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Human response to thermal environment and perceived air quality in an office with individually controlled convective and radiant cooling systems

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ABSTRACT

The purpose of this study is to analyze the human response to the indoor climate with two individually controlled convective and radiant cooling systems: a low velocity unit combined with radiant panel system (LVRP) and a personalized ventilation system combined with a radiant panel system (PVRP). As a reference system without individual control, diffuse ceiling ventilation combined with a radiant panel system (DCV-RP) was also studied. In laboratory conditions, 10 males and 10 females gave subjective response to the indoor climate during various office activities. The indoor parameters and CO_2 concentrations were measured. The results show that with the reference DCV-RP system, the indoor conditions were worse than with the LVRP and PVRP systems. The thermal sensation and perceived air quality with the PVRP system was better than the LVRP system. After a medium activity task, the thermal acceptability reverts faster with the PVRP than LVRP system. Both the LVRP and PVRP systems were able to create a micro-environment around the workstations and the CO_2 concentrations near the workstation were slightly lower than at the exhaust grille. Compared with the PVRP system, the subjects preferred the higher airflow rate at the workstation with the LVRP system. Males preferred a higher airflow rate than females under the same conditions with both micro-environment systems. This research found that there was significant variation in the control preferences of the human subjects concerning the micro-environment, and this emphasizes the need for personalized control to ensure that all occupants are satisfied with the indoor conditions.

1. Introduction

The indoor climate has a significant impact on occupant satisfaction, wellbeing, and health [1]. Additionally, earlier researchers have shown that the indoor climate has a significant influence on human performance in office environments [2–5]. Therefore together with energy-efficient buildings, comfortable and healthy indoor conditions should be considered the most important target in modern offices [6,7].

Personalized ventilation (PV) has the potential to both improve the thermal environment around the occupied zone via spot cooling, and to enhance the inhaled air quality by supplying outdoor air directly into the breathing zone [8]. Individual control of PV air parameters, such as the airflow rate, air velocity, and air temperature can compensate for large differences in individual perceptions with regard to the preferred indoor climate. Unlike mixing ventilation, which supplies outdoor air from ceiling mounted diffusers, and displacement ventilation, which supplies air from floor level mounted units, the concept of PV aims to shorten the distance between air terminal devices (ATDs) and human occupants and thus, it improves both the thermal environment and the inhaled air quality.

The enhancement of thermal comfort and air quality personal systems have been studied widely. A local heating system with a heated chair, an under-desk radiant heating panel, and a floor radiant heating panel with individual control can satisfy most occupants in typical office environments [9,10]. The effect of individually controlled personal ventilation on the inhaled air quality and thermal comfort has also been reported [9,11]. Local cooling with a radiant panel combined with a

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Nomenclature

LVRP	Low velocity unit combined with radiant panel system
PVRP	Personalized ventilation combined with radiant panel system
DCV-RP	Diffuse ceiling ventilation combined with radiant panel system
LV	Low velocity unit
PV	Personalized ventilation
DCV	Diffuse ceiling ventilation
RP	Radiant panel
ATD	Air terminal device
PAQ	Perceived air quality
SBS	Sick building syndrome
WS	Workstation
EX	Exhaust
Q1	Questionnaire 1
S	Slight task
M	Medium task

desk fan or personal ventilation has additionally been studied [12,13]. Furthermore, air ventilation clothing has been recommended with a higher indoor air temperature for office and industrial workers in warm indoor environments [14,15].

It should be noted that providing individual control has both a physiological and psychological impact resulting in increased satisfaction with the indoor climate. Studies in USA offices showed that providing a task/ambient conditioning (TAC) system providing control of the ventilation and temperature increased the occupants' overall satisfaction with the thermal quality [16]. Another study reported by Zhang et al. [17] revealed that it was more important for occupants to be able to control their local environment even if they did not necessarily utilize the functionality. By offering the possibility to control their local conditions, it significantly increased the number of satisfied respondents.

Individual control of the indoor climate has been shown to reduce sick building syndrome (SBS) symptoms and to improve the self-estimated performance [18]. It has been indicated that the self-estimated performance is significantly higher when office employees can control their own thermal environment and ventilation [19]. In an experiment with human subjects performing simulated office work (e.g., test typing and math tasks), their self-estimated performance improved when the same amount of outdoor air was introduced with a personal ventilation system via mixing ventilation. The subjects made 15% fewer errors in typing compared to the traditional mixing ventilation when the supply air temperature of the personal ventilation system was lower than the room air temperature [20]. In the same study, it was also reported that the intensity of headaches was lower, and the ability to think clearly increased. As a result, the provision of individual control over different parameters of the indoor climate may have a large impact on performance. However, the above-mentioned individual forms of control of the users' micro-environment near their workstations are very limited in typical open landscape offices with a commonly used total-volume ventilation system.

Personally controlled air movement can enhance thermal comfort especially in warm environments [21,22]. Based on human subject tests, elevated air movement by individually controlled table fans improved the thermal comfort at a temperature of 30 °C and a relative humidity of 60% without dry eyes [22]. In tropical regions, Schiavon et al. [16] found that the thermal comfort and perceived air quality (PAQ) were maintained for tropically acclimatized subjects at 29 °C with a personalized table fan. Although these mentioned studies were conducted in a controlled chamber, the effect of the air movement provided by ceiling fans on the thermal comfort was confirmed at an actual office in Singapore [23]. The thermal satisfaction and thermal acceptability were higher at 26 °C when using fans than at 23 °C without the use of fans.

Personalized control aims to create a microclimate zone around a single workstation. In this way, the control of indoor conditions is deployed only where it is actually needed, fulfilling the individual needs for thermal comfort and leading to less energy use [24]. Other researchers have also reported significant HVAC energy savings, from 4% up to 75% with individual thermal environmental control settings [24–29].

The activity level of workers and the indoor conditions varies during the day. These dynamic variations of the conditions can affect the occupants' comfort and performance. Most existing thermal comfort indices are applicable only in uniform, steady-state thermal conditions, such as the PMV-PPD model [30]. The goal of the controlling the thermal environment is to achieve a uniform air temperature and velocity distribution in the occupied zone for average people. The PMV-PPD model treats the body as a whole in terms of physiological averages and sensations [31,32]. However, large differences exist between individuals with regard to their preferred indoor climate. Humphreys and Nicol demonstrated large interpersonal differences in thermal sensation and satisfaction [10]. Under the same conditions (environmental, clothing, and metabolic), the standard deviation concerning thermal sensation could be 1.2 units on the thermal sensation scale (+3 … -3), which corresponds to a 3.6 K ambient temperature difference [33]. Therefore, environmental conditions which may be acceptable for most occupants in rooms can only be achieved by providing individual control options for each occupant [9]. Wyon [34] estimated that to achieve thermal neutrality, individual control of the air temperature at each workplace in the range of ±2.3 K around the group average neutral temperature would be necessary for 95% of office workers in their preferred clothing.

Human thermal comfort is subjective and multi-factor dependent, and the metabolic rate is one of the most significant factors affecting thermal comfort [35]. Several studies have reported the effect of the initial metabolic rate on thermal sensation [36,37]. The preferred thermal sensation and amount of air movement may change continuously depending on changes in the subjects' metabolic rate after entering a room. Therefore, some of the research findings may be somewhat limited for certain types of activity. Jin and Lin [38] found that the facial skin temperature explains the changing characteristics of thermal sensation during changes in non-uniform thermal environments by using varying local cooling methods. Li et al. [39] indicated that the wrist skin temperature and its time differential and heart rate can be used to estimate the human thermal sensation with a high degree of accuracy at different activity levels.

