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Effects of different cooling principles on thermal sensation and physiological responses

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ABSTRACT
Applying low exergy cooling concepts in the built environment allows reduction of high quality energy sources. However, application of low exergy cooling systems can result in whole body and local discomfort of the occupants. Non-uniform thermal conditions, which may occur due to application of lowex systems, can be responsible for discomfort. However, in some cases combinations of local and general discomfort factors, for example draught under warm conditions, may not be uncomfortable.
Two different cooling principles were studied: passive and active cooling. Active cooling occurred through either convection or radiation. Ten healthy male subjects (age: 20-29; BMI: 18-25) were exposed to four different experimental cases: (a) *passive cooling* through convection and (b) *active cooling* through convection, and *active cooling* by radiation via the (c) ceiling or (d) floor.
Physiological and thermal sensation data indicate significant differences between the different cases.

KEYWORDS
Thermal sensation, Physiology, Cooling, Non-uniform thermal environments

INTRODUCTION
Thermal comfort is one of the main requirements for successful application of low-exergy (lowex) HVAC systems. The IEA Annex 37 (Juusela 2003) study revealed that an optimal energy/exergy use not always results in an increased comfort level. Application of lowex systems can result in local and/or global discomfort. Non-uniform thermal conditions, which may occur due to application of lowex systems, can be responsible for discomfort. On the opposite, Arens et al. (2006) concluded that under non-uniform environments higher thermal comfort levels could be achieved in comparison to uniform thermal environments; and in some cases combinations of local and general discomfort factors, for example draught under warm conditions, may not be uncomfortable (Olesen 2004). Nevertheless, it is important to assess thermal comfort adequately in the design phase, to avoid that expected comfortable conditions in fact are uncomfortable. In general, the effects of convective flows and

radiant asymmetries play a role in the assessment of thermal comfort. The combined effects however are not extensively investigated and are therefore important to study. More knowledge on the interaction between the system, indoor climate and the human body is indispensable to design optimal systems in the future. Since cooling is assessed as an important aspect regarding both the conditioning and energy/exergy-use of buildings, the objective of this research was to study the effects of different cooling systems on human thermal comfort and physiological responses.

METHODS

To examine the influence of passive and active cooling systems a climate room set-up with experimental subjects was used. Ten healthy male subjects visited the climate chamber (Schellen et al. 2010) for four different experimental cases. The subject characteristics are summarized in Table 1.

Table 1: Subject characteristics

Age (year)	24.7±2.0
Height (cm)	181.8±8.34
Mass (kg)	77.3±8.5
BMI (kg/m^2)	23.5±3.4
Bodyfat% (%)	16.3±4.7

Values are presented as mean ± SD (n=10)

Two different cooling principles were studied: *passive* (case a) and *active* cooling (cases b,c, and d). Olesen (2004) showed that draught under warm condition (through an increased air velocity) not necessarily results in an uncomfortable situation; it may even provide comfortable cooling conditions. Furthermore, it could reduce the energy-use if air-conditioning is not necessary within certain temperature limits. With respect to the active cooling cases, two different cooling systems were studied: *active* cooling through *convection* (case b, supplying cold air by mixing ventilation) and *active* cooling through *radiation* (case c and d). Radiant panels are considered as interesting alternative for cooling through convection (supplying cold air) to improve thermal comfort and to reduce the energy consumption (Miriel et al. 2002; Roulet et al. 1999). However, these panels impose a non-uniform thermal environment and introduce a vertical temperature gradient. Two different radiant panel configurations were studied: *active* cooling through *radiation* by the *ceiling* (case c) and *floor* (d). The air supply temperature equaled the average room temperature; to enlarge the effect of a vertical temperature gradient between the floor and ceiling the floor and ceiling respectively were heated. A graphical representation of the four different cases is given in Figure 1.

