Luo et al. [27] et al. made a system (Fig. 6) consisting of local conditioning devices put on particular sensitive body parts of a person to achieve the whole-body effect of comfort according to psychological principles. Utilized conditioning devices include a wristband for heating and cooling, a heated shoe insole, small desk fan, and heated/cooled chair. The system activates when the human body drifts out of thermal neutrality in a way that it corrects the ambient temperature towards thermal neutrality.

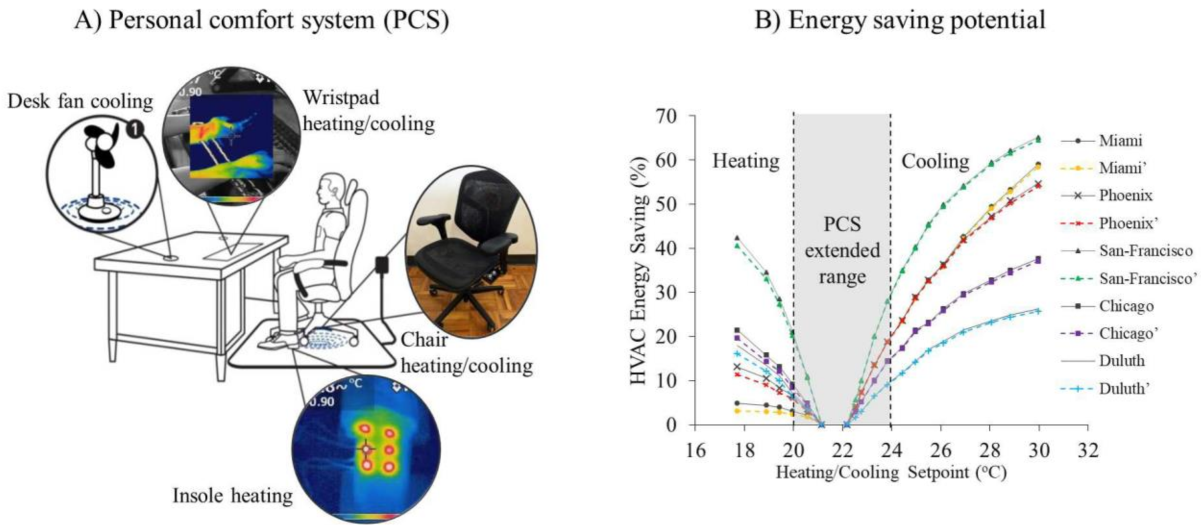

Fig. 6 Experimental setup and energy saving of PCS developed by [27]

This system has been tested on thermal-manikin and human subjects in a climate chamber under cool and warm conditions. This is potentially the greatest way to maintain the occupant's comfort in the office during the entire working day. On the downside, the initial investment in such a system may be costly, especially for controlling the comfort of a large number of employees.

Another personal comfort system called SPOT* (Smart Personalized Office Thermal comfort system) is developed by Rabbani and Keshav [44]. SPOT* consists of the fan/heater, and the actuation box, with the two sensors, for air temperature and occupancy measurement. Moreover, two power cords of the modified fan/heater are connected to the actuation box. The software which interfaces with the sensors and actuators is the device manager application executing on a Raspberry Pi (RPi). It reads values from sensors and writes commands to the actuators for turning the fan/heater on/off and selecting the necessary fan's speed. The RPi can connect to the building's WiFi network. Although the authors [44] claim that SPOT* system reduced an average absolute occupant's discomfort by 67 % compared to the same HVAC system without SPOT*, it does not solve local discomfort.

Kong et al. [45] evaluated the performance of a newly developed micro-environmental control system (μX) designed to cool the occupants individualy to reduce the HVAC cooling load. This system starts working when the ambient unoccupied room temperature rises from 23.9°C to 26.1°C. The μX was tested with a manikin wearing summer clothing and then with human participants in a climate chamber. Results show that the manikin's heat loss increased with the distance between the μX air supply diffuser and the manikin and decreased with the clothing insulation. Overall, both tests showed that the μX was able to cool the occupant in a room of expanded temperature set point. Furthermore, the Clothing Independent Thermal Comfort Model was developed, giving a consistent prediction. However, the effect of clothing, season, metabolic rate, and the local draught were not taken into account, so slight thermal discomfort was reported when the μX was working.

Another interesting personal conditioning system called Roving Comforter (RoCo) was an experiment made by Dhumane et al. [46]. RoCo (Fig. 7) represents a cooling robot that follows a person and delivers cooling through robotically-controlled air nozzles. The authors discussed [47] using phase changed material, chilled water and ice cubes inserted into a tank filled with water to deliver cooling effects. Conceptually, it enables buildings to relax their thermostat by up to 2.2°C leading to energy savings ranging from 10 up to 30% depending on climate conditions. Some of the advantages of a portable system of this kind are that it does not require retrofit of HVAC system in buildings, the comfort range is not limited to any particular spot and there is no increase in building thermal loads. On the downside, this system is still in the phase of development, which means it is not tested in real-life conditions. Although the models for optimizing the system are being developed, at this point in research, the system is heavy and costly if used per person in the building.

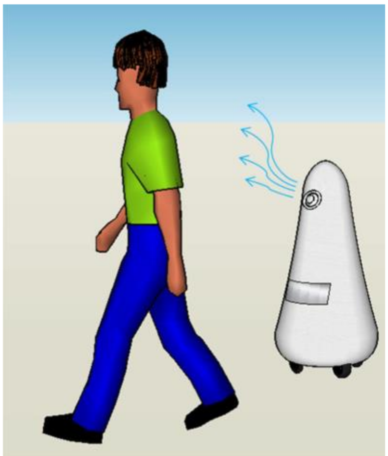

Fig. 7 Conceptual use of RoCo [46]

Personal cooling devices provide direct cooling to the individual occupant rather than cooling the entire building environment and the indoor set-point temperature in this way can be increased without compromising the thermal comfort of inhabitants. It has been found that an increase in the indoor set-point temperature by 1°C can save around 10% energy otherwise consumed by the air-conditioning systems. [48] However, in most studies reviewed, the humidity and CO_2 observed during the experiments were relatively high for the indoor environment levels because for the fans to affect, the office windows must be closed. These factors could also have contributed to the discomfort at higher temperatures, even with the personally controlled air movement.

4.3. Personal ventilation systems

The ventilation is of particular importance in open space offices in hot and humid environments as it has a refreshing effect on occupants. Today's standards stipulate a minimum number of air changes per hour in a room and hardly any buildings are used without satisfying this. Some researchers tested different systems of personal ventilation to calculate the improvement of occupants' comfort sensation. It is indicated that phase change materials (PCMs) and forced air ventilation are the two widely used techniques to develop PCSs [49, 50].

The study of Du et al. [51] of localized airflow system identified three environmental factors: temperature, air velocity, and relative humidity as having the most significant effects on thermal comfort. The authors conducted multiple laboratory experiments to examine the relationships between local air supply and human thermal comfort in warm and hot environments to predict a cooling performance based on machine learning algorithms. They identified the machine learning model, the classification tree C5.0 model with prediction performance of 83.99% accuracy with 17 original variables and it is known that the subjects in these experiments were restricted from regulating the local air-flow system. However, the expected air velocity decreases and the acceptable temperature limit increase when providing personal control to occupants [40].

Mazanec and Kabele [52] et al. deployed a system consisting of a micro air handling unit placed in the doubled floor space and personalised ventilation diffusers mounted on the workspace that were connected by insulated piping and directed to the middle of the opposite side (Fig. 8). The authors measured the impact of the air supply of the personalised ventilation system in heating and cooling. They heated and cooled the air by 4 K through its fan and Peltier cells, to measure the difference and compare it with the isothermal operation. The micro air handling unit sucked the fresh air from the doubled floor. However, the conclusion of this work is very indistinct as the authors report that the possibility of the air customisation could have a positive effect on the wellbeing and the number of people dissatisfied with the environment. The authors seem unsure of the results accuracy and effect of the proposed system.