In previous studies, the thermal comfort and indoor air quality with a local low velocity unit combined with a radiant panel system (LVRP) [13] or personalized ventilation system combined with a radiant panel system (PVRP) [40] have been reported in the same test room. The novelty of this study is to analyze the subjective response to the thermal sensation and perceived air quality with LVRP and PVRP systems under various metabolic rates (1.2–2.0 met). Diffuse ceiling ventilation combined with radiant panels were used as the reference system for individually controlled micro-environment systems. The human response to the indoor climate with a combination of convective cooling and radiant cooling was studied. Furthermore, the subjects evaluated the thermal response and perceived air quality under both a steady and active state. The specific objectives of the study were to: (1) analyze the difference between two individually controlled ventilation systems (a personalized ventilation terminal device on the table and a low velocity unit above the workstation) and the reference system to maintain a positive thermal sensation and good level of perceived air quality (PAQ) in an office; (2) measure the CO_2 exposure in different states at various locations; (3) examine the capability of the systems to restore the thermal equilibrium of the occupants after a short or medium length task.

2. Methods

2.1. Test chamber and analyzed systems

The subject tests were performed in stable laboratory conditions, where a constant room air temperature and supply airflow rates were maintained. The dimensions of the test chamber were 5.50 m (length), 3.84 m (width), and 3.20 m (height) from the floor to the diffuse ceiling panels. The total floor area was 20.9 m^2. The test chamber was located inside a laboratory hall to ensure the environment outside the chamber was stable. The climate is cold most of the year in the Nordic countries. The annual average outdoor temperature in Helsinki is 5.4 °C and the heating degree day number is 3952 Kd according to the TRY2012 reference year weather data [41]. In Nordic climate conditions, new office buildings are designed to be very airtight. Thus, infiltration was not considered in this study. The pressure difference over the envelope in the test room was monitored and adjusted to be a slight overpressure (1 Pa).

There were three analyzed systems with subjective responses in this study, as shown in Figs. 1 and 2 [13,40]. In the DCV-RP system, there was diffuse ceiling ventilation (DCV) and a radiant panel (RP) system without personalized control (as a reference system). The supply air was distributed through suspended ceiling panels into the room [42]. The panels were installed 0.35 m below the ceiling. The diffuse ceiling panel had dimensions of 600 × 600 × 20 mm^3 and the panel was made of glass-wool-plate elements. Each nozzle had a diameter of 14 mm and the overall perforation ratio was approximately 0.5%. Two Ventiduct VSR duct-diffusers were installed sequentially above the suspended ceiling. A combined duct diffuser of diameter 0.2 m extended for the entire length of the upper chamber. The supplied airflow was 180° upwards. Above the workstations, perforated radiant cooling panels were installed at a height of 2.1 m to provide local cooling.

In the LVRP system there was a low velocity unit (LV) and a radiant panel (RP) system with individual control of the airflow rate from the low velocity unit [13]. The low velocity unit was installed over the radiant panels and fresh air was supplied through these panels which created the microenvironment in the occupied zone. The average distance between the low velocity units and the subject was 70 cm.

In the PVRP system there was a personalized ventilation (PV) and radiant panel (RP) system with individual control of the airflow rate from a personalized ventilation terminal device [40]. A PV air terminal device (ATD) [43] was installed on the desk at a distance of 40 cm from the subject to supply fresh air directly to the breathing zone. The PV ATD can be rotated around its vertical axis. This allows the direction of the personalized flow in horizontal plane to be changed. The airflow rate of the personalized air supplied to the ATD can be controlled, i.e., the occupant can adjust the preferred target velocity at his/her face.

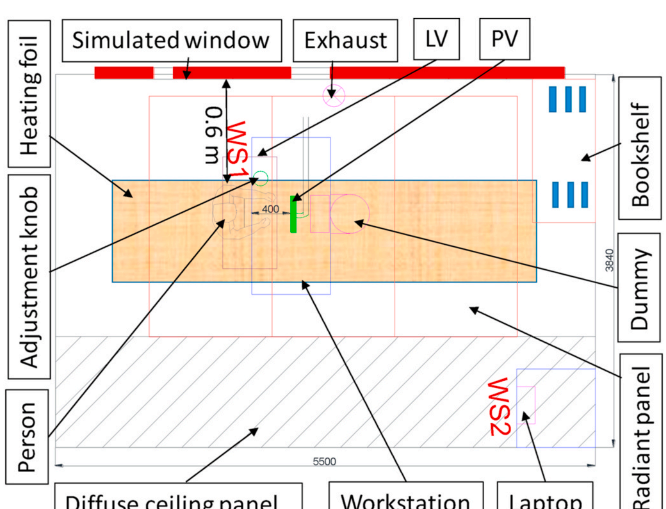

Fig. 1. The scheme of the test chamber for the human subject test with the three systems.

Diffuse ceiling ventilation was used to provide background ventilation outside the occupied zone with the LVRP and PVRP systems. In the perimeter zone over the simulation window, an exhaust grille was installed at the ceiling to directly capture the convective flow of the window (see Fig. 2).

The main workstation (WS1) with a subject and a dummy [44] on the other side was located in the middle of the room 0.6 m from the window panels. When the subject sat at WS1, he/she was able to adjust the airflow rate from the personalized air terminal devices (PV or LV) with a control knob. Another workstation (WS2) was located at the corner of the chamber where only background ventilation was served without the individually controlled system, as shown in Fig. 1.

2.2. Experimental conditions

Subject tests were conducted at a room air temperature of 26 °C. The total constant supply airflow rate was 42 l/s with the three systems. There was a constant flow damper installed in the supply duct to guarantee that the total airflow rate from the AHU to the chamber was constant. The supplied airflow rate was according to Standard EN15251 [45] Category B for low-polluting buildings. The recommended ventilation rate for this category is 2 l/s, m^2. The three systems were measured at an average heat gain of 60 W/m^2, as shown in Table 1. This total heat gain level in the design conditions without the storage effect of the building structure became the cooling load for the space [46]. The subjects' activity included being sedentary, carrying out a light task, and carrying out a medium task, and the metabolic rates were from 1.2 to 2.0 met (70–116 W) [47]. Therefore, the average heat gain of the subject was 93 W. A dummy was used to represent the heat gain of the occupant in the office. In this study, the heat load of the dummy was selected to correspond with the activity level of 1.6 met (light activity). This value describes the activity level in real office work according to the findings by Mishra [48] and Zhai et al. [49]. This is higher than the normally used 1.0–1.2 met activity level for sedentary work. Lights were installed above the workstations. The specific heat load of light was 5.8 W/m^2, which is a typical value for a modern office. A warm window surface was simulated by heated panels with warm water circulated inside. The surface temperature of the panels varied between 31 and 36 °C (average 33 °C) to simulate a sunny day. The floor was covered by electric heating foil (5.0 m × 1.0 m) to represent the direct solar radiation on the floor (see Fig. 1). The floor surface temperature with the heating foil perimeter area was 33.6 °C. In the tests, the heating power of the foil was constant. The surface temperature of the unheated floor and wall both varied between 21.7 and 22.0 °C.

Three perforated radiant cooling panels (2388 mm × 1153 mm) made of white 0.7 mm thick galvanized steel supplied the cooling load. The three radiant panels were installed above the two workstations at a height of 2.1 m from the floor. This installation height was selected so that a tall person could easily walk through the workstation. The distance between the diffuse ceiling ventilation panels to the radiant panels was 1.1 m. The temperature of the inlet water was constant at 15 °C and the water flow rate was 0.09 kg/s. The radiant panels' cooling capacity was 670 W.