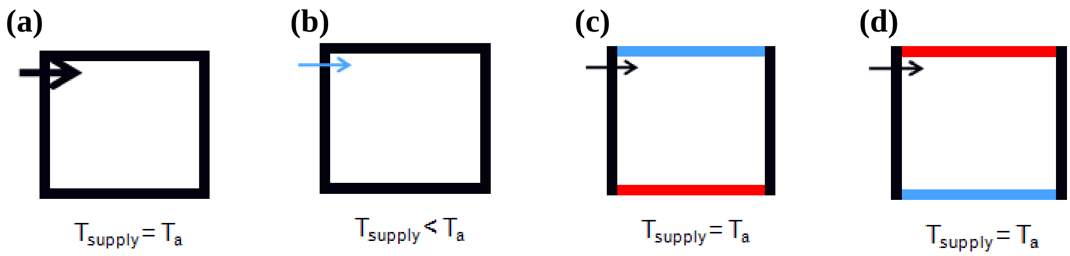

Figure 1: Graphical overview of experimental cases; (a) *passive cooling* and (b) *active cooling* through convection, and *active cooling* by *radiation* via the (c) *ceiling* and (d) *floor*

All cases were designed to achieve a neutral predicted thermal sensation (PMV≈0). Furthermore, all cases, except case (d), were designed within PD<10% with respect to local comfort effects following NEN-EN-ISO 7730 (2005); case (d) was designed to achieve a PD<20%. The details of the four different experimental cases are presented in Table 2. The ventilation inlet is situated on the right side of the subject. The width and height of the inlet differed between the passive and active cooling cases to achieve higher or lower air velocities, the ventilation rate remained at a level of 110 m^3/h for all active cooling cases. To achieve a higher air velocity near the subject during the passive cooling case, the ventilation rate for case (a) was 600 m^3/h.

Table 2: Case details

Variable	**Case (a)**	**Case (b)**	**Case (c)**	**Case (d)**
Operative temperature [°C]	25.2±0.2	24.9±0.1	24.4±0.1	24.3±0.1
Air temperature [°C]	25.5±0.2	24.9±0.1	24.2±0.1	24.6±0.1
Air velocity [m/s]	0.23±0.03	0.15±0.01	0.14±0.01	0.07±0.01
Turbulence intensity [%]	67.8±5.2	30.4±1.5	34.8±1.6	15.0±1.8
Wall temperature [°C]	25.0±0.1	24.8±0.1	23.6±0.03	24.8±0.2
Floor temperature [°C]	24.9±0.1	24.8±0.1	28.9±0.1	19.7±0.2
Ceiling temperature [°C]	25.0±0.1	24.9±0.1	18.0±0.2	30.6±0.1
Mean radiant temperature [°C]	25.0±0.1	24.8±0.1	24.7±0.03	24.0±0.1
Δ Plane radiant temperature (floor – ceiling) [°C]	n/a	n/a	8.1±0.2	8.0±0.2
Δ Air temperature Left (1.7m - 0.1m) [°C]	n/a	n/a	-1.3±0.0	3.7±0.3
Δ Air temperature Right (1.7m - 0.1m) [°C]	n/a	n/a	-1.3±0.0	3.7±0.3
PMV [-]	0.3±0.05	0.1±0.03	0.1±0.02	0.2±0.0

Values are presented as mean ± SD

Measurements

Prior to the measurements the subjects performed a light exercise until vasodilatation occurred (approximately 5 minutes, assessed by the skin temperature difference between forearm and top of the forefinger) to ensure all subjects entered the climate room in an identical thermal state. After entering the climate room the experiment started with an acclimatization period (30 minutes). A detailed time line is given in Figure 2.

During the experiments the subjects wore standardized clothing, consisting of jogging pants, thin T-shirt, underpants, socks and (low) shoes. The clo-values were estimated according to NEN-EN-ISO 9920 (2009) and McCullough et al. (1989). The total heat resistance of the clothing ensemble, including desk chair, was approximately 0.7 clo,

which represents typical (office) summer clothing. The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met according to ISO-EN 7730 (2005).
The volunteers were given detailed information regarding the main purpose and the methods used in the study, before written consent was obtained. However, they were not informed on the actual conditions they were exposed to.

