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

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Abstract. The purpose of this study is to analyse 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 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. 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]. 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 [2]. Another study reported by Zhang et al. [3] 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. 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.

In previous studies, the thermal comfort and indoor air quality with a local low velocity unit combined with a radiant panel system (LVRP) [4] or personalized ventilation system combined with a radiant panel system (PVRP) [5] have been reported in the same test room. The novelty of this study is to analyse 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.

2 Methods

2.1 Test chamber and analysed 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. There were three analyzed systems with subjective responses in this study, as shown in Figures 1 and 2 [4], [5]. 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 [6]. Above the workstations, perforated radiant cooling panels were installed at a height of 2.1 m to provide local cooling.

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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 [4]. 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 [5]. A PV air terminal device (ATD) was installed on the desk at a distance of 40 cm from the subject to supply fresh air directly to the breathing zone.

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 Figure 2). The concentration of CO2 was measured at WS1, WS2, and exhaust grille.

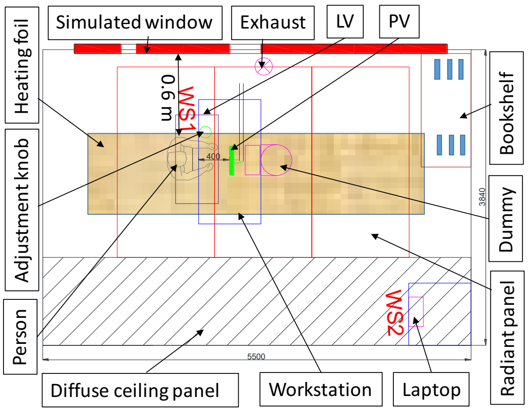

Figure 1. The scheme of the test chamber for the human subject test with the three systems.

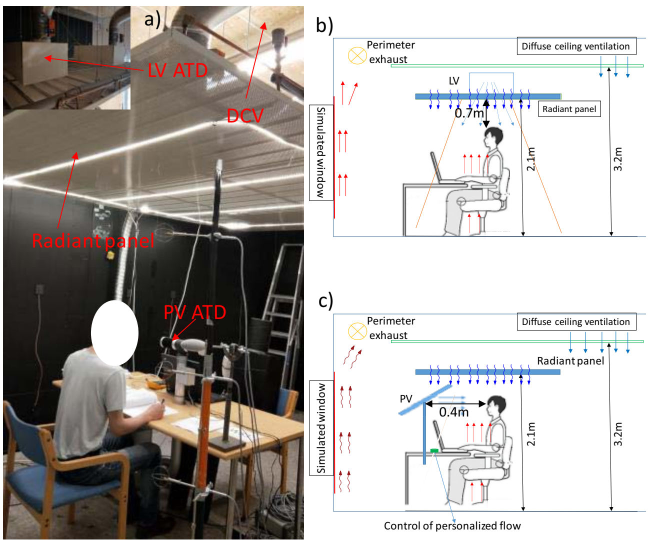

Figure 2. a) The set-up of the low velocity unit (LV) and personalized ventilation (PV) air terminal device (ATD) at workstation 1 (WS 1), b) diagram LVRP and c) diagram of the PVRP systems.

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. The subjects' activity included being sedentary, carrying out a light task, and carrying out a medium task, and the metabolic rates were from 1.2-2.0 met (70-116 W) [7].

The subjects had the possibility to control the airflow rate from the PV or LV diffusers by using an adjustment knob, as shown in Table 1.

Table 1. Airflow rates of three systems studied.

DCV-RP (reference system)	LVRP		PVRP	
	personalized unit	background ventilation	personalized unit	background ventilation
DCV	LV at WS1	DCV	PV at WS1	DCV
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)

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. 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.

Each test took altogether 140 minutes, including one adaptation period (30 min) at WS2, three 30 min sedentary periods at WS1 and WS2, and three active breaks (Figure 3). 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 minutes 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 mins 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.

