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Use of local convective and radiant cooling at warm environment

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SUMMARY
The effect of four local cooling devices (convective, radiant and combined) on SBS symptoms reported by 24 subjects at 28 ˚C and 50% RH was studied. The devices studied were: (1) desk cooling fan, (2) personalized ventilation providing clean air, (3) two radiant panels and (4) two radiant panels with one panel equipped with small fans. A reference condition without cooling was tested as well. The response of the subjects to the exposed conditions was collected by computerized questionnaires. The cooling devices significantly (p<0,05) improved subjects' thermal comfort compared to without cooling. The acceptability of the thermal environment was similar for all cooling devices. The acceptability of air movement and PAQ increased when the local cooling methods were used. The best results were achieved with personalized ventilation and cooling fan. The minimal improvement in PAQ was reported when the radiant panel was used alone. The use of the local cooling devices led to increase of eye irritation. The reported SBS symptoms increased during the exposure time in all studied conditions, i.e. with and without cooling devices. The lowest prevalence of symptoms was with personalized ventilation and with radiant panel with attached fans, which also helped people to feel less fatigue. The SBS symptoms increased the most when the cooling fan, generating movement of polluted room air, was used.

KEYWORDS
Human response, warm environment, convective and radiant cooling, thermal comfort and perceived air quality, eye discomfort and SBS symptoms, personalised ventilation

1 INTRODUCTION

In industrialised countries substantial part of the energy is used in buildings. Ventilation and air conditioning is a major energy consumption source in buildings. The strategy of keeping room air temperature high (2-3 °C above the comfortable room temperature) and improving occupants' thermal comfort by moving room air at high velocity (most often by cooling fans) is suggested in the present standards and has been implemented in practice. The strategy may lead to energy saving in some buildings, however, in other buildings it may have the opposite effect, i.e. may lead to increase of the energy use (Schiavon and Melikov, 2008).

It has been also documented that perceived air quality (PAQ) decreases and SBS (Sick Building Syndrome) symptoms increase when pollution, temperature and relative humidity of inhaled air increase (ASHRAE Guideline 10 2011). Moving of polluted room air, e.g. by cooling fan, will increase the convective cooling of the body and will improve occupants' thermal comfort and perceived air quality (PAQ). Personalized ventilation providing clean air to the breathing zone has been also used for local convective cooling at warm environment. Melikov and Kaczmarczyk (2012) reported that air movement in itself has no impact on Sick

Building Symptoms (SBS) symptoms while pollution, increased temperature and humidity of the inhaled air affect negatively the SBS symptoms. Thus improving occupants' thermal comfort by moving polluted room air may have negative impact on occupants' health and work performance. An increase in air temperature and relative humidity decreases the evaporation of the tear film and thus the blink rate, while increase of air velocity increases the evaporation and results in increase of the blink rate (Wolkoff et al. 2003). High indoor air pollution has negative impact on eye. Research indicates that facially applied flow of polluted room air didn't have significant impact on blink rate compared with the case without air movement and that the increase of blink rate due to decrease of temperature and humidity and increase of velocity may be compensated due to the increase in air cleanness (Melikov et al. 2011).

Local radiant cooling can also be used for improving occupants' thermal comfort at warm environment, especially local cooling of the head (which is an active heat dissipater) and the upper body part. In this case occupants' will breathe warm and polluted room air. The simultaneous impact of radiant cooling of the face and inhaling warm polluted room air on the PAQ is not known. It may be expected that the negative effect of warm air on PAQ will be compensated by the local radiant cooling. However this needs to be studied. The combined impact of radiant cooling and increase of room air temperature on eye discomfort has not been studied. Similarly as in the case of PAQ radiant cooling of the face may diminish the effect of warm and polluted air on tear film stability and affect eye blink rate.

Local cooling, convective or/and radiant, generates non-uniform thermal environment. The control of the local convective cooling is fast and therefore it can be used at workstation under the individual control of occupants. The control of radiant cooling (e.g. by cooling panels) is slow and may not be effective, in some cases even frustrating for occupants. The separate and combined impact of convective and radiant local cooling on occupants' thermal comfort, PAQ, health (SBS symptoms, eye symptoms, etc.) and performance has not been studied sufficiently and the mechanisms are not well known. Human subject experiments were performed to study this impact. This paper presents results on thermal comfort and PAQ.