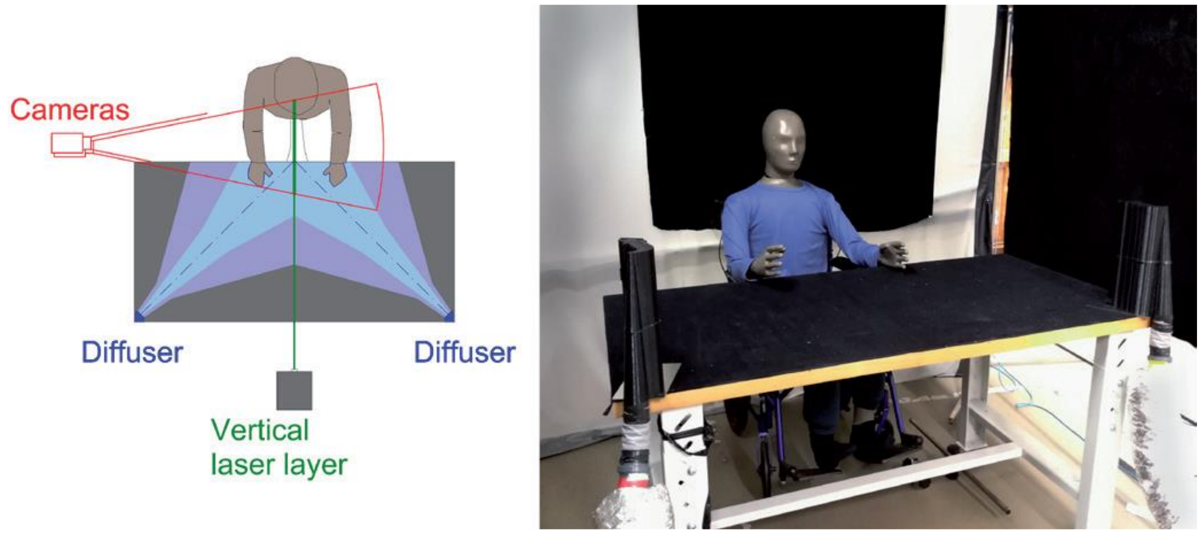

Fig. 8 Experimental setup of personal ventilation system [52]

The near-range energy transfer technologies, such as personal ventilation (PVent), personal air conditioning [36], thermal chair [32] and personal evaporative coolers, are facing challenges including high cost, and system complexity. For example, both the PVent and personalized air conditioning systems use an additional air distribution system that is connected to the building air conditioning system. This makes the whole system more complicated and costly, even for furniture-integrated PVent systems.

4.4. Thermoregulatory clothing

Research efforts for providing comfort have been devoted to incorporate active cooling/heating elements (fan [53, 54], water circulation system) and phase change materials [55] in different kinds of garments.

Itani et al. [53] developed a portable TECU (thermoelectric energy conversion unit shown in Fig. 10). The TECU converts electricity into cooling and heating energy and supplies cool air or warm air to a human body, respectively. The air is supplied by using a micro-blower through a tree-like rubber tube network, knitted into an undergarment. The authors asserted that TECU is able to expand building temperature set points by 2.2°C on both sides (hot and cold).

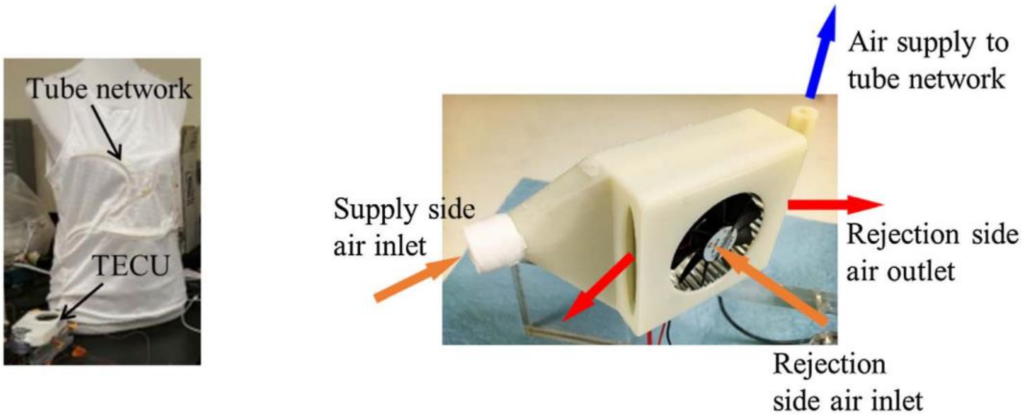

Fig. 10 Thermoelectric energy conversion unit [53]

Song et al. [54] conducted a 90-minutes experiment which included 11 men wearing a long-sleeve cotton/polyester jacket and full-length cotton/polyester pants incorporated with air ventilation fans and PCM packs shown in Fig. 11.

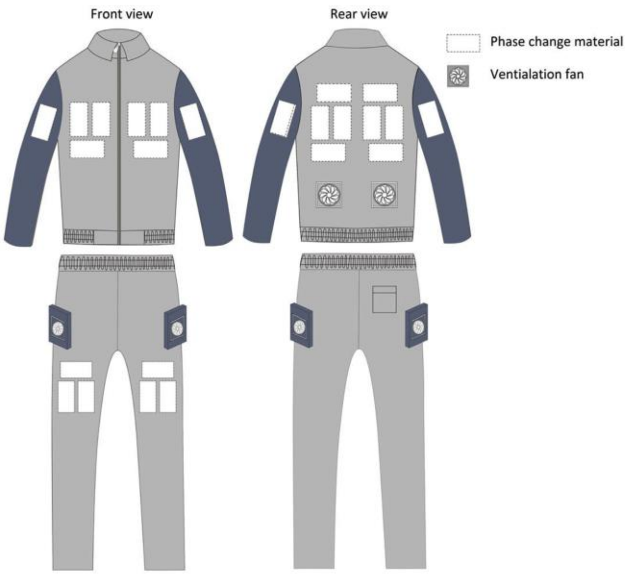

Fig. 11 The schematic diagram of the hybrid personal cooling garment [54]

Zhang et al. [56] investigated clothing made from textiles that can dynamically gate infrared radiation and found that dynamic infrared gating effect mainly arises from distance-dependent electromagnetic coupling between neighbouring coated fibres in the textile yarns. In their report, Xu et al. [57] developed and examined dynamically adjustable thermoregulatory fabric consisting of adaptive infrared-reflecting platforms that feature a simple actuation mechanism inspired by cephalopod skin. Both systems [56] and [57] are in the process of research with the potential of enabling wearable thermoregulatory technologies. Optimization of mechanical actuation strategies or the reduction of the associated operating voltages will be required for application in the field.

Itani et al. [55] proposed the cooling vest with optimized PCM targeting torso sensitive areas that trigger comfort when cooled for improving human comfort in hot conditions. An integrated fabric-PCM and bio-heat simulation model was used in the optimization to predict human segmental core and skin temperatures to determine overall human thermal comfort during moderate activity in hot environment over a specified working period. The results showed that at different ambient conditions, different arrangements and number of PCM packets are needed to improve thermal comfort. The study was done for the outdoor workers and the model was not applied for office working environment. The general problem with PCM is that the textile fibres treated with PCM microcapsules or coated with PCMs to enhance the moisture transport through the cooling system. Nevertheless, textiles coated with PCMs usually fail to provide sufficient body cooling because the limited mass of the PCMs added to textiles. On the other hand, PCM packs containing a large amount of PCMs could offer a relatively long cooling period. It should be emphasized that PCMs with a low melting temperature may cause local skin vasoconstriction and increase tissue insulation [58].

Although the aforementioned approaches were effective in coping with heat stress on individuals indoors this is not always feasible for office workers because they have to wear vocational clothing even in hot summer due to social etiquette requirements [54].

By and large, while used in military, medicine, fire fighting and sports, for formal office wear; it is bulky, heavy and has poor ergonomics. Therefore, wearing this kind of garment is not neither pleasant nor practical, especially in the summer when people wear light clothes. Thus, undergarment itself can cause discomfort. Forcing workers to wear special clothing appears to be both onerous and impractical. Moreover, the liquid cooled and air cooled clothes are often costly, complex especially due to the refrigeration system [54].

The most of the existing thermoregulatory clothing systems have significant drawbacks in aesthetics, size and weight. They are usually not appropriate for use in the general indoor environment [30]. Among those, some thermoregulatory clothing systems can provide only cooling or heating, instead of both.

4.5. Thermoregulatory devices

Lopez et al. [59] developed a Peltier element based wrist-mounted thermoregulatory device and apply both static and cycling temperature patterns on different locations of the wrist. They found that for whole body thermal sensation the cyclic heating rhythms are more efficient than continuous heating. Furthermore, their results showed that the wrist warming can improve thermal sensation of fingertips. Although results contribution is valuable, the prototype should be made for cooling as well.

Wang et al. [60] tested 6.25 cm^2 thermoregulatory devices, Embr Wave, powered by a Li-ion battery, to deliver local heating and cooling. The device delivers dynamic waveforms of cooling or warming to the inner wrist. 49 subjects participated in three thermal comfort tests conducted in a climate chamber with temperatures between 20 and 28 °C, and the analysis [61] showed that the device exhibited a corrective potential of 2.5 °C within 3 min. They found that a wearable device delivering dynamic thermal waveforms to the skin of the wrist can statistically improve whole-body thermal sensation for about 0.5–1 scale unit, which is equivalent to about 2 to 3 °C ambient temperature, while consuming ~1 W of power. The impact on the left wrist is about 2 times stronger than the impact on the whole body. Limitation of this study is that is focused primarily on studying short-term effects using trials that lasted only 3 min, so the results do not address the effectiveness of the device over many hours or a full working day and are not validated in field studies.

All the PCSs with their possibilities described above are summarised in Table 3.