The indoor thermal parameters for the air temperature, air velocity, turbulence intensity, and draught rate were measured by hot-sphere anemometers at 2 locations (P1 and P2), as shown in Fig. 3. The measurement points (P1 and P2) were located at the side of the subject to evaluate average thermal conditions close to the workstation. The location in front of the dummy was not used because that location may have an influence on the direct airflow from the PV unit. The anemometers were installed in a measuring mast at the heights of 0.1 m, 0.6 m, 1.1 m, and 1.7 m. The operative temperature was measured at a

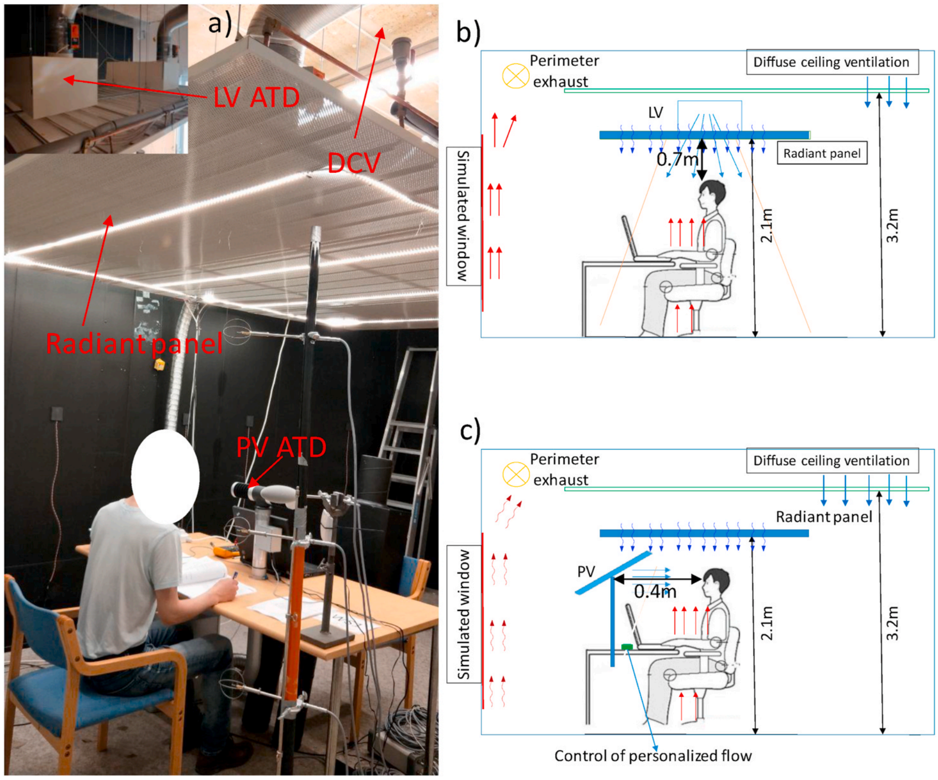

Fig. 2. a) The set-up of the low velocity unit (LV) and personalized ventilation (PV) air terminal device (ATD) at workstation 1 (WS 1), b) a diagram of the low velocity unit combined with the radiant panel system (LVRP), and c) a diagram of the personalized ventilation system combined with the radiant panel system (PVRP).

Table 1
The heat gains used in the measurements.

Heat flux	Subject	Dummy	Laptops (2 pc.)	Monitors (2 pc.)	Window panels (7 pc.)	Light	Solar heat gains at floor
(W/floor-m^2)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
60	93	90	75	78	381	116	420

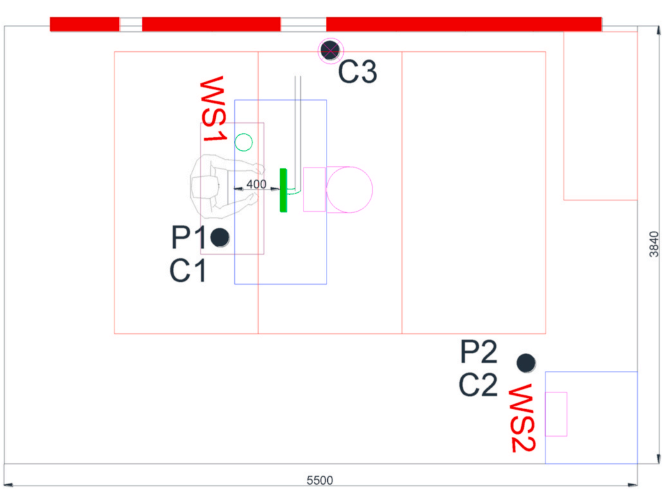

Fig. 3. The measured locations of airflow characteristics and CO_2 concentration close to workstation 1 (WS1) and workstation 2 (WS2). P1 and P2 are the air temperature and velocity measurement locations, and C1–C3 are the CO_2 measurement locations.

height of 1.1 m according to Standard 55–2010 [50] at P1. The surface temperature (walls, floor, ceiling, windows) and humidity of the air were measured using Tinytagplus-2-meters. In the LVRP and PVRP systems, the variable airflow rate from the LV or PV ATD was logged using a Swema micromanometers which measured the pressure difference variation over the IRIS damper. The concentration of CO_2 was measured at WS1, WS2, and exhaust grille (locations of C1–C3 in Fig. 3). All measurement sensors were calibrated prior to the measurements, as shown in Table 2. The adjustment knob (potentiometer) was calibrated before the subject test to determine the correlation between its scale and the airflow rate.

The subjects were not able to control the temperature and flow pattern of the PV or LV. However, the subjects had the possibility to control the airflow rate from the PV or LV diffusers by using an adjustment knob. With the LVRP system, the subjects using the LV were able to individually control the airflow rate with an adjusted scale from 7, 10, 12–15 l/s, as shown in Table 3. The total airflow rate was always constant at 42 l/s. The airflow rate from the DCV was changed when the subject's control of the personalized airflow rate from the LVRP system in the following steps from 35, 32, 30 to 27 l/s. The temperature of the LV air was the same as the supply air from the DCV (15 °C). With the PVRP system, the subjects using the PV were able to individually control the airow rate with an adjusted scale from 5, 7, 9–11 l/s. The airflow rate of the PVRP was controlled with in steps from 37, 35, 33 to 31 l/s,

Table 2
The measuring instruments.

Variable	Meter-type	Accuracy
Temperature Air velocity Turbulence intensity Draught rate Radiant temperature	Omnidirectional probe 54T33 Draught Probe	Air speed (v): range 0–1.0 m/s ±2% or ±0.0 2 m/s on 9 reference velocities (from 0.1 m/s to 5 m/s) Temperature (t): range 0–45 °C ± 0.2 °C
Operative temperature	ComfortSense temperature 54T38	±0.3 °C on the reference temperatures (10.84 °C, 25.39 °C and 40.13 °C)
Temperature Relative humidity	Tinytagplus-2	−25 … +85 °C 0%–100% RH ±3.0% RH at 25 °C
Airflow rate	Swema	±0.3% read value, lowest ± 0.3 Pa
Airflow rate	IRIS 200 damper	Air tightness in class C according to EN 1751
Adjustment knob	Potentiometer XB4	±10% of precision of internal conversion resistor
CO_2 concentration	Tinytag CO_2	< ± (50 ppm + 2% of measuring value)

respectively.

The supplied fresh air from the AHU was 15 °C. To increase the supply air temperature of the PV unit, the connected duct of the personalized ventilation system was attached to the surface of the heated window without insulation. Therefore, the cold air in the duct could be warmed by the heated window and the surrounding room air (around 26 °C). The temperature of fresh air from the personalized ventilation ATD was increased to 19.8–20.2 °C when the supply airflow rate varied between 5 and 11 l/s.

The total airflow rate into the room space was always constant. The airflow rate ranges of the three systems analyzed were shown in Table 3.

2.3. Human subject study

A total of twenty human subjects were exposed to personally controlled air movement provided by the PV and LV ATD in the test chamber. The number of human subjects selected for this study was higher than the reference study [22] where 16 subjects were used. All the subjects successfully completed three experimental sessions. The subjects reported their thermal comfort, perceived air quality (PAQ), and sick building syndrome (SBS) symptoms during the tests. There were ten male and ten female subjects in the tests (see Table 4 for the human subjects' characteristics). The subjects were instructed to dress in typical summer clothes (0.5clo): a T-shirt or short sleeve shirt, jeans or light pants, underwear, light socks, and sandals.

All subjects were healthy, and they were required to have a good rest before the experiment. During the test period, the subjects were allowed to adjust their clothing. After the last assessment, the subjects reported on the clothing they were wearing and provided comments on their perceptions of the thermal comfort and indoor air quality with the three different systems. A difference in the control of the airflow rate between the male and female subjects was also observed in this study.

During the 140-min long sessions, 20 subjects were asked to fill in 8 questionnaires. The questionnaires served to subjectively evaluate the indoor climate. The main focus was on perceived air quality (PAQ), thermal comfort, and sick building syndrome (SBS) [51]. Some additional questions regarding the subjects' clothing were included.