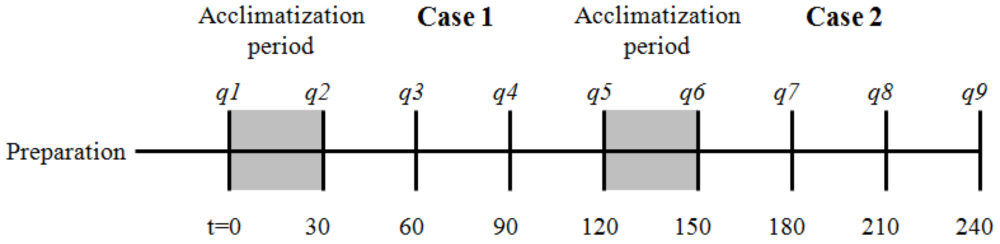

Figure 2: Time line of measurement protocol; q is representing the questionnaire moments

During the experiments both physical and physiological measurements were performed continuously. Environmental parameters (air temperature, relative humidity, air velocity, mean radiant temperature and illuminance) were measured according to NEN-EN-ISO 7726 (2001). Air temperature, RH, and air velocity were measured on two comfort stands at 0.1, 0.6, 1.1 and 1.7 m height. These comfort stands were placed on the left and right side of the subject, at a distance of 0.2m. Mean skin temperature was calculated based on the 14 point weighing proposed by NEN-EN-ISO 9886 (2004). To study the effects of the asymmetrical conditions 10 measurement sites were added (Figure 3, left). The extent of vasomotion can be assessed by the difference in skin temperature between forearm and top of forefinger (location 15 and 16; 18 and 20, Figure 3, left). Skin temperatures were measured using wireless sensors (accuracy ±0.125°C) which were attached to skin using semi-permeable adhesive tape. The core temperature is measured through a telemetry pill (accuracy ±0.1°C), ingested 30 minutes before entering the climate room.

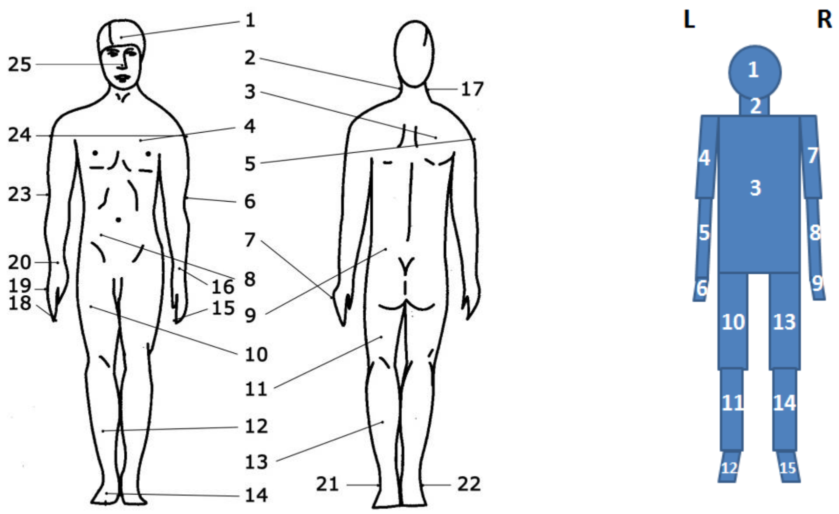

Figure 3: (left) Measurement sites skin temperature, adjusted from NEN-EN-ISO 9886 (2004), (right) schematic representation of body parts to assess local thermal sensation and comfort

Questionnaires

After the acclimatization period, the subjects were asked to fill in a questionnaire at a 30 minute interval. The questionnaire included among others 7-point interval scales to assess global and local (15 body parts, Figure 3, right) thermal sensation, questions regarding the acceptability of the thermal environment, and Visual Analogue Scales (VAS) to assess the perceived indoor environment (NEN-EN-ISO 7730 2005) (Kildeso et al. 1999). The questionnaires were presented in Dutch to the subjects through an Internet browser. A commercially available statistical software package (PASW Statistics 18.0, SPSS Inc., Chicago, USA) was used to analyze the data.