Table 3 *PCSs possibilities summary*

PCS	Heating possibility	Cooling possibility	Cost	Energy consumption	Ergonomics
Thermal chair	+	-	-	+	-
Desk fan	-	+	+	+	+
Cooling desk	-	+	-	-	-
Following robot	-	+	+	+	+
Thermoregulatory clothing	+	+	-	+	-
Thermoregulatory devices	+	+	/	+	+

5. THERMAL COMFORT DIAGNOSTIC DEVICES

5.1. Thermal camera

A plethora of research concentrated on skin temperature as crucial parameter for measuring personal thermal comfort using thermal camera (Fig. 12a) for data collection.

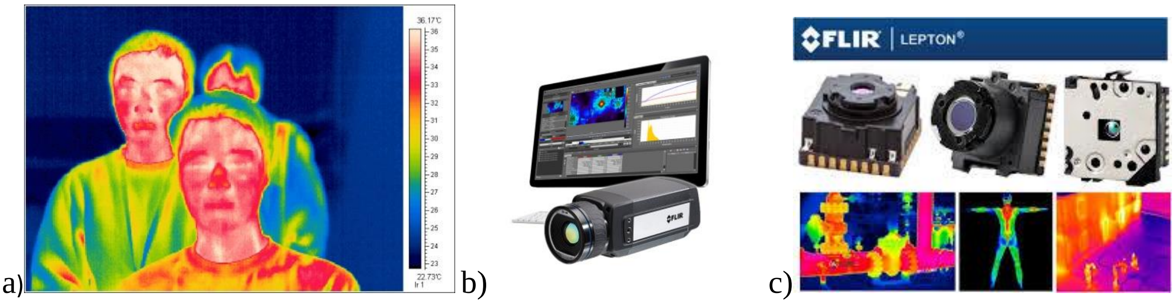

Fig. 12 Thermal cameras used as a diagnostic device in thermal comfort assessment

Ranjan and Scott [62] used the FLIR A655sc camera (Fig 12b) to take thermographic images of occupants two times a day during experimental period of five weeks. They correlated each thermal image that was manually labelled offline to identify the skin temperature of different body regions with the reported thermal preference. However, experiments based on collecting termografic images of several body segments assume continuous, unobstructed visual contact with the skin surface of one or more local body parts. This is usually not practical in this vein, given the office setup, as some body parts could be temporarily occluded by people, furniture, clothes or by other body parts. That is the reason that most of the research experiments measuring skin temperature focused on the occupants' face, least likely body part to be covered in clothing. Moreover, the recent thermoregulation studies [62 - 66], identified the face as a relevant body part for thermal comfort assessment. Furthermore, automated facial recognition (identifying a region in an image as a face) is now achievable with high accuracy [67]. Metzmacher et al. [68] used FLIR A35 camera to collect thermographic image of different facial regions and to continuously extract an occupant's skin temperature for real-time analysis. Nonetheless, thermal cameras in above mentioned studies are generally expensive (over $5000). To overcome this limitation, [69] tested a low cost camera (FLIR Lepton, cost: $200, FIigure 12c) to assess thermal comfort through the skin temperature of six facial regions and compared it to reported thermal comfort from the survey. The results showed 85% accuracy in predicting a three-point thermal preference in real time. The authors continued their work in [70] and investigated an infrared thermal camera network to extract skin temperature features and predict occupants' thermal comfort at flexible distances and angles. However, the skin temperature collected from frontal and profile faces was not differentiated and the measurements showed great fluctuations. Furthermore, the proposed camera network was tested in a simplified multi-occupancy environment with only two subjects. It is questionable how would the occupant thermal recognition have been in larger space with more subjects and possible occlusions and increased viewing distance.

Some researchers presented the eyeglasses outfitted with point Infrared (IR) sensors for measuring face skin temperature at multiple locations to monitor occupants' thermoregulation. Ghahramani et al. [64] (Fig. 13) collected infrared radiations on four facial points: front face, cheekbone, nose, and ear. The authors also used four temperature and humidity sensors located in space around the occupants and have occupants to report their thermal sensation every 15 minutes. The wearable device in the paper served its purpose but the need for constant feedback is time consuming and inappropriate in everyday working environment. Being aware of this limitation, the authors continued their work in [71] and developed a hidden Markov model (HMM) based learning method to define three thermal states of occupants (uncomfortably warm, comfortable and uncomfortably cool) to avoid the need for thermal feedback. However, the impact of other influential factors on skin temperature, such as activity level or sweating for example might have impact on the infrared measurements, as the skin surface characteristics may change, but were not considered in experiment. Moreover, the authors claim these goggles are non-invasive but the Fig. 13 might suggest different. Meaning, the occupants might feel uncomfortable wearing the glasses tag along with bunch of cables hanging around them. In addition, it is not clear what about the occupants who usually wear glasses? They should put glasses under glasses?

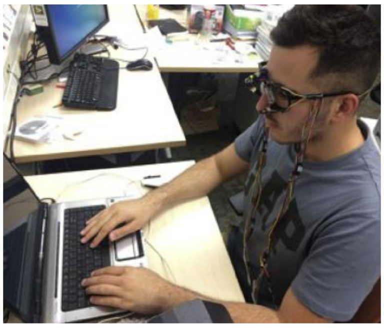

Fig. 13 Thermal imaging through goggles [64]

Another approach for monitoring the occupants' thermal sensation based on thermal imaging, which is indeed non-invasive is done by mechatronic device developed by [72]. The imaging is performed on the forehead skin and then correlated with occupants' thermal sensation. Although the forehead temperature proved to efficaciously detect thermal sensation variation, without adequate prediction model, personal thermal comfort conations in office cannot be modified in real time.

On the other hand, Cosma and Simha [1] proposed visual sensing platform that combines a termografic camera for reading 5 different facial points temperature with image processing algorithms and machine learning. The subjects were exposed to two different scenarios, fixed setting environment with constant room temperature, and dynamic environment with variable room temperature and clothing insulation. Two different thermal models were tested in both scenarios. First one, based on manually selected best features considered in literature and second one, based on machine learning techniques to select best features for thermal comfort. Even though the research idea is overall well designed, the models are weak in performance. The model trained on fixed conditions predicted personal thermal comfort in dynamic environment with 68.2% accuracy while the automated model had more than 76% accuracy. Moreover, for the dynamic scenario, the results showed drop in performance for both models. Another study [66] deployed model using machine learning for prediction of personal thermal comfort and mean time to warm discomfort accuracy higher than 80%. The devices used in experiment were a thermographic camera, a colour camera and a depth sensor. They were used to detect space occupants and their body parts, from which skin and clothing temperatures were extracted. An analysis of the model performance compared with classical measurements such as skin temperature along with the approach of using multi-part measurements and derived data improved the prediction model accuracy prediction by an average of 60%. This approach shows a great potential but other parameters need to be included in model, such as metabolic rate of an occupant to achieve better prediction accuracy.

5.2. Wearable devices

Over the past few decades, the tremendous advance in electronic and nanomaterials led to the development of wearable devices, real-time and non-invasive sensors for the continuous monitoring of building occupants [73]. Wearable devices are developed in the form of accessories attached to a person's body, and provide a function of measuring parameters such as skin temperature and heart rate (HR) [74], sweat rate [75], puls rate [76], electrodermal activity (EDA) and stress activity [77]. The skin temperature and its time differential as well as the heart rate are often used to estimate human thermal sensation while EDA measures the conductance of the skin. It has been reported that EDA can be a useful indicator of stress. Stress as a psychological state often has an impact on physiological changes on human body and thus on TSV. Group of researchers Yoon et al. have developed wearable flexible patch for stress monitoring measuring the same parameters [78] as well as [79]. Still, one of the biggest applications of wearable devices is in human activity monitoring [80]. Self-powered as well as low power devices such as wrists (watches, bracelets and gloves), heads (glasses and helmets), body clothes (coats, underwear and pants), and feet [81, 82] are a particularly popular area of research currently with many devices under development [83]. Different kinds of wearable devices are shown in Fig. 14.