The all questions can be divided into four different scales:

1. An acceptability scale-divided into two parts, in a range from −0.01 to −1 and 0.01 to 1, representing ''just unacceptable'' to ''clearly unacceptable'' and ''just acceptable'' to ''clearly acceptable'', respectively.
2. A 6-point scale regarding odor in a range from "no odor'' 0, to "slight odor'' 1, "moderate odor'' 2, "strong odor'' 3, "very strong odor'' 4, and "overwhelming odor'' 5.
3. A 7-point scale regarding thermal comfort in a range from "hot'' +3, to "warm'' +2, "slightly warm'' +1, "neutral'' 0, "slightly cool'' −1, "cool'' −2, and "cold'' −3.
4. A continuous scale in a range from 0% to 100% for the feeling of body conditions.

Each test took altogether 140 min, including one adaptation period (30 min) at WS2, three 30 min sedentary periods at WS1 and WS2, and three active breaks (Fig. 4). At the beginning of each test, the subjects sat at WS2 in the chamber to adapt to the indoor climate. During the adaptation period (1.2 met), they answered questionnaire 1 (Q1) and questionnaire 2 (Q2) during the first and last 10 min of the period. The subjects were instructed to adjust their airflow rate freely during the sedentary periods at WS1 and the values of the airflow rate were recorded, but not during break periods.

The first two breaks (light task break) lasted for 5 min, in which the subjects were asked to stand up and leave their workstation and walk around in the chamber at a normal speed (1.6 met). This was to simulate activity levels in offices when occupants are away from their desks (going to the coffee machine, printer, etc.). After the exercise break, the subjects went back to another workstation and answered the next questionnaire.

The last break (medium task break) lasted for 10 min. The subjects were instructed to move books from the top shelf to the bottom shelf on a bookshelf (2.0 met). Another 30 min elapsed until the second break with three surveys. After this break, the subjects resumed a sedentary position at WS1 for a final 30 min, then answered the final two questionnaires, and left the test chamber.

Table 4
Overall human subjects' characteristics.

Ge[b]der	Numb[a]r	Age	Height (m)	Weight [a]kg)	BMI [b]
Male	10	35.9 ± 7.9 [a]	1.82 ± 0.08	86.4 ± 16.0	26.5 ± 4.5
Female	10	29.6 ± 5.7	1.64 ± 0.03	60.4 ± 7.7	22.4 ± 2.3

[a] Standard deviation.
[b] BMI: Body mass index = weight/(height)^2.

Table 3
Airflow rates of three systems studied (diffuse ceiling ventilation combined with a radiant panel system, a low velocity unit combined with a radiant panel system, and personalized ventilation combined with a radiant panel system).

System	DCV-RP (reference system)	LVRP personalized unit	background ventilation	PVRP personalized unit	background ventilation
Air diffuser type	DCV	LV at WS1	DCV	PV at WS1	DCV
Airflow rate	42 l/s (constant)	steps from 7,10, 12, to 15 l/s (controlled by subject)	steps from 35, 32, 30, 27 l/s (changed with subject control)	steps from 5, 7, 9, to 11 l/s (controlled by subject)	steps from 37,35, 33, 31 l/s (change with subject control)

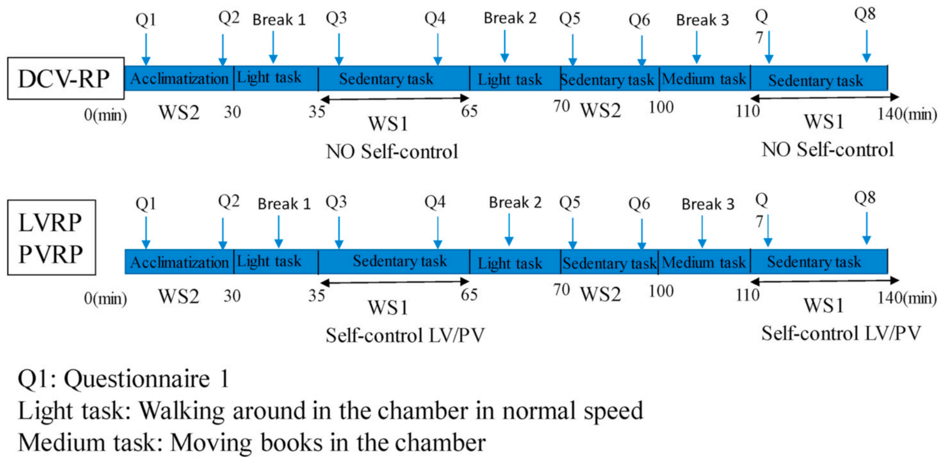

Fig. 4. The experimental procedure for the subject tests.

3. Results

3.1. Self-controlled airflow rate from a personal device

The average self-control airflow rates at WS1 for 10 male and 10 female subjects are shown in Fig. 5. Differences between the male and female subjects in the control patterns of the LVRP and PVRP systems were observed. The mean flow rates used by the female and male subjects were 13.0 l/s and 13.9 l/s, respectively, with the LVRP system (Fig. 5a). The corresponding values were 6.8 l/s and 7.9 l/s for the PVRP system ((Fig. 5b). Thus, the overall airflow rate chosen by the male subjects was higher than that chosen by the female subjects over time. With the LVRP, the mean airflow rate chosen by the female and the male subjects increased by 0.9 l/s and 1.6 l/s, respectively, from the first period to the second one. However, with the PVRP system, the flow rate used by the female subjects was kept the same while it increased to 1.3 l/s with the male subjects.

The reasons for the control pattern differences between the two genders may be attributed to the psychological and physiological differences between the male and female subjects. Female occupants are generally more sensitive towards air movement than male occupants as females have been found to prefer a higher room temperature than males [52], and their attire was also lighter than their male counterparts. Therefore, the LVRP and PVRP systems can fulfill different preferences due to gender differences.

The mean airflow rate used in the second period (110–140 min) was higher than the first period (35–65 min). With the LVRP system, 90% of the male subjects chose the highest flow rate (15 l/s), while more than 60% of the females used a higher flow rate (9 l/s and 11 l/s). This is because the subjects preferred to increase the local flow rate after short term medium task. Therefore, the individually controlled systems have the potential to meet demands for a variable airflow rate.

3.2. Indoor thermal environment

The average conditions of the room air temperature, air velocity, and draught rate were measured near the two workstations throughout the 20 subject tests. The average relative humidity was 40.1% in the test room. In this study, two measurement points (P1, P2) located at the side of the seated human subjects were used to evaluate the average thermal conditions close to the workstation with the three systems, as shown in Fig. 3. The location in front of the dummy was not used because that location may influence the direct airflow from the PV unit. The average values of the thermal conditions measured at a height of 1.1 m and are shown in Table 5. When subjects sat at WS1, they were allowed to control the local airflow rate with the LVRP and PVRP system, but there was no possibility for control available at WS2.

The room air temperature at WS2 was slightly higher than at the WS1 because the local ventilation and radiant panels' location were close to WS1. Moreover, as it could be expected, the average temperature at WS1 with two individually controlled systems was lower than the reference system.