2 METHOD

Experimental facilities

Experiments with 24 subjects were carried out in a climate chamber with accurately controlled and monitored air temperature and humidity. Mean radiant temperature was equal to the air temperature, radiant asymmetry was low and low vertical air temperature gradient (<0.2 °C) and air velocity (<0.06 m/s) were ensured by upward "piston flow" ventilation. Ten workstations (WS) were arranged in the chamber (Figure 1): 2 workstations (1 and 2) with personalized ventilation (PV), 2 workstations (3 and 4) with personal cooling fan (FAN), 2 workstations (7 and 8) with radiant panel (RP) or with radiant panels with small fans (RP with fans) and 2 workstations (5 and 6) without devices (W – referred to in the following as "No device"). The half of experiments using workstations 7 and 8 were performed with RP and the rest with RP with fans. There were partitions between the workstations. The desks with PV, FAN and RP were placed considering not influencing the other workstations. The workstations consisted of a desk, adjustable office chair, laptop PC, pen, box with set of paper questionnaires and box for collecting the filled-in paper questionnaires (only few times during the exposure). Old carpet and linoleum with surface area equal to the floor area of the chamber hanged on supporting frame (PS) and hidden from the subjects were used to generate typical office pollution.

The PV systems was equipped with a circular air terminal device (ATD) attached to a movable arm allowing to change the distance between the user and the ATD as well as the direction of the personalized flow. The ATD was designed for minimal mixing of the supplied clean personalized air with the polluted room air (Bolashikov et al. 2003). A workstation with the PV is shown in Figure 1a. During the experiments the subjects could adjust the position of the ATD, the direction and the flow rate of the supplied personalized air. This was recorded. The FANs (each 30 W) were attached to the two desks (Figure 1b). The subject at the desk could adjust the positioning height of the fan as well as the direction and the strength (i.e. speed) of the generated flow. This was continuously recorded. Two RP (0.6 m x 0.7 m each) were placed at two desks, one above and one bellow the desk table. The top panels were inclined to provide cooling to the upper body part of the person seated at the workplace (Figure 1c). The panels bellow the desk cooled users' lower body, i.e. thighs, lower legs and feet. The back of the panels were insulated. Chilled water supplied to the panels was used to keep their surface temperature at 17 °C (the lowest level without condensation). Due to the long response time of the radiant panels individual control of the surface temperature was not possible. During half of the sessions three small fans (DC 12 V each) and adjustable plates were attached to upper panels at the two workstations (Figure 1 d). The exposure to this arrangement is referred RP+Fans. The fans transported the warm room air downward along the panels. The air was cooled and then redirected against the person at the workplace by the plate. In this way convective and radiant cooling was provided to subject's upper body. The power to the small fans, i.e. the generated flow rate, was kept constant (defined in pre-tests). Subjects could adjust the position of the plate and thus the direction of air flow (Figure 1d). The position of the plate was monitored and recorded.

Subjects

The subjects (15 males and 9 females), all university students, were non-smokers, did not have asthma, allergy and chronic diseases and did not wear glasses or contact lenses. The subjects were paid for taking part in the experiment.

Questionnaires

During the experiments the subjects were asked to fill in several questionnaires. Most of the questionnaires were computerized but some were on paper. Subjects evaluated thermal sensation for the whole body and for the body parts (neck, head, arms, back, thighs, lower leg and feet) on ASHRAE's 7-point scale (cold: -3, cool: -2, slightly cool: -1, neutral: 0, slightly warm: 1, warm: 2, hot: 3), feeling of air movement (yes/no) and air movement preference (more, less or no change in air movement), on continuous scales on odor intensity (no odor, slight odor, moderate odor, strong odor, very strong odor, overwhelming odor), air freshness (air stuffy – air fresh), air humidity (air too humid – too dry), noise level (too quite – too noisy) and reported acceptability of thermal sensation, perceived air quality and air movement on continuous scale from clearly unacceptable (-1) to just unacceptable (-0.1) and then from just acceptable (0.1) to clearly acceptable (1). Furthermore subjects voted on eye dryness (no dryness, moderate dryness, overwhelming dryness), throat dryness (through dry – throat not dry), lips dryness (lips dry – lips not dry), headache (severe headache – no headache), thinking difficulty (difficult to think – head clear), well-being (feeling bad – feeling good), fatigue (tired – rested), ability to concentrate (difficult to concentrate – easy to concentrate), level of arousal as well as eye irritation (yes/no). Except eye irritation continuous scale was used for the SBS symptoms (0 = difficult to concentrate/difficult to think/severe headache/low ability to work, 100 = easy to concentrate/head clear/no headache/high ability to work).

A questionnaire, designed to record modifications in the subject's clothing during the experiment, was filled in several times during each exposure.