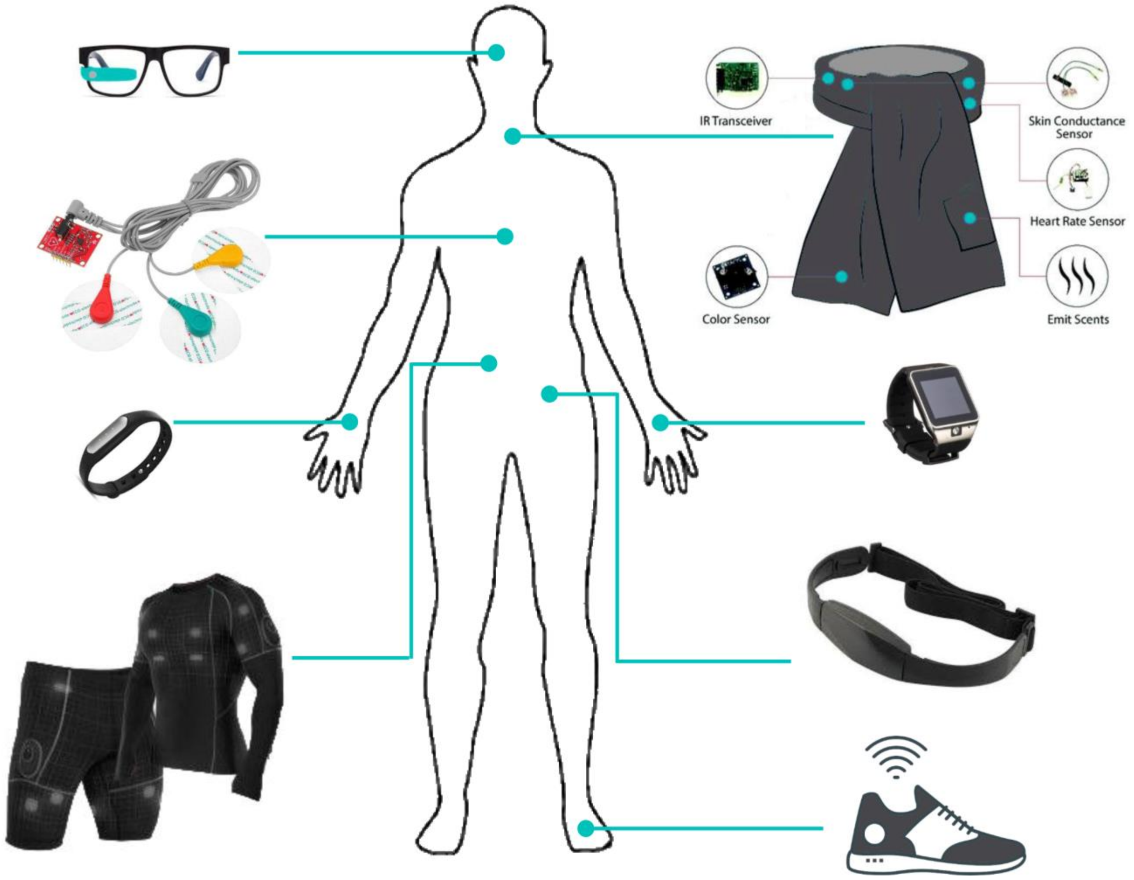

Fig. 14 Wearable device for thermal comfort monitoring

5.2.1. Bracelets and watches

Wrist-mounted devices, such as fitness bands and smart watches are typical non-invasive monitoring devices that carry out two functions: communication with electronic devices and monitoring of human physiological and activity signals.

Hasan et al. [84] conducted a half day experiment with 2 subjects, male and female in their twenties and thirties wearing a Fitbit® wearable watch. They were also asked to carry HOBO MA1101 data logger to record indoor conditions (ambient temperature and relative humidity). The purpose of WD Fitbit® was to monitor their heart rate, activity level, and rate of caloric consumption per minute. The students were asked to mark their clothing status through a smart phone application. The Fitbit® data, the HOBO data, and the clothing status were all joined using a python based application. These data were used to determine the students PMV values every minute and then averaged for each 30 minutes. The study took place over summer 2016 which means that results are not relevant for other periods of year. Another limitation of this work is the absence of the model for the correlation of biometric data with occupant feedback.

In their research, Moatassem et al. [85] used Basis wristband devices (Fig. 15), wearable sensors to collect skin temperature, heart rate, and skin conductivity along of four subjects. They also measured environmental conditions such as air temperature and relative humidity and deployed four cell phones with the developed feedback sensation application installed.

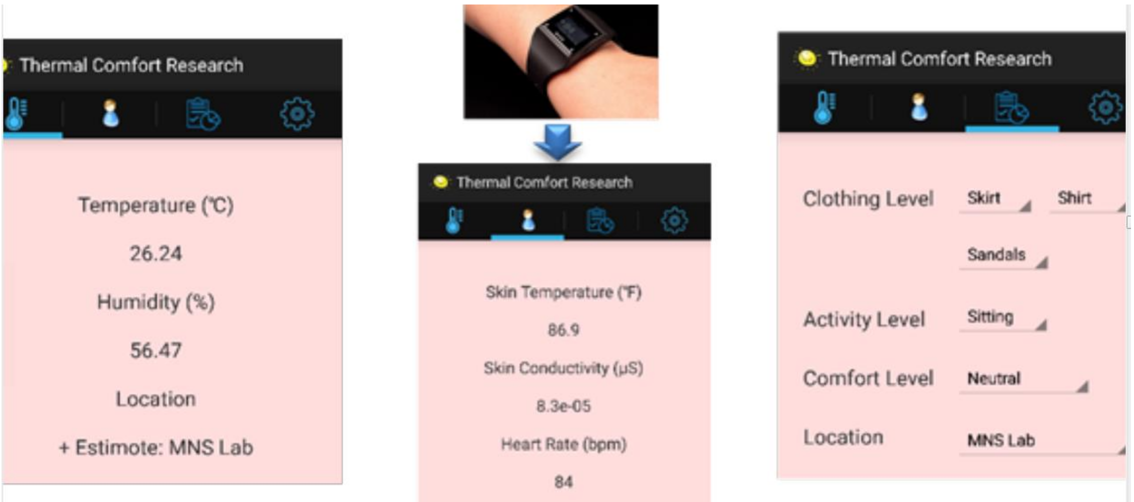

Fig. 15 Basis wristband devices [85]

However, the authors did not develop a model based on their results because the study was of informative nature, conducted in August lasting one day only. They neglected the need for the model even in their next study [86] where they proposed the system which consists of three primary functional components: sensing, controlling, and reporting. Even though the centralized server adapts local indoor environments through smart vents, smart thermostats, and smart blinds readily installed in targeted rooms, the missing model provides the necessity of continuous feedback given by occupants' trough mobile which is time-consuming.

Kamišalić et al. [82] reviewed wristband wearable devices for physiological monitoring, activity monitoring, and environmental monitoring. Their research revealed that the border between commercial products and research prototypes is very narrow as commercial products mostly use older, low cost standardized and well-established sensors for monitoring/tracking and research prototypes that are proposing new sensors which are still not mature enough for inclusion in commercial products.

Sim et al. [75] proposed 30 g-weight sweat rate sensor watch (Fig. 16) capable of automatic natural ventilation by integrating miniaturized thermo-pneumatic actuators, able to operate for 4 hours at 6 V batteries. Their experiment results showed the average sweat rate difference of three subjects for each thermal status shows (32.06 ± 27.19) g/m2h in thermal statuses: ‘comfortable,’ ‘slightly warm,’ ‘warm,’ and ‘hot.’ The measurement error was less than 10% under the air velocity of 1.5 m/s, which corresponds to human walking speed. The proposed sensor is light and insensitive to the wind and thereby has a high potential for thermal comfort monitoring. The drawback of this kind of sensor measuring sweat is that it can only be used in hot and humid climates during summer.

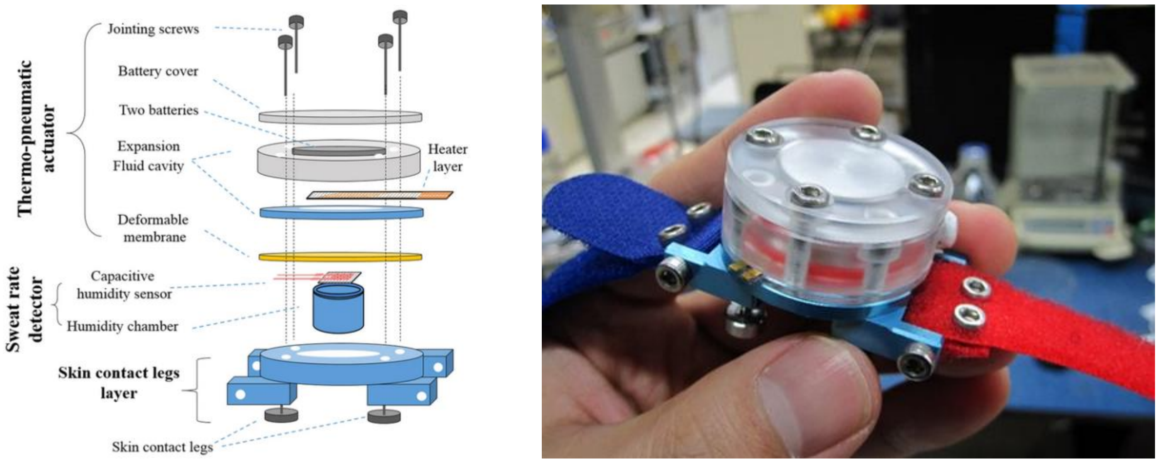

Fig. 16 Sweat rate watch adopted from [75]

Various applications using a photoelectron imaging (PPG)-based heart rate sensor mounted on the wrist have been proposed [87] but most of them were used for human health monitoring, i.e. medical purposes.