During the 20 subject tests, the average highest velocity (0.11 m/s) was generated by the LVRP at WS1 compared to the PVRP and the reference (DCV-RP) systems. However, this velocity was still rather low. Therefore, the local draught risk was small (under 10%) with the individually controlled systems. This indicates that the personal devices (LV and PV) could create comfortable local thermal conditions without a

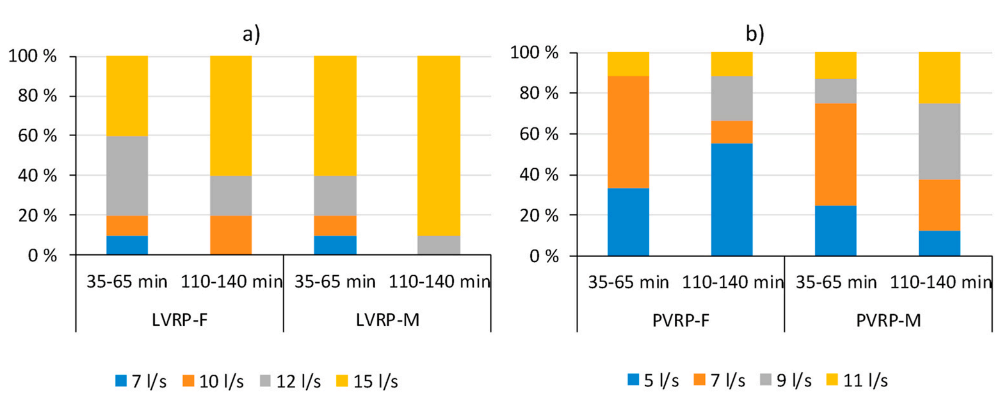

Fig. 5. Self-controlled air flow rates from a) a low velocity unit combined with a radiant panel system (LVRP), and b) personalized ventilation combined with a radiant panel system (PVRP) adjusted by female (F) and male (M) subjects.

Table 5
The average thermal conditions during the 20 subject tests near the two workstations at 1.1 m height.

	WS1 (with personalized control)			WS2 (without personalized control)		
	Temperature [°C]	Velocity [m/s]	Draught Rate [%]	Temperature [°C]	Velocity [m/s]	Draught Rate [%]
DCV-RP (reference system without personalized control)	26.1	0.09	5.1	26.3	0.07	2.5
LVRP	25.6	0.11	8.8	26.1	0.06	2.0
PVRP	25.9	0.09	5.1	26.1	0.07	2.5

draught risk in a microenvironment close to the workstation.

Fig. 6 shows the average operative temperature for 20 subjective tests with three systems at WS1 over the whole test period. The data distributions were analyzed using a frequency box-plot. With the same total airflow rate and radiant cooling power, the operative temperature with the LVRP and PVRP systems was lower than with the DCV-RP (reference) system at WS1. The lowest operative temperature occurred with the LVRP system (25.9 °C). This is because of the downward supplied air flow when the supplied air temperature from the LV ATD was 15 °C, which was lower than that of the PV ATD (20 °C). Additionally, the local airflow rate with the LVRP was higher than the PVRP system. Furthermore, the interquartile range (25th-75th) of the operative temperature was larger with the PVRP (0.36 °C) than the DCV-RP (0.28 °C) and the LVRP (0.26 °C). Therefore, the subjects' range of control of the airflow rate from the PV ATD was wider. However, the difference in the operative temperatures was small, and this indicates that the local radiant panel did not have a significant influence on the operative temperature even though it was installed above the human subjects. The reason for this was the reasonably high surface temperature of the panel (around 18 °C).

3.3. Subjective responses

3.3.1. Indoor air perception

Altogether 8 questionnaires (Q1-Q8) were given to the subjects to determine the perceived air quality (PAQ) and odor throughout the test procedure. The results for the three systems are shown in Fig. 7. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2 without the possibility to control the airflow rate. Questionnaires Q3, Q4, Q7 and Q8 were answered at WS1 where there was the possibility for self-control of airflow rate was via the LVRP and PVRP systems. Every subject was able

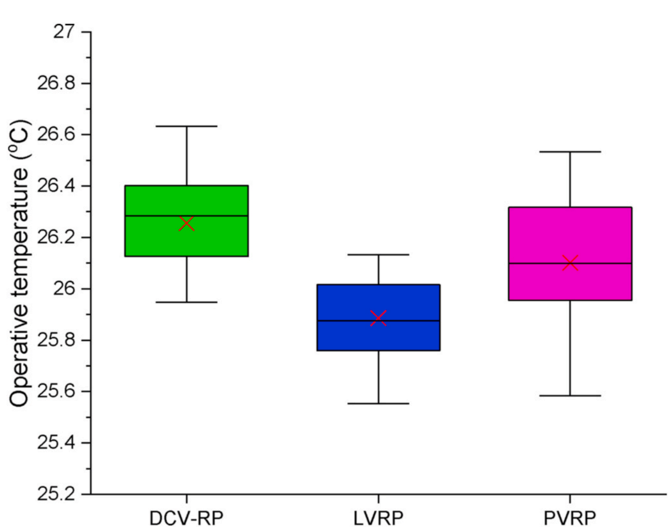

Fig. 6. The operative temperature measured at WS1 with 20 subject tests with the three systems. The middle horizontal line is the median; the red cross is the average; the box bottom and top show the 25th and 75th percentiles, respectively. The vertical lines show the smaller of the extrema or 1.5 times the interquartile range of the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

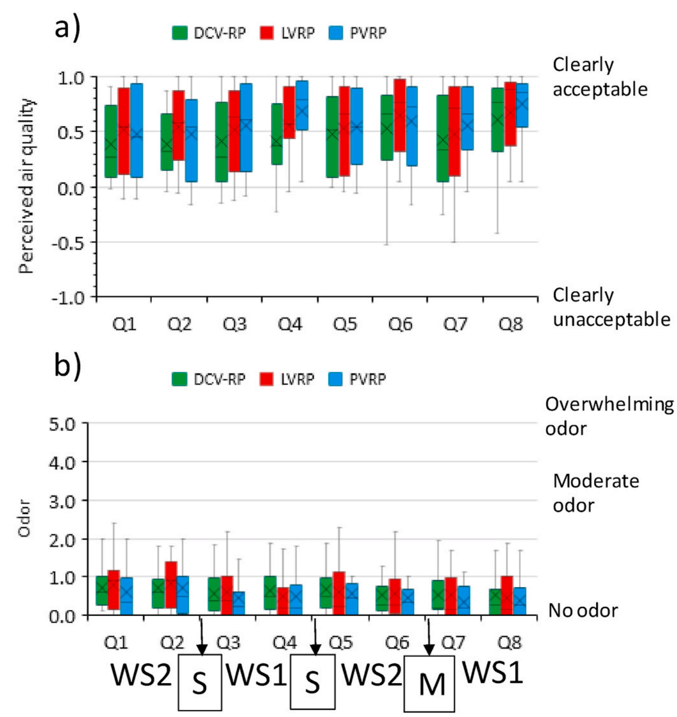

Fig. 7. a) Perceived air quality and b) odor ratings for the three systems. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1. "S" refers to the slight task; "M" means medium task.

to adjust the airflow rate from the LV/PV after answering questionnaires Q3 and Q7.

The subjective perception of the air quality was indicated on a rating scale ranging from clearly unacceptable (−1) to clearly acceptable (+1). In this study, the median value of the PAQ was in the acceptable range of the scale for all sessions. With the DCV-RP system, as could be expected, the PAQ was similar (0.45) at WS1 according to the results of the questionnaires Q3, Q4, Q7 and Q8 and WS2 according to the results of the questionnaires Q1, Q2, Q5 and Q6 (0.47) (Fig. 7a). A small difference between the two locations was noticed because the fresh air from the ceiling was supplied from the corridor side where the air was first distributed in the WS2 area (Fig. 1). When the subjects were able to control their own airflow at WS1, the median value of the PAQ increased from the value of 0.66 (0.19, 0.90) [1] at WS2 to 0.71 (0.20,0.92) [1] at WS1 with the LVRP system. This phenomenon was more significant with the PVRP system, which increased from 0.58 (0.17, 0.88) [1] at WS2 to 0.74 (0.41, 0.92) [1] at WS1 as the PV ATD was closer to the breathing zone. Therefore, the PAQ tended to increase with a more individually controlled system.

The perception of the odor was quite low with all three systems and mostly the rates given were between no odor and a slight odor. The median value of the odor rating was 0.44 (0.22, 0.94) at WS2 and

[1] The 25th and 75th percentiles.

dropped to 0.28 (0.11, 0.94) at WS1 with the DCV-RP system (Fig. 7b). A possible reason for this was that the location of WS2 was close to the wall where books on the shelf release some odor that could have affected the ratings given at WS2. With the individually controlled system, the ratings fell to 0.19 (0,1) and 0.22 (0, 0.69) at WS1 under the LVRP and PVRP, respectively.