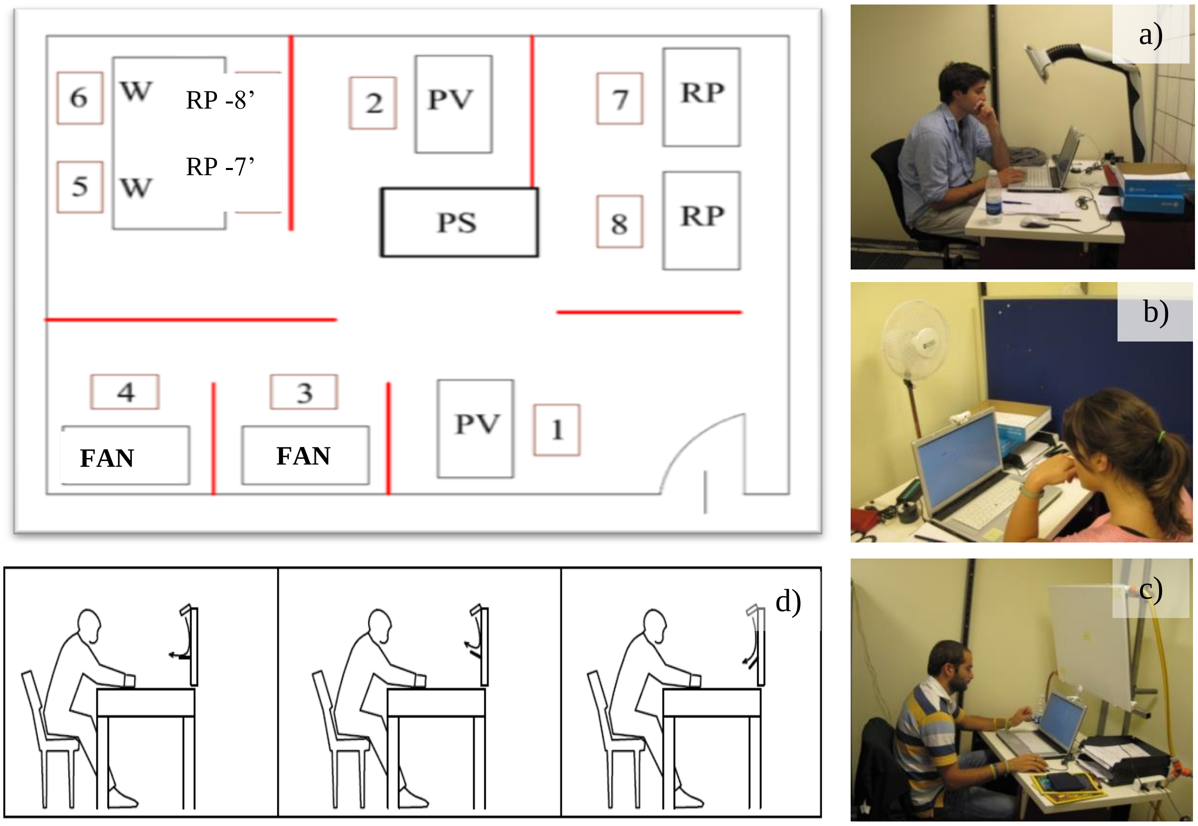

Figure 1. The layout in the chamber. Workstations with PV (a), PF(b) and RP (c).Control of position of the plate and flow direction with RP+ Fans (d).

Experimental Conditions and Procedure

The subjects were divided in 3 groups of 8 people. Each group was assigned to participate in the experiment in a specific weekday. The subjects were exposed randomly to four conditions: PV, FAN, RP (12 subjects) or RP with fans (12 subjects) and without any local cooling. The temperature in the chamber was kept at 28 °C and relative humidity at 50%. Each experimental session started at 1 pm and lasted 4 hours. The session was divided into three parts: 30 min acclimatization to the conditions in the chamber without use of the devices, 30 min acclimatization to the devices and 180 min performance tasks when exposed to the devices. There was 10 min break after 150 min when subjects could leave the chamber. The questions on the SBS symptoms were asked at the beginning (upon entering the chamber) and after 15, 30 (end of the first acclimatization period), 145 min (before the break) and 240 min (end of the experiment). During the experiment subjects could drink water. They were encouraged to modify their clothing to feel comfortable (this was recorded). Before the experiment start the subjects spent about 10-15 min outside the chamber where the temperature was 20 °C. The workstations with PV (1 and 2), FAN (3 and 4) and without cooling device (5 and 6) were used already from the beginning of the experiment (it was easy to switch on the PV and the FAN after 30 min). The control of the surface temperature of the panels was slow therefore it was kept constant during the whole experiment. The subjects assigned to use the workstations (7 and 8) with RP spend the first 30 min of the experiment at workstations RP-7' and RP-8' in the corner of the chamber (near the workstations 5 and 6) as indicated on Figure 1. During the acclimatization periods the subjects were allowed to read books or magazines. After that they were engaged with performance tests (not reported in this paper).