5.2.2. Smart diagnostic clothing

Unlike aforementioned thermoregulatory clothing, smart diagnostic clothing consists of conductive devices and clothing material that is attached to or woven with the conductive devices. Textile-based diagnostic devices incorporate sensors, such as electrodes [88] and are used to monitor human physiological signals, biomechanics and physical activity [89]. The issue with these kinds of diagnostic wearables remains the ergonomics, which could be dangerous because this may be the reason for the investigation's false results.

5.2.3. Scarf

Guo et al. [90] developed a smart scarf with a heart rate and EDA sensor to detect and recognize emotional information. According to the authors, this scarf can also respond to negative emotions when detected, by changing its colour and emitting an odour to promote positive emotions. However, this paper presented only the physiological measurement device and it does not have connection with personal thermal comfort sensation.

5.2.4. Smart shoes

Leea et al. [91] conducted a pilot study with the sensor equipped smart shoes and the associated algorithms. Together, they were developed for clinical trials to quantify the functional level for degenerative spinal disorder patients by analyzing their walking ability and clinical information. It would be interesting to apply this research equipment for building occupants' activity measuring.

5.2.5. Sensitised Belt

Nowadays, many types of sensitised belt are developed in order to monitor a user's daily activities for maintaining occupants' health and comfort. Belt-type wearable devices such as Welt [92] and Belty [93] are commercially available that can provide the function of waist measurement, activity tracking, and step counting. However, application for obtaining sensing data is not provided, and it is not suitable for research purposes. The smart belt such as WELT (Wellness Belt) or BELTY to monitor information such as waist size, food intake and movement of users like step count, and sitting time were investigated by [94] Generally, it is hard for ordinary researchers to embed sensors and battery into a small buckle size case that can be worn in everyday life. Nam et al. [95] have proposed a belt-attached device for monitoring posture. However, the device has not reached a sufficient level to be used on a daily basis because of exposed wiring and uncool appearance.

Casaccia et al. [96] monitored of users' health status by a commercial wearable monitoring device BioHarness 3.0 BH3, (Fig. 17) for the continuous acquisition of Heart Rate - HR and Breathing Rate – BR and Electrocardiogram ECG. Calvaresi et al. [97] applied the same device for an estimation of *M* with an accuracy of ±10%. Each subject completed the activity profiles (sitting, walking, upstairs, downstairs) in 20 minutes. The results have showed that, under the conditions of the test proposed, the use of a constant *M* provided an error of 3.2°C in the calculation of the PMV-based comfort temperature with respect to the calculation performed with a dynamic *M*. Furthermore, the study revealed a consequent condition of overheating and a gap between ideal and actual management in the order of 32%.

a)  b) 

Fig. 17 Different kinds of Sensitised Belt
a) Wellness belt [92] *b) BioHarness 3.0 BH3* [96]

5.2.6. Multitype WD for various parameters monitoring

Another study [80] used multiple wearable devices to investigate the relationship among physiological signals, environmental conditions, and activity level. The researchers built a linear model for HR where as predictors they extract various features from measurements of environmental temperature and humidity, body temperature, ankle acceleration, wrist acceleration, and EDA. This study aimed to develop separate regularized regression models for each activity state allowing the use of fewer sensors during specific activities and therefore reducing total power consumption and increasing prediction performance by removing irrelevant features. Limitation is that the model was not tested in real life conditions. Moreover, relevance of the results is questionable since there was only one subject tested whose age is unknown.

Das et al. [98] provided a study with 14 occupants wearing multiple devices around their bodies, 20 hours a week. The weakness of their work was in low reliability of the model. This goes by the fact that all occupants did not participate at the same time but occasionally during the year. Moreover, self assessment of thermal sensation, like it was emphasized many times in the text is not appropriate for reliable measurement.

There are plenty of reviews focused on certain types of sensors, but they are not applicable for building occupants and their TSV estimation purposes. For instance, Gao et al. [99] and Nag et al. [100] reviewed wearable physiological systems and technologies, whereas Li et al. [101] reviewed flexible temperature sensors. Majumder et al. [102] conducted a review of sensors for remote monitoring for the general population and compared various physiological and activity monitoring solutions aimed at the older population. Specifically, separate comparative studies for wearable monitoring devices of the cardiovascular system, body temperature, oxygen level parameters, and activity trackers were presented. At the end of this section, it is worth mentioning the kind of wearable devices that use the human body as a continuous supply of energy to achieve self-powered operation [103] or extend the battery lifetime significantly [104]. Although it would be interesting to apply this knowledge to create a diagnostic tool for investigating human comfort, currently, this is not the case.

6. CONCLUDING REMARKS AND FUTURE DIRECTIONS

This paper emphasized and discussed the importance of the overall comfort of people working in an indoor environment in terms of health, productivity, and energy consumption. The reviewed studies in the last five years proved that PCSs are promising attempts to satisfy occupant needs for visual, acoustic and thermal comfort. Although the noise is proved to be the cause of the discomfort of many tested occupants, there is a lack of investigation of smart technologies for sound masking other than simple earphones. Further, there were several types of research on smart lighting and shading systems explored in this review with the one that modelled user's profiles according to four group modes (activeness, tolerance, dominance and preference) having the best results. Hence, this research field could be upgraded by taking into account brightness of the colleague space and verbal agreements reflecting the preference which was not the case hitherto.

The research papers that dealt with achieving the thermal comfort of the building occupants have tested various methods for implementing PCSs, including different forms of cool air delivery, fans, heating elements, and task lights. However, a preferred equipment configuration does not seem to have emerged yet. In detailed, the most investigated PCSs, especially for heating period, are thermal chairs. Nonetheless, these PCSs have plenty of limitations for daily use in the office at this point, such as batteries runtime, ergonomics and cost. Still, according to presented experiments and prototypes, the best thermal chair solution is the one in combination with leg-warmers. However, the prototype needs further investigation. For the cooling period, different cooling, conditioning and ventilation systems were introduced. The general problems these systems face are high cost and complexity due to the use of an additional air distribution system connected to the building air conditioning system. Other, more straightforward solutions like desk fans can be a better option in terms of cost if the mapping algorithm to automatically adjust the fan input power to generate the desired airspeed is installed. Further, thermoregulatory clothing is turned out to be all-inclusive in terms of heating and cooling but impractical for the indoor environment.

The main drawback of reviewed studies is that many of the existing research were carried out in climatic chambers and only a few tested in the field. After a conducted experiment with the manikin or human subject in chambers, the proposed method should be tested in real-life conditions to validate the results. All in all, it appears that energy savings from PCSs can be significant. It counts about 20 to 30% for heating and cooling, and about 40 to 75% for lighting. Given the demonstrated potential for increased occupant satisfaction and energy savings, PCSs merit further development to refine the equipment and control methods and verify these potentials through new field trials. Inevitably, significant roles in that have sensing devices. Diagnostic devices represent a valuable tool for continuously monitoring the person's physiological signals and assessing their emotional well-being. Depending on parameters needed to measure for model development, sensing devices are wearable at wrists (watches, bracelets and gloves), heads (glasses and helmets), body clothes (coats, underwear and pants), and feet. Different types of non-invasive wearable sensing devices described in the paper showed potential in supporting and complementing existing PCSs to ensure better comfort for the occupants and energy efficiency of the building. These findings could serve as valuable information to help a future researcher in designing and creating a smart technology system that is capable of providing optimal comfort for building occupants without an increase in energy consumption and environmental pollution.

REFERENCES

[1] Cosma, A. C. and Simha, R.: “Using the contrast within a single face heat map to assess personal thermal comfort,” *Build. Environ.*, vol. 160, Aug. 2019.

[2] Karmann, C.; Schiavon, S.; Graham, L. T.; Raftery, P. and Bauman, F.:“Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings,” *Build. Environ.*, vol. 126, pp. 431–441, 2017.

[3] Zhai, Y.; Miao, F.; Yang, L.; Zhao, S.; Zhang, H. and Arens, E.: “Using personally controlled air movement to improve comfort after simulated summer commute,” *Build. Environ.*, vol. 165, no. July, p. 106329, 2019.

[4] Sekhar, S. C.: “Thermal comfort in air-conditioned buildings in hot and humid climates - why are we not getting it right?,” *Indoor Air*, vol. 26, no. 1, pp. 138–52, 2016.

[5] Chaudhuri, T.; Soh, Y. C.; Li, H. and Xie, L.: “A feedforward neural network based indoor-climate control framework for thermal comfort and energy saving in buildings,” *Appl. Energy*, vol. 248, pp. 44–53, Aug. 2019.

[6] Luo, M.; Ji, W.; Cao, B.; Ouyang, Q. and Zhu, Y.:“Indoor climate and thermal physiological adaptation: Evidences from migrants with different cold indoor exposures,” *Build. Environ.*, vol. 98, pp. 30–38, 2016.