The air freshness rating range extended from stuffy air (0) to fresh air (+1) (see Fig. 8a). The sensations of freshness were rather similar at both workstations with the DCV -RP and LVRP systems and both medians were close to 0.5 (acceptable air). However, with the PVRP, the median was 0.75 (0.53, 0.88) at WS1. Thus, air was perceived to be the freshest with the PV ATD.

In all tests, the subjects perceived the air as being between dry to neutral over the test period (Fig. 8b). The measured average relative humidity during the test was 40.1%. The sensation of humidity with the DCV-RP system was 0.42 (0.32, 0.5) at WS2 and decreased to 0.38 (0.29, 0.5) at WS1. The perceived humidity in the test room was considered to be neutral at 40.1% relative humidity. With the two individually controlled systems, the medians and 75th percentile were quite the same with the diffuse ceiling and radiant panel system, and around half of the subjects indicates that the humidity felt neutral. The sensation of humidity was fairly similar regarding each of the three studied systems.

3.3.2. Thermal sensation

The results for the whole-body thermal sensation and its acceptability reported by the subjects are shown in Fig. 9. The whole-body thermal sensation ratings were scaled from cold (−3) to hot (+3). The median rating for the DCV-RP system was 0.92 (0.08,1.78) at WS2 and 1.00 (0.24,2.00) at WS1. The main reason for this was that the temperature was slightly higher at WS1 than at WS2. With the LVRP system however, the median rating significantly decreased to 0.44 at WS1. Moreover, the corresponding value decreased to 0.28 with the PVRP system. Without the possibility of control at WS2, the median values were 0.92 and 0.36 with the LVRP and PVRP, respectively. Moreover, the variation in thermal sensation with the PVRP system was much smaller than the LVRP at WS1. Therefore, the thermal sensation increased with the possibility for personalized control with the PV ATD where the air movement could be directed towards the human body.

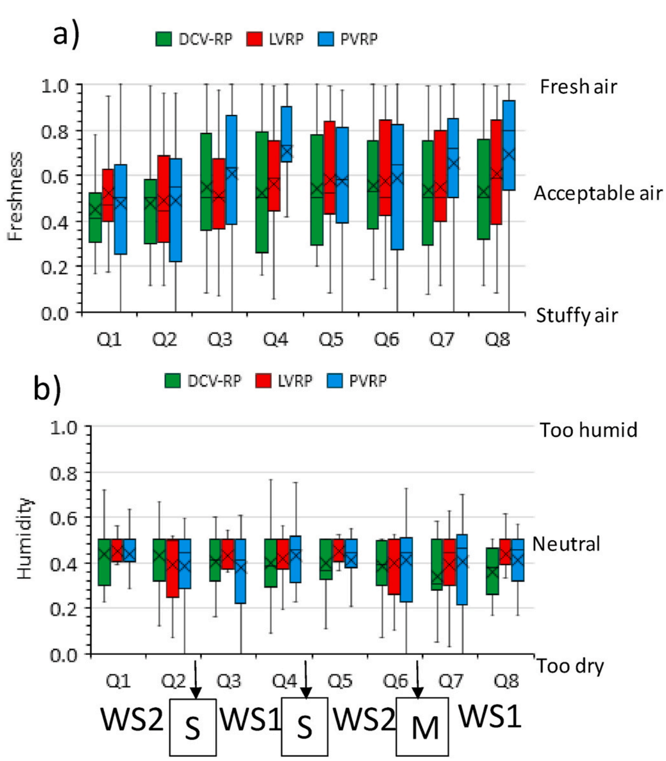

Fig. 8. a) Air freshness and b) humidity ratings for the three systems. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1. "S" refers to the slight task; "M" refers to the medium task.

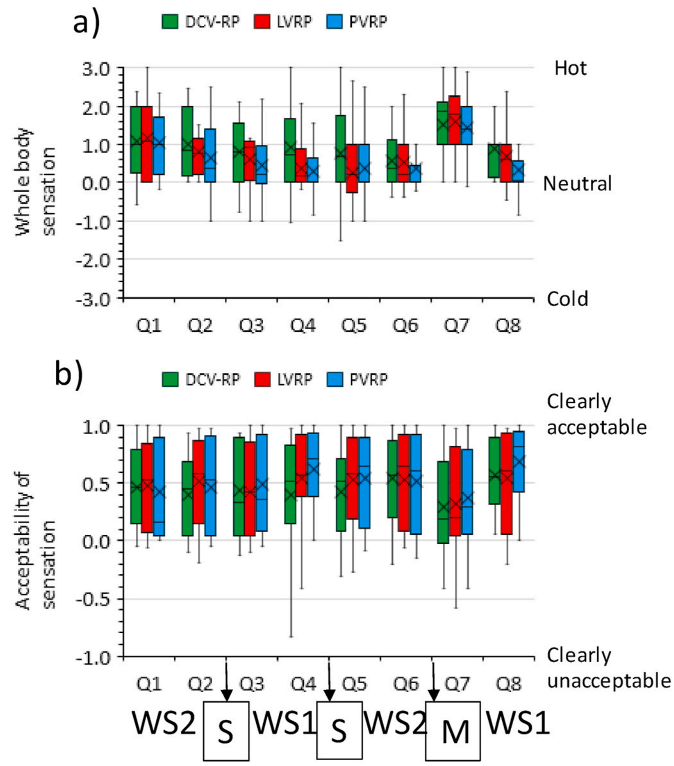

Fig. 9. a) Whole-body thermal sensation and b) acceptability for the three systems. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; Questionnaires Q3, Q4, Q7 and Q8 were answered at WS1. "S" refers to the slight task; "M" refers to the medium task.

The acceptability of thermal sensation was rated by the subjects on a scale ranging from clearly unacceptable (−1) to clearly acceptable (+1). The results were in the acceptable part of the scale in all test conditions. The difference in thermal acceptability was not notable and the medians were between 0.4 and 0.6 for the three systems. In the questionnaires at WS1 (Q3 and Q4), the ratings of acceptability were the same (0.4) for the DCV-RP system. For the LVRP and PVRP systems, the medians increased to 0.5 and 0.7 in Q3 and Q4. This indicates that the individually controlled system had the potential to improve thermal acceptability. When the subjects finished the high activity (moving books for 10 min) task and then moved back to WS1 again (Q7), the rating declined to 0.4 and 0.5 with the LVRP and PVRP systems, respectively. However, the median significantly increased after 10 min to 0.8 (0.45, 0.91) in Q8 with the PVRP system. Therefore, the subjects could quickly return the thermal equilibrium with PVRP system after a short term medium heavy work task. Thus, the personalized airflow rate significantly enhanced the recovery of comfort after the tasks requiring a medium amount of exertion.

Fig. 10 presents the preference of the subjects to the air movement with the LVRP and PVRP systems. The overall requirement for air movement with the LVRP was higher than PVRP during the time subject worked at the WS1 (Q3-Q4 and Q7-Q8). This indicates that the subjects preferred higher airflow rates at WS1 with the LVRP system than the PVRP system. With the PVRP system, the subjects mostly preferred no change after carrying out a task requiring a medium level of exertion for 10 min (from Q4 to Q7). The air movement of the personalized ventilation device could quickly meet the people's perception of air movement after doing an activity. It should be noted that after the subject

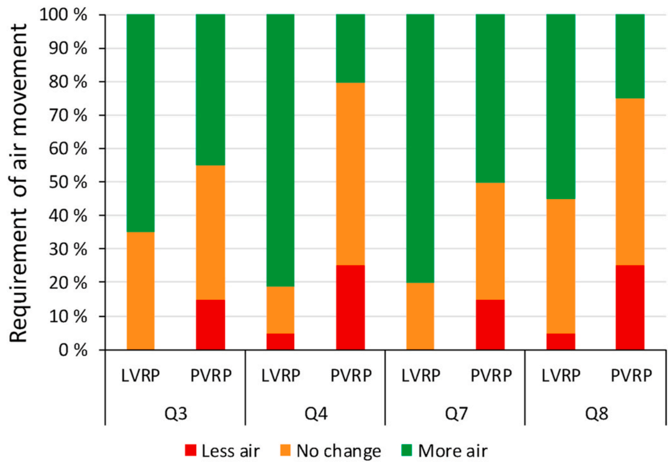

Fig. 10. The requirement for air movement using individually controlled low velocity (LVRP) and personalized ventilation (PVRP) systems.

stayed at the WS1 for 10 min (Q3 and Q7), the requirement for air movement decreased with the two individually controlled systems.