RESULTS

Physiological measurements

Mean, distal, and proximal skin temperatures and core temperature differed significantly between the cases (ANOVA, $p<0.001$). Although the differences were relatively small (some within the measurement accuracy), highest mean skin temperatures were found during case (a) and case (d). Highest distal skin temperature was found during case (a), followed by cased (d). Highest proximal skin temperatures were measured during case (d), followed by case (a).

Table 3: Mean, distal, and proximal skin temperatures and core temperature during all experimental cases

Variable	Case (a)	Case (b)	Case (c)	Case (d)
Mean skin temperature [°C]	33.1±0.1*	32.9±0.1*	32.8±0.1*	33.1±0.1*
Core temperature [°C]	37.0±0.1*	37.0±0.0*	37.0±0.0*	37.1±0.0*
Distal skin temperature [°C]	32.0±0.2*	31.3±0.2*	31.3±0.3*	31.6±0.3*
Proximal skin temperature [°C]	34.1±0.1*	33.8±0.1*	33.7±0.1*	34.2±0.1*

Values are presented as mean ± SD, *significant case effect (ANOVA, $p<0.001$)

Subjective responses

The subjective responses were analyzed for the last four questionnaires of each case (i.e. Case 1: q2-q5 and Case 2: q6-q9; Fig. 2). The case effect was significant (ANOVA, $p<0.05$) different for whole body thermal sensation (WB TS) (Figure 4). With respect to the means (AMV, Table 4) and medians, the lowest WB TS was found for case c (*active* cooling through *radiation* by the *ceiling*), the highest mean WB TS was found for d (*active* cooling through *radiation* by the *floor*). The predicted mean votes (PMV), according to the model of Fanger (Fanger 1970), were for all cases significantly different from the AMV (Wilcoxon signed-rank test, $p<0.05$). For all cases, except (d), actual mean votes were significantly lower compared to PMV. This indicates that during these cases subjects were, on average, feeling significantly colder than predicted; this is confirmed by the shift in boxplots (Figure 4) towards -1 (slightly cold).

Table 4: Predicted mean vote (PMV) and actual mean vote (AMV) for all experimental cases

Variable	Case (a)	Case (b)	Case (c)	Case (d)
PMV [-]	0.3±0.1	0.1±0.03	0.1±0.02	0.2±0.04
AMV [-]	-0.3±0.64*	-0.1±0.45*	-0.3±0.41*	0.5±0.59*

Values are presented as mean ± SD, * $P < 0.05$ versus PMV

Regarding the mean WB thermal comfort (TC), Figure 5, Case (a) and Case (d) were overall less comfortable in comparison to the other cases (lowest frequencies of comfortable votes).