Before the main experiment the subjects participated in a training session to get acquainted with the cooling devices, the questionnaires and the experimental procedure.

3 RESULTS

The results presented in this paper focus only on the SBS symptoms. Large database was collected and analyzed separately for each subject and for all subjects together. Only some of the results are reported in the following. The subjects participated in four experiments at different experimental conditions. Their state with regard to SBS symptoms may have been different at the beginning of each experiment because of other previous activities. In order to account for this factor the analyses were made by comparing the difference in the SBS symptoms reported at the end and the beginning of the exposure period. The difference in the same SBS symptom was calculated for each subject and then the average values (ΔSBS) for all subjects were determined. The lower ΔSBS the better the impact of the environmental condition with regard to the SBS symptom is. A ranking of the exposure conditions for each subject was done by comparing ΔSBS for the four exposures. The lower value of ΔSBS the higher ranking of the condition was. Based on the ranking obtained for each person a ranking of the experimental conditions with different cooling devices was made. All 24 subjects were exposed to the "FAN" and the condition "No device", 23 subjects were exposed to the "PV" (one subject was missing). The subjects were divided into two groups of 12 subjects and each group was exposed to one of the remaining two experimental conditions – "RP" or "RP+fans". Therefore the ranking has only four categories: 1- best exposure condition (with the lowest ΔSBS, i.e. the lowest increase of the SBS symptoms), 2 – second best exposure condition, 3 – second worst exposure condition and 4 – worst exposure condition.

The SBS symptoms increased with the time during all exposures. The increase was significant ($p<0.05$) only for some of the exposures. The increase was different for the different cooling devices. Figure 2 shows that the difficulty to concentrate, the difficulty to think, the arousal and the headache increased least when subjects used the PV. Only for the exposure to RP+Fans the difficulty to concentrate was lower than that with the PV. This may be due to the difference in the number of exposed subjects (23 with PV and 12 with RP+Fans). The highest increase in the SBS symptoms, i.e. the highest ΔSBS, was during the exposures with the "Fan" and with "No device". The SBS symptoms (except headache) increased in time more when subjects used the Fan than without any cooling device. Except for the headache the increase of the SBS symptoms was rather high with the RP as well. It was less difficult for the subjects to concentrate and to think when they were exposed to RP+Fan than to RP only. The additional convective cooling of the head/face by the flow generated with the small fans attached to the radiator may be the reason. The discussed above effects on the SBS symptoms were significant ($p<0.05$) only during some periods of the exposure.

Results of the ranking are listed in Table 1. One of the subjects did not participate in the PV exposure and therefore was removed from the ranking. Thus 23 subjects were included in the ranking of the exposures to PV, FAN and No device, 11 subjects in the case of RP and 12 subjects in the ranking of the exposure to RP+Fans. The comparison of the results in the table clearly shows that the exposure to the PV leads to least decrease in the SBS symptoms for more subjects. The exposure to the FAN was one of the worst.