[7] Wang, H. and Hu, S.: “Experimental study on thermal sensation of people in moderate activities,” *Build. Environ.*, vol. 100, pp. 127–134, 2016.

[8] Zhang, K.; Ni, J.; Yang, K.; Liang, X.; Ren, J. and Shen, X. S.: “Security and Privacy in Smart City Applications: Challenges and Solutions,” *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 122–129, 2017.

[9] He, Y.; Wang, X.; Li, N.; He, M. and He, D.: “Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter,” *Energy Build.*, vol. 158, pp. 1106–1116, Jan. 2018.

[10] Zhang, F.; de Dear, R. and Hancock, P.:“Effects of moderate thermal environments on cognitive performance: A multidisciplinary review,” *Appl. Energy*, vol. 236, no. July 2018, pp. 760–777, 2019.

[11] Dong, B.; Prakash, V.; Feng, F. and O’Neill, Z.: “A review of smart building sensing system for better indoor environment control,” *Energy Build.*, vol. 199, pp. 29–46, 2019.

[12] “www.scopus.com (Last accesed, 20th of June, 2020).” .

[13] Kim, J.; Schiavon, S. and Brager, G.: “Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control,” *Build. Environ.*, vol. 132, pp. 114–124, 2018.

[14] Choi J. H. and Yeom, D.: “Development of the data-driven thermal satisfaction prediction model as a function of human physiological responses in a built environment,” *Build. Environ.*, vol. 150, no. September 2018, pp. 206–218, 2019.

[15] Godithi, S. B.; Sachdeva, E.; Garg, V.; Brown, R.; Kohler, C. and Rawal, R.: "A review of advances for thermal and visual comfort controls in personal environmental control (PEC) systems," *Intell. Build. Int.*, vol. 11, no. 2, pp. 75–104, Apr. 2019.

[16] Xavier, N.; Kumar, A. and Panda, S. K.: "Design, Fabrication and Testing of Smart Lighting System," in *Proceedings of Future Technologies Conference : 6-7 December 2016, IEEE*, 2016, pp. 763–768.

[17] Heydarian, A.; Pantazis, E.; Carneiro, J. P.; Gerber, D. and Becerik-Gerber, B.: "Lights, building, action: Impact of default lighting settings on occupant behaviour," *J. Environ. Psychol.*, vol. 48, pp. 212–223, 2016.

[18] Sadeghi, S. A.; Karava, P.; Konstantzos, I. and Tzempelikos, A.: "Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study," *Build. Environ.*, vol. 97, pp. 177–195, Feb. 2016.

[19] van Duijnhoven, J.; Burgmans, M. J. H.; Aarts, M. P. J.; Rosemann, A. L. P. and Kort, H. S. M.: "Personal lighting conditions to obtain more evidence in light effect studies," in *Advances in Intelligent Systems and Computing*, 2019, vol. 827, pp. 110–121.

[20] Kumar, A.; Kajale, A.; Kar, P.; Warier, R. and Panda, S. K.: "Implementation and Integration of a Smart App in a Smart Building for Personal Visual Comfort," in *IEEE PEDS*, 2017.

[21] Despenic, M.; Chraibi, S.; Lashina, T. and Rosemann, A.: "Lighting preference profiles of users in an open office environment," *Build. Environ.*, vol. 116, pp. 89–107, May 2017.

[22] "CEN (European Committee for Standardization), ISO 11654:Acoustics-Sound Absorbers for Use in Buildings-Rating of Sound Absorption, Geneva Int Stand. Organ., 1997." p. 11654, 1997.

[23] "CEN (European Committee for Standardization), ISO EN 13779: Ventilationfor Non-residential Buildings − Performance Requirements for Ventilationand Room Conditioning Systems, Standard, European Committee forStandardization, Bruxelles, 2005.," p. 13779, 2005.

[24] Antoniadou P. and Papadopoulos, A. M.: "Occupants' thermal comfort: State of the art and the prospects of personalized assessment in office buildings," *Energy Build.*, vol. 153, pp. 136–149, 2017.

[25] Mao, N.; Pan, D.; Li, Z.; Xu, Y.; Song, M. and Deng, S.: "A numerical study on influences of building envelope heat gain on operating performances of a bed-based task/ambient air conditioning (TAC) system in energy saving and thermal comfort," *Appl. Energy*, vol. 192, pp. 213–221, 2017.

[26] Rawal, R.; Schweiker, M.; Kazanci, O. B.; Vardhan, V.; Jin, Q. and Duanmu, L.: "Personal comfort systems: A review on comfort, energy, and economics," *Energy Build.*, vol. 214, p. 109858, 2020.

[27] Luo, M.; Arens, E.; Zhang, H.; Ghahramani, A. and Wang, Z.: "Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices," *Build. Environ.*, vol. 143, pp. 206–216, Oct. 2018.

[28] He, Y.; Li, N.; Zhang, W. and Zhou, L.: "Thermal comfort of sellers with a kind of traditional personal heating device (Huotong) in marketplace in winter," *Build. Environ.*, vol. 106, pp. 219–228, 2016.

[29] He, Y.; Li, N.; Zhou, L.; Wang, K. and Zhang, W.: "Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel)," *Build. Environ.*, vol. 112, pp. 285–295, Feb. 2017.

[30] Deng, Q.; Wang, R.; Li, Y.; Miao, Y. and Zhao, J.: "Human thermal sensation and comfort in a non-uniform environment with personalized heating," *Sci. Total Environ.*, vol. 578, pp. 242–248, Feb. 2017.

[31] Yang, H.; Cao, B.; and Zhu, Y.: "Study on the effects of chair heating in cold indoor environments from the perspective of local thermal sensation," *Energy Build.*, vol. 180, pp. 16–28, Dec. 2018.

[32] Shahzad, S.; Calautit, J. K.; Aquino, A. I.; Nasir, D. S. N. M. and Hughes, B. R.: "A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance," *Appl. Energy*, vol. 207, pp. 283–293, Dec. 2017.

[33] Shahzad, S.; Calautit, J. K.; Calautit, K.; Hughes, B.; and Aquino, A. I. : "Advanced personal comfort system (APCS) for the workplace: A review and case study," *Energy and Buildings*, vol. 173. Elsevier Ltd, pp. 689–709, 15-Aug-2018.

[34] Veselý, M.; Molenaar, P.; Vos, M.; Li, R. and Zeiler, W.: "Personalized heating – Comparison of heaters and control modes," *Build. Environ.*, vol. 112, pp. 223–232, 2017.

[35] Kim, J.; Bauman, F.; Raftery, P.; Arens, E.; Zhang, H.; Fierro, G.; Andersen, M. and Culle, D: "Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers," *Build. Environ.*, vol. 148, pp. 348–360, Jan. 2019.

[36] Shetty, S. S.; Chinh, H. D.; Gupta, M. and Panda, S. K.: "Personal Thermal Comfort Management in existing Office Buildings using Energy-efficient Fans," in *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*.

[37] Shetty, S. S.; Hoang, D. C.; Gupta, M. and Panda, S. K.: "Learning desk fan usage preferences for personalised thermal comfort in shared offices using tree-based methods," *Build. Environ.*, vol. 149, pp. 546–560, Feb. 2019.

[38] He, M.; Li, N.; He, Y.; He, D. and Song, C.: "The influence of personally controlled desk fan on comfort and energy consumption in hot and humid environments," *Build. Environ.*, vol. 123, pp. 378–389, Oct. 2017.

[39] Zhai, Y.; Arens, E.; Elsworth, K. and Zhang, H.:"Selecting air speeds for cooling at sedentary and non-sedentary office activity levels," *Build. Environ.*, vol. 122, pp. 247–257, 2017.

[40] He, Y.; Li, N.; Li, N.; Li, J.; Yan, J. and Tan, C.: "Control behaviors and thermal comfort in a shared room with desk fans and adjustable thermostat," *Build. Environ.*, vol. 136, pp. 213–226, May 2018.

[41] He, Y.; Li, N.; Wang, X.; He, M. and He, D.: "Comfort, energy efficiency and adoption

of personal cooling systems in warm environments: A field experimental study," *Int. J. Environ. Res. Public Health*, vol. 14, no. 11, 2017.

[42] Liu, S.; Yin, L.; Ho, W. K.; Ling, K. V. and Schiavon, S.: "A tracking cooling fan using geofence and camera-based indoor localization," *Build. Environ.*, vol. 114, pp. 36–44, Mar. 2017.

[43] Xu, Z.; Liu, S.; Hu, G. and Spanos, C. J.: "Optimal coordination of air conditioning system and personal fans for building energy efficiency improvement," *Energy Build.*, vol. 141, pp. 308–320, Apr. 2017.

[44] Rabbani, A. and Keshav, S.: "The SPOT personal thermal comfort system," in *Proceedings of the 3rd ACM Conference on Systems for Energy-Efficient Built Environments, BuildSys 2016*, 2016, pp. 75–84.