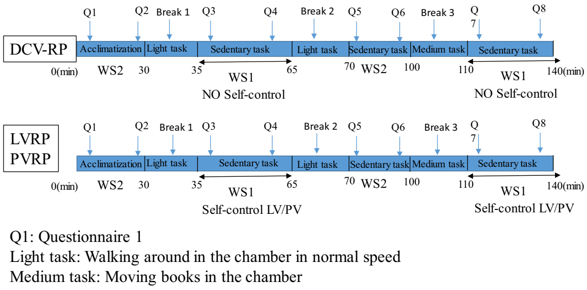

Figure 3. The experimental procedure for the subject tests.

3 Results

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 (Figure 4a). The corresponding values were 6.8 l/s and 7.9 l/s for the PVRP system (Figure 4b). 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 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.

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) (Figure.5a). 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 (Figure 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) at WS2 to 0.71 (0.20,0.92) at WS1 with the LVRP system. This phenomenon was more significant with the PVRP system, which increased from 0.58 (0.17, 0.88) at WS2 to 0.74 (0.41, 0.92) 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 dropped to 0.28 (0.11, 0.94) at WS1 with the DCV-RP system (Figure. 5b). 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.

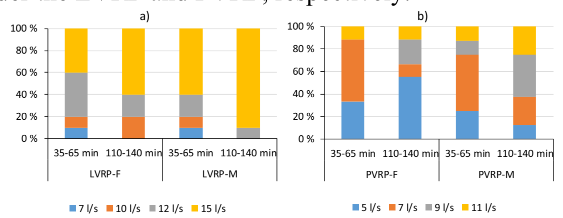

Figure 4. Self-controlled air flow rates from a) a low velocity unit combined with a radiant panel system (LVRP), and b) personalized ventilation combined with a radiant panel system (PVRP) adjusted by female (F) and male (M) subjects.

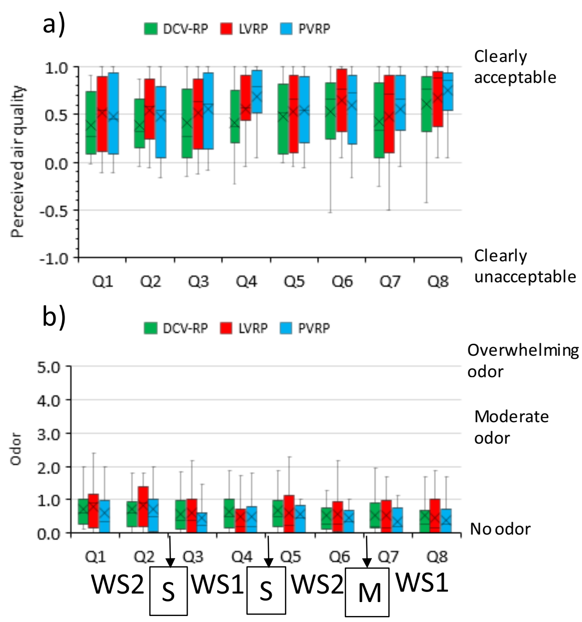

Figure 5. a) Perceived air quality and b) odor ratings for the three systems. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1. “S” refers to the slight task; “M” means medium task.

The results for the whole-body thermal sensation and its acceptability reported by the subjects are shown in Figure 6. 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.

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 0.4-0.6 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 minutes) 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 minutes 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.