3.3.3. Sick building syndrome symptoms

The increased airflow of the LV/PV ATD may lead to discomfort in the subjects and also increase sick building syndrome (SBS) due to the higher air velocity near the face. Based on the response of the subjects, the SBS symptoms and variation under all the tested conditions were rather low. The sensations of eye dryness, throat dryness, headaches and concentration were rated by the subjects with the three systems during eight periods (questionnaires Q1-Q8).

The sensation of eye dryness and throat dryness was expected to occur with PVRP at WS1, where the slightly cool air (20 °C) was supplied downwards directly into the face. However, the results showed that the subjects reported better conditions regarding dry eyes and dry throats with the PVRP than when experiencing the other systems (Fig. 11). The mean ratings by the subjects concerning eye and throat dryness were reported above 0.8, where 1 means no dryness. This indicates that the PV ATD controlled by the subjects did not cause any discomfort in the eyes or throat. Additionally, the ratings regarding eye dryness were fairly similar (0.7) between the LVRP and the reference (DCV-RP) systems.

As for headaches, the mean rating was above 0.8 in all the questionnaires with the PVRP system, while the ratings declined significantly at the end of the test period (Q8) with the LVRP and the reference (DCV-RP) systems. The mean ratings on the ability to concentrate were 0.78, 0.77 and 0.86 at WS1 with the DCV-RP, LVRP and PVRP systems, respectively. Thus, the PV system was considered the best system especially in the last questionnaires (Q7-Q8).

Similar findings were reported in other questionnaires regarding well-being including the general feeling and self-assessed performance in the office during the tests (Fig. 12). The mean ratings regarding general feeling and performance with the PVRP system were slightly higher than the reference (DCV-RP) and LVRP at WS1. The difference between the DCV-RP and LVRP was rather small.

3.4. CO_2 concentration

CO_2 concentration was measured at the side of the two workstations in Fig. 3. With the local airflow from the LV/PV ATD at WS1, the CO_2 concentration was lower than the reference system. Fig. 13 shows the mean CO_2 concentration measured at two workstations over time. The CO_2 concentration was less than 700 ppm during the whole process with the three systems when the outdoor CO_2 concentration was 412 ppm. As could be expected, the values of CO_2 with the LVRP and PVRP were both slightly lower than the DCV-RP at WS1. However, this difference was not obvious between the localized and reference systems. This is because the distance between the LV ATD and breathing zone was long (70 cm). In the installation, the supply airflow rate induced room air and thus, increased the CO_2 level at the workstation. When the subjects stayed at WS2 (70–100 min), the CO_2 concentration was lower with the DCV-RP than with the other systems. The reason for this was that the total airflow rate was kept the same in the three systems and when the subjects increased the flow rate at WS1 with the individually controlled

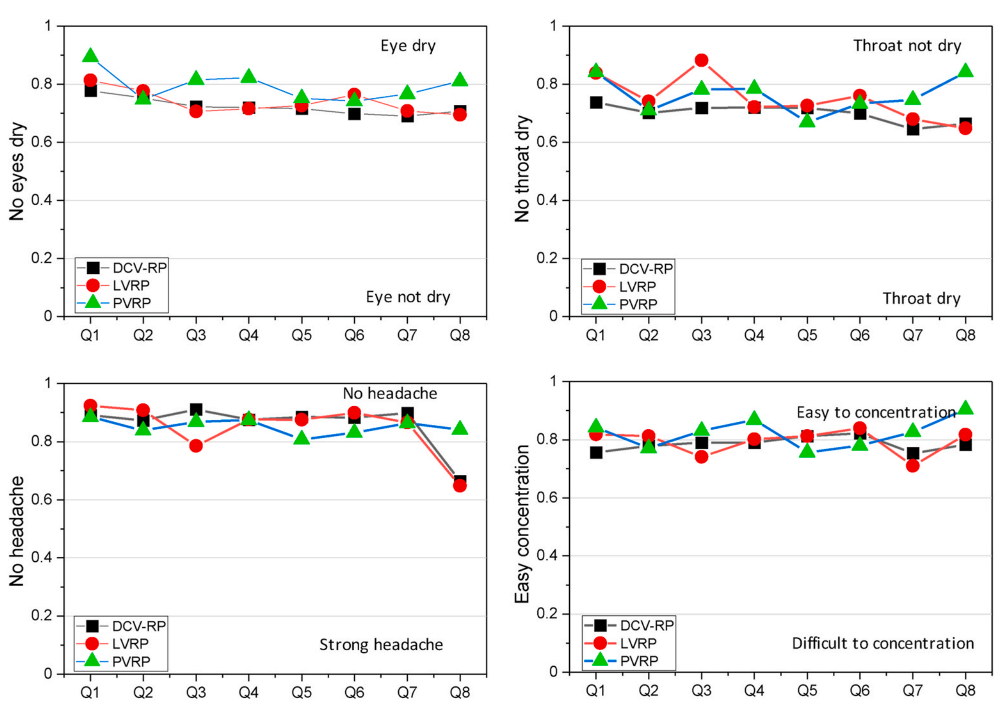

Fig. 11. Subjective ratings for the three systems concerning eye dryness, throat dryness, headaches, and concentration. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1.

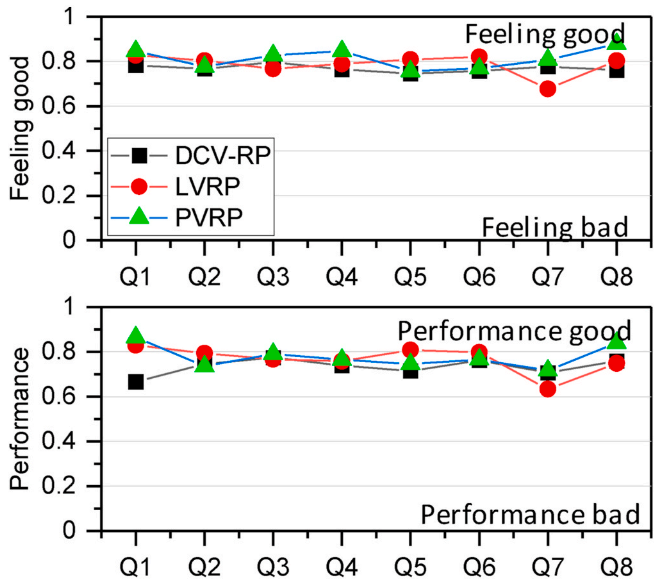

Fig. 12. Subjective ratings with the three systems about generally feeling good and self-assessed performance. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1.

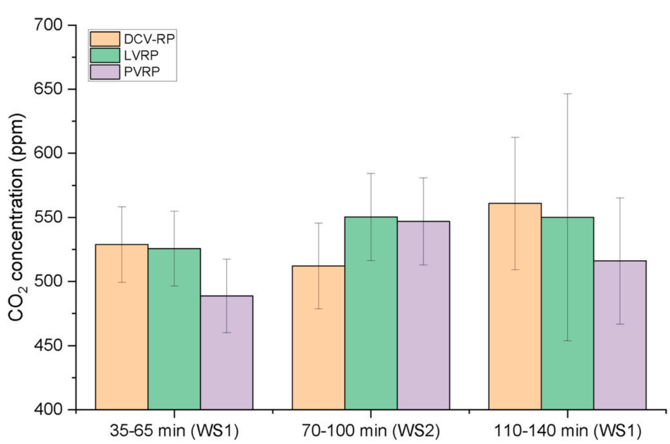

Fig. 13. The mean CO_2 concentration at two workstations during sedentary periods with the three systems.

device, the airflow rate at WS2 would decrease accordingly. It should be noted that the CO_2 was a little bit higher with the LVRP than PVRP at WS2. The difference in the CO_2 concentration between the DCV -RP and PVRP was 45 ppm at WS1.