[45] Kong , M.; Zhang, J.; Dang, T.Q.; Hedge, A.; Teng, T.; Carter, B.; Chianese, C. and Khalif, H. E.: "Micro-environmental control for efficient local cooling: Results from manikin and human participant tests," *Build. Environ.*, vol. 160, no. February, p. 106198, 2019.

[46] Dhumane, R.; Qiao, Y.; Ling, Y.; Muehlbauer, J.; Aute, V.; Hwang, Y. and Radermacher, R.: "Improving system performance of a personal conditioning system integrated with thermal storage," *Appl. Therm. Eng.*, vol. 147, pp. 40–51, 2019.

[47] Dhumane, R.; Ling, J.; Aute, V. and Radermacher, R.: "Portable personal conditioning systems: Transient modeling and system analysis," *Appl. Energy*, vol. 208, pp. 390–401, Dec. 2017.

[48] Uday, R.; Li. Z., Ke, Y. Wang, F. and Yang, B.: "Personal cooling strategies to improve thermal comfort in warm indoor environments: Comparison of a conventional desk fan and air ventilation clothing," *Energy Build.*, vol. 174, pp. 439–451, Sep. 2018.

[49] Hamdan, H.; Ghaddar, N.; Ouahrani, D.; Ghali, K. and Itani, M.: "PCM cooling vest for improving thermal comfort in hot environment," *Int. J. Therm. Sci.*, vol. 102, no. 2016, pp. 154–167, 2016.

[50] Fonseca, A.; Mayor, T. S. and J. B. L. M. Campos, "Guidelines for the specification of a PCM layer in firefighting protective clothing ensembles," *Appl. Therm. Eng.*, vol. 133, pp. 81–96, 2018.

[51] Du, C.; Li, B.; Liu, H.; Ji, Y.; Yao, R. and Yu, W.: "Quantification of personal thermal comfort with localized airflow system based on sensitivity analysis and classification tree model," *Energy Build.*, vol. 194, pp. 1–11, Jul. 2019.

[52] Mazanec V. and Kabele, K.: "Personalised Ventilation with Air Temperature Customisation: Impact on the Design and Thermal Comfort of the User," *Vytapeni, Vetrani, Instal*, vol. 27, pp. 362–365, 2018.

[53] Zhao, D.; Lu, X.; Fan, T.; Wu, S. Y.; Lou L.; Wang, Q.; Fan, J. and Yang, R.: "Personal thermal management using portable thermoelectrics for potential building energy saving," *Appl. Energy*, vol. 218, pp. 282–291, May 2018.

[54] Song, W.; Wang, F. and Wei, F.: "Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment," *Build. Environ.*, vol. 100, pp. 92–101,

May 2016.

[55] Itani, M.; Ghaddar, N.; Ghali, K.; Ouahrani, D. and Chakroun, W.: “Cooling vest with optimized PCM arrangement targeting torso sensitive areas that trigger comfort when cooled for improving human comfort in hot conditions,” *Energy Build.*, vol. 139, pp. 417–425, Mar. 2017.

[56] Zhang, X. A.; Yu, S.; Xu, B.; Li, M.; Peng, Z.; Wang, Y.; Deng S.; Wu, X.; Wu, Z.; Ouyang, M. and Wang, YH.: “Dynamic gating of infrared radiation in a textile,” *Science,* vol. 363, pp. 619-623, 2019.

[57] Xu, C. Stiubianu, G. T. and Gorodetsky, A. A.: “Adaptive infrared-reflecting systems inspired by cephalopods,” *Science* vol. 359, pp. 1495–1500, 2018.

[58] Kang, Z.; Uday, R.; Wan, X. and Wang, F.: “A new hybrid personal cooling system (HPCS) incorporating insulation pads for thermal comfort management: Experimental validation and parametric study,” *Build. Environ.*, vol. 145, pp. 276–289, Nov. 2018.

[59] Lopez, G.; Tokuda, T.; Oshima, M.; Nkurikiyeyezu, K.; Isoyama, N. and Itao, K.: “Development and Evaluation of a Low-Energy Consumption Wearable Wrist Warming Device,” *Int. J. Autom. Technol.*, vol. 12, no. 7, pp. 911–920, 2018.

[60] Wang, Z.; Luo, M. and Wang, H.: “The Effect of a Low-Energy Wearable Thermal Device on Human Comfort,” *15th Conf. Int. Soc. Indoor Air Qual. Clim.*, pp. 0–9, 2018.

[61] Wang Z.; Warren, K.; Luo, M.; He, X.; Zhang, H.; Arens, E.; Chen, W.; He, Y.; Hu, Y.; Jin, L.; Liu, S.; Cohen-Tanugi, D. and Smith, M. J.: “Evaluating the comfort of thermally dynamic wearable devices,” *Build. Environ.*, vol. 167, no. July 2019, pp. 106443, 2020.

[62] Ranjan, J. and Scott, J.: “ThermalSense: Determining dynamic thermal comfort preferences using thermographic imaging,” *UbiComp 2016 - Proc. 2016 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput.*, pp. 1212–1222, 2016.

[63] Choi J. H. and Yeom, D.: “Study of data-driven thermal sensation prediction model as a function of local body skin temperatures in a built environment,” *Build. Environ.*, vol. 121, pp. 130–147, 2017.

[64] Ghahramani, A.; Castro, G.; Becerik-Gerber, B. and Yu, X.: “Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort,” *Build. Environ.*, vol. 109, pp. 1–11, Nov. 2016.

[65] Cosma A. C. and Simha, R.: “Thermal comfort modeling in transient conditions using real-time local body temperature extraction with a thermographic camera,” *Build. Environ.*, vol. 143, no. June, pp. 36–47, 2018.

[66] Cosma A. C. and Simha, R.: “Machine learning method for real-time non-invasive prediction of individual thermal preference in transient conditions,” *Build. Environ.*, vol. 148, pp. 372–383, Jan. 2019.

[67] Wei, S. E.; Ramakrishna, V.; Kanade, T. and Sheikh, Y.: “Convolutional pose machines,” *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit.*, vol. 2016-Decem, pp. 4724–4732, 2016.

[68] Metzmacher, H.; Wölki, D.; Schmidt, C.; Frisch, J. and van Treeck, C.: "Real-time human skin temperature analysis using thermal image recognition for thermal comfort assessment," *Energy Build.*, vol. 158, pp. 1063–1078, 2018.

[69] Li, D. Menassa, C. C. and Kamat, V. R.: "Non-intrusive interpretation of human thermal comfort through analysis of facial infrared thermography," *Energy Build.*, vol. 176, pp. 246–261, 2018.

[70] Li, D. Menassa, C. C. and Kamat, V. R.: "Robust non-intrusive interpretation of occupant thermal comfort in built environments with low-cost networked thermal cameras," *Appl. Energy*, vol. 251, Oct. 2019.

[71] Ghahramani, A.; Castro, G.; Karvigh, S. A. and Becerik-Gerber, B.: "Towards unsupervised learning of thermal comfort using infrared thermography," *Appl. Energy*, vol. 211, pp. 41–49, Feb. 2018.

[72] Pavlin, B.; Pernigotto, G.; Cappelletti, F.; Bison, P.; Vidoni, R. and Gasparella, A.: "Real-time monitoring of occupants' thermal comfort through infrared imaging: A preliminary study," *Buildings*, vol. 7, no. 1, 2017.

[73] Erwin, J.: "Cool people : Wearable and personal comfort products that will contribute to an overall energy efficiency strategy Key findings," in *Proceedings of the 9th International Conference on Energy Efficiency in Lighting and Domestic Appliances*, 2017.

[74] Li, W.; Zhang, J. and Zhao, T.: "Indoor thermal environment optimal control for thermal comfort and energy saving based on online monitoring of thermal sensation," *Energy Build.*, vol. 197, pp. 57–67, 2019.

[75] Sim, J. K.; Yoon, S. and Cho, Y.-H.: "Wearable Sweat Rate Sensors for Human Thermal Comfort Monitoring," *Sci. Rep.*, vol. 8, no. 1, p. 1181, 2018.

[76] Chaudhuri, T.; Soh, Y. C.; Li, H. and Xie, L.: "Machine learning driven personal comfort prediction by wearable sensing of pulse rate and skin temperature," *Build. Environ.*, vol. 170, p. 106615, 2020.

[77] Taj-Eldin, M.; Ryan, C.; O'flynn, B. and Galvin, P.: "A review of wearable solutions for physiological and emotional monitoring for use by people with autism spectrum disorder and their caregivers," *Sensors (Switzerland)*, vol. 18, no. 12. MDPI AG, 01-Dec-2018.

[78] Yoon, S.; Sim, J. K. and Cho, Y. H.: "A Flexible and Wearable Human Stress Monitoring Patch," *Sci. Rep.*, vol. 6, no. August 2015, pp. 1–11, 2016.

[79] Guk, K.; Guk, K.; Han, G.; Lim, J.; Jeong, K.; Kang, T.; Lim, E. K. and Jung, J.:"Evolution of wearable devices with real-time disease monitoring for personalized healthcare," *Nanomaterials*, vol. 9, no. 6. MDPI AG, 2019.