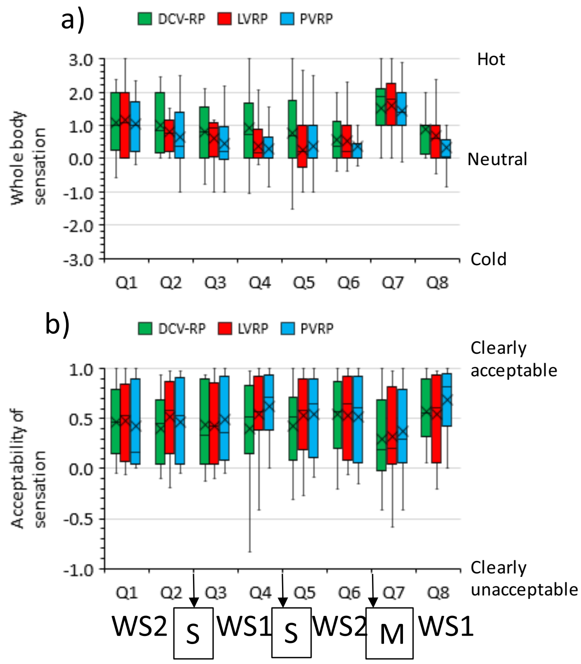

Figure 6. a) Whole-body thermal sensation and b) acceptability for the three systems. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; Questionnaires Q3, Q4, Q7 and Q8 were answered at WS1. “S” refers to the slight task; “M” refers to the medium task.

The sensation of eye dryness and throat dryness was expected to occur with PVRP at WS1, where the slightly cool air (20ºC) 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 (Figure.7). 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).

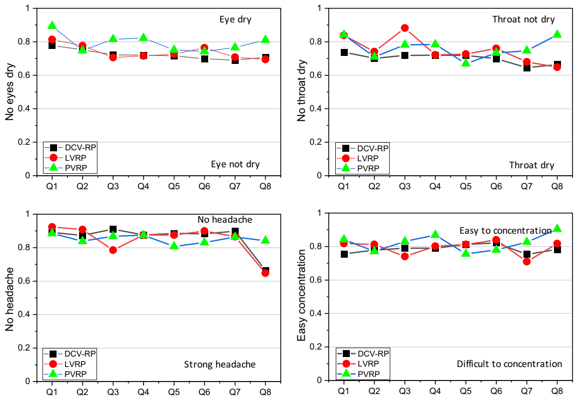

Figure 7. Subjective ratings for the three systems concerning eye dryness, throat dryness, headaches, and concentration. Questionnaires Q1, Q2, Q5 and Q6 were answered at WS2; questionnaires Q3, Q4, Q7 and Q8 were answered at WS1.

CO2 concentration was measured at the side of the two workstations and exhaust. With the local airflow from the LV/PV ATD at WS1, the CO2 concentration was lower than the reference system. Figure 8 shows the mean CO2 concentration measured at two workstations over time. The CO2 concentration was less than 700 ppm during the whole process with the three systems when the outdoor CO2 concentration was 412 ppm. As could be expected, the values of CO2 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 CO2 level at the workstation. When the subjects stayed at WS2 (70-100 min), the CO2 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 device, the airflow rate at WS2 would decrease accordingly. It should be noted that the CO2 was a little bit higher with the LVRP than PVRP at WS2. The difference in the CO2 concentration between the DCV -RP and PVRP was 45 ppm at WS1.

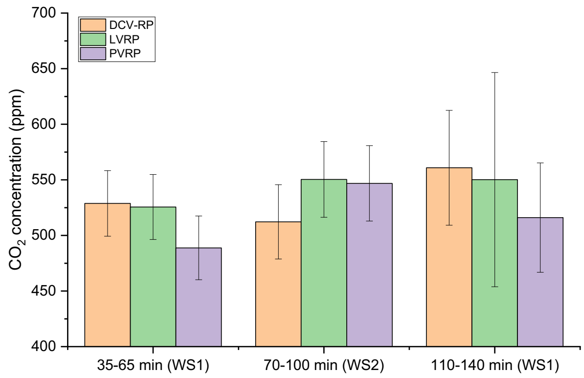

Figure 8. The mean CO2 concentration at two workstations during sedentary periods with the three systems.

Table 2. The variation of CO2 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

Table 2 shows the relative CO2 concentration over time at different measurement locations. The negative value means the CO2 concentration at the measured workstation (WS1 or WS2) was lower than the exhaust. During three sedentary periods, the relative CO2 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 CO2 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 CO2 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.

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.

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.

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.

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 minutes, 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 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 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.

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 CO2 exposure level was 45 ppm less than without air flow rate control near the workstation. Additionally, the CO2 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.

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