Table 6 shows the relative CO_2 concentration over time at different measurement locations. The negative value means the CO_2 concentration at the measured workstation (WS1 or WS2) was lower than the exhaust. During three sedentary periods, the relative CO_2 concentration at two workstations was much higher than the exhaust with the DCV-RP system. This indicates the airflow was not fully mixed in the whole space and the ventilation efficiency of the reference system was lower than the fully mixed ventilation. With the individually controlled ATD, the relative difference was insignificant (0–3 ppm) during the first period at WS1. Until the second period at WS1, the CO_2 concentration was lower than the exhaust. This indicates the LV and PV ATD can bring fresh air into the breathing zone in a more efficient way and make the air inhaled better. The measured CO_2 difference between the exhaust and WS1 points with the LVRP and PVRP systems were only slightly lower than with the DCV-RP system. This means that the LVRP and PVRP systems could only create slightly better indoor air quality than the DCV-RP system in the micro-environment near the workstation. Because the PV ATD was installed close to the breathing zone, the performance of the PVRP was slightly better than the LVRP.

Table 6
The variation of CO_2 concentrations between measurement locations (WS1, WS2) and exhaust (EX).

Concentration difference (ppm)	DCV-RP	LVRP	PVRP
WS1-EX (35–65 min)	15	3	0
WS2-EX (70–100 min)	19	14	10
WS1-EX (110–140 min)	10	−6	−10

4. Discussion

By reducing the conditioning area and making the area close to the human body, task ambient conditioning (TAC) systems, personal environmental control systems (PECS), and the personal thermal management (PTM) systems have been developed in recent years. The aim of these systems is to create the intensified conditioning of human-occupied areas and less intensified conditioning of the surrounding areas. The conditioning systems are designed for the whole space system, localized systems, and wearable systems. In this process, the occupants can customize their own micro-environment.

With personalized control only in the occupied zone, there are less requirements for the ambient environment. The studied systems (LVRP and PVRP) in this paper overcome individual differences, then improve the overall satisfaction through the individual control of personalized micro-environments and achieve maximum energy efficiency at the same time.

When the local conditions are controlled, ASHRAE Standard 55–2010 [53] allows that elevated air velocity can compensate for higher room air temperatures. The benefits gained by increasing the air velocity depend on the clothing worn and the activity of the room occupants. The maximum used air velocity depends on whether there is available local control of the air velocity or not. Moreover, elevated air velocity has a positive effect on the PAQ and perception of humidity with an individually controlled device. Facial air movement has been found to improve the acceptability of inhaled air compared to the conditions without air movement [54].

In this study, the subjects preferred a higher amount of air movement during the higher metabolic rate period. For the preferred air movement during the test, the performance of the PV ATD was better than LV ATD. Therefore, individually controlled devices moving closer to the human body will create a well-controlled micro-environment and improve the satisfaction of users. Energy consumption is expected to decrease when the room occupants are in a sedentary state and the satisfaction of users can be improved when engaged in heavy tasks. Previous studies also confirm the trend of the most preferred solutions ranging from task ambient conditioning [16], personal comfort systems [55], to personal thermal management systems [56]. For the different installations of the LV and PV ATDs, the thermal sensation was slightly better with the PVRP than for the LVRP. The air movement with the PVRP was more acceptable, while less local airflow rate was required. However, the duct connection of the PVRP maybe not suitable for all layouts of space.

A properly designed, individually controlled system would lead to substantial reductions in temperature in the micro-environment and thus will further improve the acceptability of the perceived air quality (PAQ) compared to total volume ventilation. In this study, the perceived air quality with personalized control fared slightly better than the fully mixed reference system under the same airflow rate.

In previous studies when subjects chose higher airflow rates in micro-environments, users have sometimes complained about eye and throat dryness and discomfort. However, in this study, it did not happen. A possible reason for this was that the evaporation on the surface of the skin caused by a higher airflow rate was insignificant, and the possibility for micro-environment control may have reduced the eye and throat dryness symptoms.

The designed dynamic test conditions in this study described real office work with varied active states and loads. Compared to studies with a steady state of activity, the human response to the indoor climate was more accurate in reflecting the performance of the PVRP and LVRP systems in real applications.

However, there are some limitations in the present study that should be addressed. The exposure time was 140 min, which is a relatively long test time for thermal comfort and perceived air quality studies. However, it should be noted that the exposure time was much shorter than the working hours in a real office. This may have resulted in less variation in the human perception of the indoor environment, especially with the individually controlled devices. Therefore, the subjective response to the performance of the LVRP and PVRP may be better during long exposures.

The individuals involved in the subject test came from the university, including master's degree students, doctoral students, and senior researchers. Therefore, the age of the subjects varied between 23 and 47. Only 20 individuals were involved in the subject test and most of the subjects lived in the Nordic countries. There may be some variation in the subjective preferences to the indoor environment with subjects from a different climate and culture. Further studies with a larger number of subjects with a wider background would be necessary to obtain a substantial sample for statistical analysis.

During the subject test, none of the participants displayed dissatisfaction with the radiant panel in their feedback. The distance between the radiant panel and the heads of the seated subjects was around 0.7 m. The radiant panel was installed over the workstation at a height of 2.1 m, so it would not affect human movement no matter whether during sitting or standing. The subjects considered this type of installation to be acceptable.

There is scientific proof of the benefits of micro-environment control [43]. However, the practical applications are still limited. The flexibility of layout changes should be considered in the design process. In common with all room systems, e.g., VAV, chilled beams and radiant ceilings have similar challenges with certain limitations for layout changes if the office layout is changed. To improve the flexibility of PVRP systems, novel pipe and duct connections [54] should be developed to make layout changes easier and thus reduce the cost of retrofitting. With a PVRP system, the investment in equipment is not part of the normal construction process and it requires that the end-users should be aware of micro-environmental solutions. In order to maximize performance, a personalized unit (LV or PV) and its location in the office layout need to be carefully considered to be suitable for the open layout office. The flexibility of layout changes should be predesigned to make changes cost-effective. Additionally, design guidebooks should be available for consulting engineers to make more usage of novel micro-environment solutions possible.

5. Conclusion

The present study analyzed the human response to the thermal environment and perceived air quality with individually controlled convective and radiant cooling systems: a low velocity unit and radiant panel system (LVRP) and a personalized ventilation and radiant panel system (PVRP). As a reference system, a radiant panel and diffuse ceiling ventilation system (DCV-RP) were used.

The responses to the air quality with the studied systems were acceptable. The perceived air quality (PAQ) ratings were similar (0.45) for the DCV-RP system at the two different workstations. For the individually controlled systems, the average perceived air quality (PAQ) ratings increased to 0.74 at WS1, which was higher than for WS2 (without control). Similarly, the acceptability of the freshness and humidity sensations with the individually controlled system was 0.33 higher than the reference system. The ratings were higher concerning the PVRP than the LVRP system. Furthermore, SBS symptoms did not occur and the self-estimates were better with the individually controlled system. With the self-control devices, the CO_2 exposure level was 45 ppm less than without air flow rate control near the workstation. Additionally, the CO_2 concentration at the main workstation was slightly lower than at the exhaust with personalized control.

The thermal perception was noticeably different for the studied systems. The average rating for the whole-body sensation indicated that the DCV-RP system (reference) felt slightly warm. The thermal sensation can be maintained so it is close to neutral with a self-control device in the office. Moreover, after the task with a medium level of exertion, thermal comfort can be recovered faster using micro-environment control systems than with the total volume system. Additionally, the acceptability of thermal sensation with the PVRP was higher than with the LVRP system. The self-controlled airflow rate from the low velocity units installed over the workstation was nearly twice as high than with the personalized ventilation devices. Furthermore, it was noted that the males preferred a higher degree of air movement than females, especially under higher activity levels. Therefore, with individually controlled systems, the variable demands of the subjects can be satisfied and the perceived air quality and thermal sensation can be improved significantly.

Declaration of competing interest

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

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