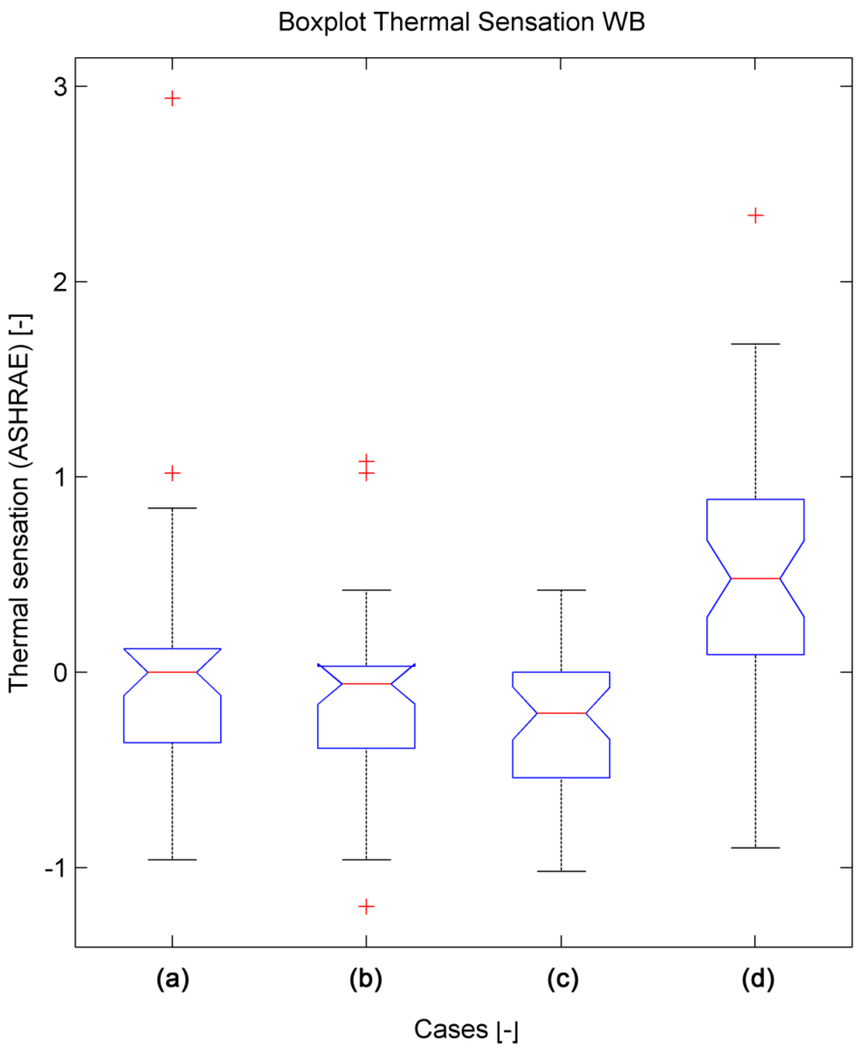

Figure 4: Boxplot whole body thermal sensation, the red line indicates the median, the bottom and top of the box represent respectively the 25th and 75th percentile, the black horizontal lines present 1.5 IQR, and the red crosses indicate outliers.

Regarding local thermal sensation, significant case effects were found for all body parts except for the right upper leg. The largest F ratio's were found for the uncovered extremities (the hands and forearms both left and right) and the upper arms. The largest correlation for local TS and WB TS were found for the hands, although the correlation was significant the r was relatively low (around 0.2).

The largest correlation for local TS versus local skin temperature was found for the right hand (r=0.4).

With respect to local thermal comfort, significant case effects were found for left and right hands and forearms and right upper arm.

However, all these parameters, both for local thermal sensation and comfort could not be indicated as significant predictive parameter for whole body thermal sensation or comfort.