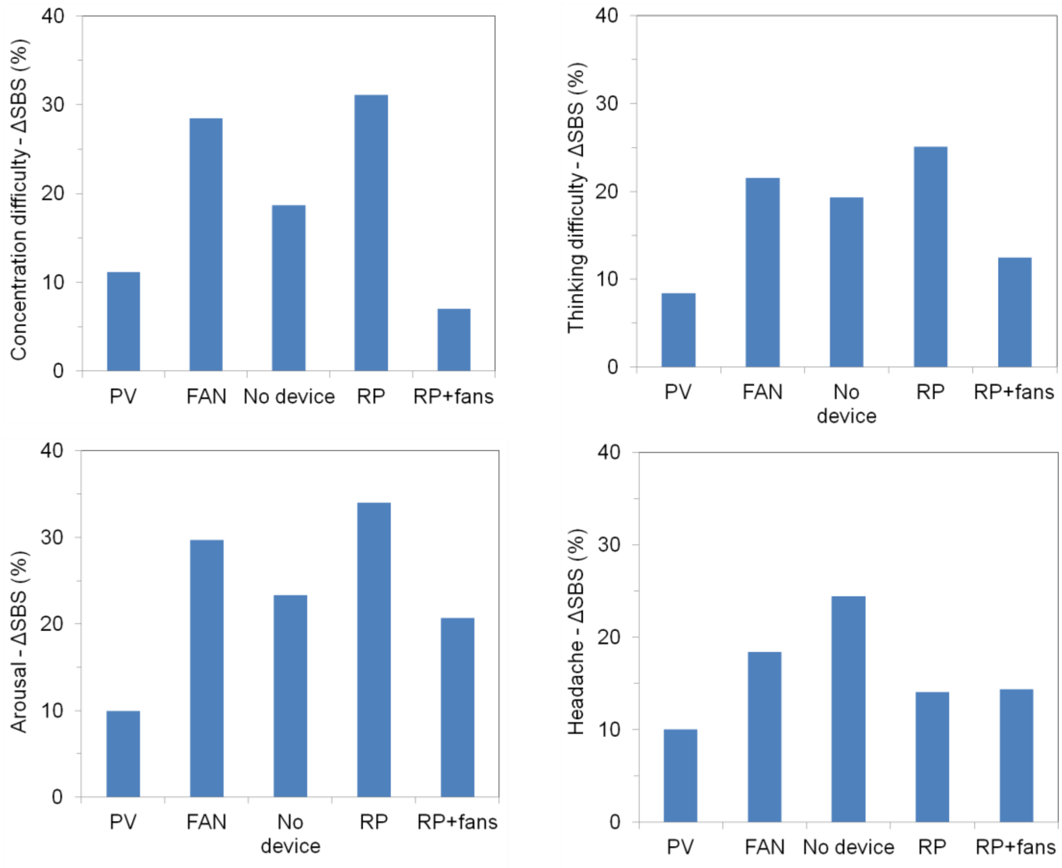

Figure 2. Increase of SBS symptoms during the exposures.

4 DISCUSSION

As expected all local cooling methods improved subjects' thermal comfort in comparison with the condition "No device". However with regard to subjects' health (the SBS symptoms) their performance was quite different. The increase of the SBS symptoms with time was least when subjects were exposed to the PV providing clean air for breathing. At the remaining conditions subjects inhaled the polluted room air. The results of the present study show that air movement in itself has no impact on SBS symptoms but the pollution has. It was already discussed that the energy saving strategy of elevating indoor air temperature and improving occupants' thermal comfort by air movement with increased velocity may not be valid when cooling fans with relatively high power consumption are used. Present results reveal that the strategy of moving polluted air for cooling of occupants may not be advantageous in buildings with high indoor pollution. The losses of decreased work performance as a result of increased SBS symptoms may be higher than the savings due to decreased energy consumption.

The analyses of the results (not shown) indicated that compare to the case without local cooling the thermal sensation and its acceptability for the whole body and the head was improved with all tested cooling methods almost to the same level. The acceptability of the air quality and air freshness was also improved. It was highest for the exposures with PV, FAN, and RP+Fans. The analyses indicated that in comparison with the FAN and the case "No device" the SBS symptoms intensified during the exposure to the RP and decreased during the exposure to the RP+Fans. The SBS symptoms increased during the exposure to the RP and RP+Fans in comparison with the exposure to the PV. This result indicates that the temperature of the inhaled air in addition to its cleanness may be important for the prevalence of the SBS symptoms. This however needs to be studied with large number of subjects.

Table 1. Ranking of the exposure conditions based on the least increase (ΔSBS) of the SBS symptoms from the beginning to the end of the exposure. Number of subjects is listed.

Difficult to concentrate					
Ranking level	Number of subjects				
	PV	FAN	No device	RP	RP+Fans
1 – best	11	2	6	1	3
2 – second best	4	5	10	2	3
3 – second worst	4	6	5	4	5
4 - worst	4	10	3	4	1
Difficult to think					
1 – best	8	6	4	2	3
2 – second best	8	3	6	3	3
3 – second worst	5	7	5	2	4
4 - worst	2	7	8	4	2
Arousal level					
1 – best	12	3	5		3
2 – second best	3	6	9	2	3
3 – second worst	4	8	5	4	2
4 - worst	4	6	4	5	4
Headache					
1 – best	12	4	1	4	4
2 – second best	5	5	7	2	3
3 – second worst	2	6	9	2	3
4 - worst	4	8	6	3	2

5 CONCLUSIONS

The SBS symptoms increased during the exposure time. The elevated air movement had minimal or no impact on SBS symptoms but the symptoms increased when pollution level increased. Results indicate that the temperature of the inhaled air rather than the local cooling of the head is important for the SBS symptoms. However this needs to be studied. The strategy of moving polluted room air for cooling of occupants may increase the SBS symptoms leading to decreased work performance.

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