[80] Starliper, N.; Mohammadzadeh, F.; Songkakul, T.; Hernandez, M.; Bozkurt, A. and Lobaton, E.: "Activity-aware wearable system for power-efficient prediction of physiological responses," *Sensors (Switzerland)*, vol. 19, no. 3, 2019.

[81] Gui H. and Liu, J.: "Latest Progresses in Developing Wearable Monitoring and Therapy Systems for Managing Chronic Diseases," pp. 1–30, 2018.

[82] Kamišalić, A.; Fister, I.; Turkanović, M. and Karakatić, S.:“Sensors and functionalities of non-invasive wrist-wearable devices: A review,” *Sensors (Switzerland)*, vol. 18, no. 6, Jun. 2018.

[83] Lou, Z.; Li, L.; Wang, L. and Shen, G.: “Recent Progress of Self-Powered Sensing Systems for Wearable Electronics,” *Small*, vol. 13, p. 1701791, 2017.

[84] Hasan, M. H.; Alsaleem, F. and Rafaie, M.: “Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation,” *Build. Environ.*, vol. 110, pp. 173–183, Dec. 2016.

[85] Moatassem, A.; Clevenger, C.; Vu, T. and Nguyen, A.: “Sensing occupant comfort using wearable technologies,” in *Construction Research Congress 2016*, 2016, pp. 1–11.

[86] Moatassem, A.; Clevenger, C. and Vu, T.: “Exploring fusing wearables and mobile technologies to optimize energy demand and occupant comfort,” in *Leadership in Sustainable Infrastructure*, 2017, pp. 1–7.

[87] Hwang, S. and Lee, S.: “Wristband-type wearable health devices to measure construction workers ’ physical demands,” . *Autom. Constr.*, vol. 83, pp. 330 – 340, 2017.

[88] Yetisen, A. K.; Martinez-Hurtado, J. L.; Ünal, B.; Khademhosseini, A. and Butt, H.: “Wearables in Medicine,” *Adv. Mater.*, vol. 30, no. 33, 2018.

[89] Seneviratne, S.; Hu, Y.; Nguyen, T.; Lan, G.; Khalifa, S.; Thilakarathna, K.; Hassan, M. and Seneviratne, A.: “A survey of wearable devices and challenges,” *IEEE Commun. Surv. Tutor.*, vol. 19, pp. 2573 – 2620, 2017.

[90] Guo, C.; Chen, V. Y.; Qian, C. Z.; Ma, Y.; Dinh, H. and Anasingaraju, S.: “Designing a Smart Scarf to Influe nce Group Members’ Emotions in Ambience: Design Process and User Experience,” in *UAHCI 2016: Universal Access in Human-Computer Interaction. Interaction Techniques and Environments*, 2016, pp. 392–402.

[91] Leea, S. I.; Parkc, E.; Huange, A.; Mortazavic, B.; Garst, J. H.; Jahanforouz, N.; Espinal, M.; Siero, T.; Pollack, S.; Afridi, M.; Daneshvar, M.; Ghias, S.; Lue, D. C. and Sarrafzadeh, M.: “Objectively Quantifying Walking Ability in Degenerative Spinal Disorder Patients using Sensor Equipped Smart Shoes,” *Med Eng Phys*, vol. 38, no. 5, pp. 442–449, 2016.

[92] “Welt: The smart belt for fashion and health,’ https://www.weltcorp.com/.” September 11, 2020.

[93] “Belty power: The belt your really deserve,’ https://www.belty.co/.” September 11, 2020.

[94] Nakamura, Y.; Arakawa, Y.; Kanehira, T.; Fujiwara, M. and Yasumoto, K.: “SenStick: Comprehensive Sensing Platform with an Ultra Tiny All-In-One Sensor Board for IoT Research,” *J. Sensors*, vol. 2017, 2017.

[95] Nakamura, Y.; Matsuda, Y.; Arakawa, Y. and Yasumoto, K.: “Waistonbelt x: A belt-type wearable device with sensing and intervention toward health behavior change,” *Sensors (Switzerland)*, vol. 19, no. 20, 2019.

[96] Casaccia, S.; Pietroni, F.; Calvaresi, A.; Revel, G. M. and Scalise, L.: “Smart monitoring of user’s health at home: Performance evaluation and signal processing of a wearable sensor for the measurement of Heart Rate and Breathing Rate,” in *BIOSIGNALS 2016 - 9th International Conference on Bio-Inspired Systems and Signal Processing, Proceedings; Part of 9th International Joint Conference on Biomedical Engineering Systems and Technologies, BIOSTEC 2016*, 2016, pp. 175–182.

[97] Calvaresi, A.; Arnesano, M.; Pietroni, F. and Revel, G. M.: “Measuring metabolic rate to improve comfort management in buildings,” *Environ. Eng. Manag. J.*, vol. 17, no. 10, pp. 2287–2296, 2018.

[98] Das, H. P.; Schiavon, S.; Liu, S.; Jin, M. and Spanos, C. J.: “Personal thermal comfort models based on physiological parameters measured by wearable sensors,” 2018.

[99] Gao, W.; Brooks, G. A. and Klonoff, D. C.: “Wearable physiological systems and technologies for metabolic monitoring,” *J. Appl. Physiol.*, vol. 124, no. 3, pp. 548–556, 2018.

[100] Nag, A.; Mukhopadhyay, S. C. and Kosel, J.: “Wearable Flexible Sensors: A Review,” *IEEE Sens. J.*, vol. 17, no. 13, pp. 3949–3960, 2017.

[101] Li, Q.; Zhang, L.; Tao, X. and Ding, X.: “Review of flexible temperature sensing networks for wearable physiological monitoring,” *Adv. Healthc. Mater.*, vol. 6, p. 1601371, 2017.

[102] Majumder, S. Mondal, T. and Deen, M. J.: “Wearable sensors for remote health monitoring,” *Sensors (Switzerland)*, vol. 17, no. 1, 2017.

[103] Nozariasbmarz, A. Collins, H.; Dsouza, K.; Polash, M. H.; Hosseini, M. and Hyland, M.: “Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems,” *Appl. Energy*, vol. 258, no. April, p. 114069, 2020.

[104] Sargolzaeiaval, Y., Ramesh, V.P.; Neumann, T. V.; Misra, V.; Vashaee, D.; Dickey, M. D. and Öztürk, M. C.“Flexible thermoelectric generators for body heat harvesting – Enhanced device performance using high thermal conductivity elastomer encapsulation on liquid metal interconnects,” *Appl. Energy*, vol. 262, no. September 2019, p. 114370, 2020.

ABSTRACT

This paper presents comprehensive review of the existing research findings on the design and performance of personalized comfort systems (PCSs) in the office environment in the last five years. Different types of personal comfort systems as well as experimental approaches to maintain a pleasant working environment are identified and compared regarding their advantages and potential limitations. The review investigates and summarizes the capabilities of existing systems and devices to maintain comfort in a wide range of ambient temperatures in an office environment emphasizing the importance of comfort diagnostic sensors and devices in predicting and defining occupants' comfort sensation. The major findings were highlighted and discussed with focus on investigations of human perception of comfort achieved by various personal comfort systems in office environments. The reviewed studies agreed that PCSs are promising attempts to satisfy occupant needs for comfort. Moreover, energy savings from PCSs to meet user needs can be significant compared to standard operational systems. The in-depth review of these papers provides not only an overview of the state of the art, but also contributes to the identification of existing gaps in this area and the corresponding need for further research.

SAŽETAK

Ovaj rad predstavlja sveobuhvatan pregled postojećih rezultata istraživanja u posljednjih pet godina o dizajnu i performansama personaliziranih sustava za osiguravanje ugodnosti u uredskim prostorima. S obzirom na njihove prednosti i potencijalna ograničenja, napravljena je identifikacija i usporedba različitih vrsta sustava za stvaranje individualne ugodnosti, kao i eksperimentalnih prototipova za održavanje ugodnih uvjeta u radnoj okolini. Ovaj pregled analizira mogućnosti postojećih sustava i uređaja za održavanje ugodnosti u širokom rasponu okolnih temperatura u uredskom prostoru, naglašavajući važnost dijagnostičkih senzora u predviđanju i definiranju individualne ugodnosti korisnika. Fokus rada je na istraživanju ljudske percepcije ugodnosti postignute različitim personaliziranim sustavima, koji su se do sada pokazali kao obećavajući način zadovoljenja potreba korisnika za ugodnošću u uredskim prostorima. Također, korištenjem ovakvih sustava ušteda energije može biti značajna u usporedbi s uobičajenim sustavima za grijanje, hlađenje i ventilaciju prostorija. Pregled i analiza ovih radova ne daje samo pregled trenutnog stanja, već doprinosi i identifikaciji potencijalnog prostora za daljnje istraživanje u ovome području.