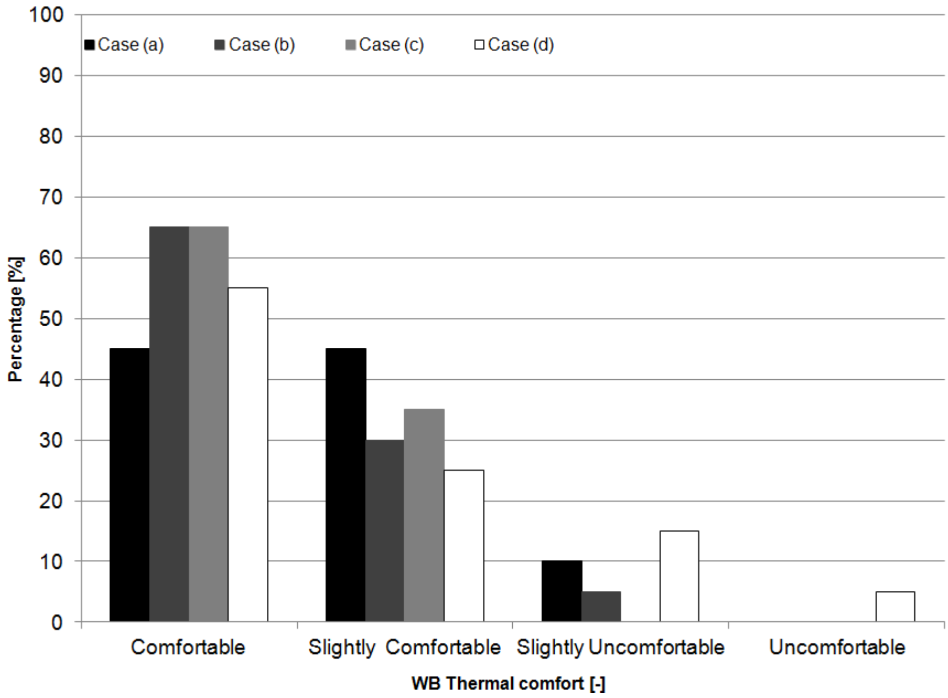

Figure 5: Frequency plot of whole body (WB) thermal comfort votes for all cases

DISCUSSION

Thermal sensation data indicate significant differences between the *passive* (a) and *active* cooling cases (b,c, and d), although the differences in physiological data were relatively small (some within measurement accuracy). For instance, thermal sensation was significantly lower during the *passive* cooling case (a) in comparison to *active* cooling through *convection* (mean AMV=-0.3±0.64 and -0.1±0.45 respectively). Furthermore, all actual thermal sensation votes (AMV) significantly differed from the predicted mean votes (PMV) for all cases (Table 4). The largest deviations were found for the *passive* cooling case (a) and case (d) *active* cooling through *radiation* by the *floor*. During (a) the subjects were feeling significantly colder than predicted, and during (d) they were feeling significantly warmer than predicted. The difference for (a) is caused by local thermal sensation differences, i.e. during passive cooling the head and lower arms felt colder in comparison to the rest of the body caused by an increased air velocity near the subject (Table 2). Although significant local effects were found, these local thermal sensations could not be indicated as significant predictive parameter. Therefore, it is not yet clear in which way local effects influences whole body subjective votes (both thermal sensation and comfort). During (d) no local deviations in thermal sensation votes were observed.

During cases (c) and (d) the subjects were exposed to respectively cooling through the *ceiling* and *floor*. Although mean operative temperature differed on average only 0.1°C, AMV differed significantly (-0.3±0.41 vs 0.5±0.59). This indicates that the operative temperature only, as used in the PMV, is not sufficient regarding the prediction of thermal sensation under non-uniform thermal environments. With respect to the plane radiant temperature asymmetry, a warm ceiling is more critical regarding discomfort compared to a cool ceiling (NEN-EN-ISO 7730 Organization 2005); this is confirmed in this study. Case (d) is perceived as most uncomfortable; the largest deviation from a neutral thermal sensation occurred and the largest

(statistical) dispersion with respect to WB TS was found within the results for this case (Figure 4). During this case the subjects were feeling significantly warmer than predicted; as a result 55% of the thermal comfort votes differed from 'Comfortable' (Figure 5).
According to the thermal sensation votes, case (b) *active* cooling through *convection* appears to be the most comfortable case (AMV closest to neutral). However, from the thermal comfort votes, cases (c) *active* cooling through *radiation* through the *ceiling* appears to be most comfortable. Relatively small differences were found in physiological responses between the cases. Though, significant differences in thermal sensation votes were noticed; probably, local effects (i.e. local skin temperatures and sensations) have a large influence on whole body thermal comfort and are important regarding the assessment of the thermal environment. However, more research is needed to clearly indentify these influences.

CONCLUSION

For the prediction of thermal sensation under non-uniform conditions, the operative temperature only is not sufficient. Highly non-uniform environments, as case (c) can achieve a comparable or even more comfortable assessment compared to uniform environments, as case (b). Under the uniform conditions studied the thermal sensation can be predicted well by the PMV model. Contrary, non-uniform environments, as case (d) can achieve significantly different thermal sensation votes as predicted in advance. These differences are most probably caused by local effects (local thermal sensations and local skin temperatures). More research is needed to indentify the relations between these local effects and whole body thermal assessment. Prudence is required in order to design thermal comfortable conditions if low exergy/energy systems (e.g. high temperature cooling by means of radiation) are applied.

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