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Thermal comfort, physiological responses and performance during exposure to a moderate temperature drift

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SUMMARY
The objective of this research was to study the effects of a moderate temperature drift on human thermal comfort, physiological responses, productivity and performance. A dynamic thermophysiological model was used to examine the possibility of simulating human thermal responses and thermal comfort under moderate transient conditions. To examine the influence of a moderate temperature ramp, a climate room set-up with experimental subjects was used. Eight subjects visited the climate room on two occasions: 1) exposure to a transient condition (a moderate temperature ramp) and 2) a steady temperature corresponding with a neutral thermal sensation (control situation). During the experiments both physiological responses and thermal sensation were measured. Productivity and performance were assessed with a 'Remote Performance Measurement' (RPM) method. Physiological and thermal sensation data indicate significant differences between the transient condition and the control situation. Productivity and performance tests show no significant changes between the two situations. Simulations obtained with the thermophysiological model were in good agreement with the measurements. Possible improvements of the performance and productivity tests and the thermophysiological model will be discussed.

KEYWORDS
Thermal comfort, Physiological responses, Productivity, Moderate temperature drift, Thermophysiological model

INTRODUCTION
About one-third of the primary energy used in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings (IEA ECBCS, 2007). Results from previous studies indicate that, in comparison with constant temperature, allowing the temperatures to drift could be a means to reduce this energy-use. Griffiths and McIntyre (1974) and Berglund and Gonzalez (1978) concluded that slow temperature ramps (0.5K/h) were not significantly noticeable to the occupants. Berglund and Gonzalez also stated that at fast temperature changes (1.0K/h and 1.5K/h) the allowable deviation from the optimum thermal condition was larger. More recent studies also revealed that air-conditioned buildings, with a constant indoor climate, do not always lead to optimal thermal comfort. These studies have shown that occupants in naturally ventilated, free running buildings are more often satisfied with their thermal environment and accept a wider temperature range than occupants in buildings with a constant indoor climate [Jaakkola, 1991; De Dear and Brager, 2001; Olesen

and Parsons, 2002; Olesen, 2004; Ye et al., 2006]. The challenge is to explore the range in which the temperatures changes are applicable in air-conditioned buildings.

The objective of this research was to study the effects of a moderate temperature drift on human thermal comfort, physiological responses and performance. Furthermore, a thermophysiological model was used to examine the possibility of simulating human thermal responses and thermal comfort under moderate transient conditions.

METHODS

Design

To examine the influence of a moderate temperature ramp, a climate room set-up with test subjects was used. The measurements were conducted at Eindhoven University of Technology (Figure 1). Eight healthy subjects (male; age: 22-25; height: 1.83±0.11m, weight: 82.7±8.6kg; BodyFat%: 14.5±3.3) visited the climate room on two occasions. On these occasions they were exposed to either a transient condition, session 2, i.e. a moderate temperature ramp (duration: 8h; temperature range: 17-25°C; temperature drift: first 4h: +2K/h, last 4h: -2K/h, Figure 2), or to a steady temperature (21.5°C), session 1, corresponding with a neutral thermal sensation, a so called control situation. The order of the conditions was alternated.

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 equal thermal state. After entering the climate room the experiment started with an acclimatization period (30 minutes). During the experiments the subjects wore standardized clothing, consisting of a cardigan, jogging pants, thin T-shirt, underpants, socks and shoes. The clo-values were estimated according to ISO 9920 (1995) and the database of McCullough et al. (1998; 2004). The total heat resistance of the clothing ensemble, including desk chair, was approximately 1.0 clo.

The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained.

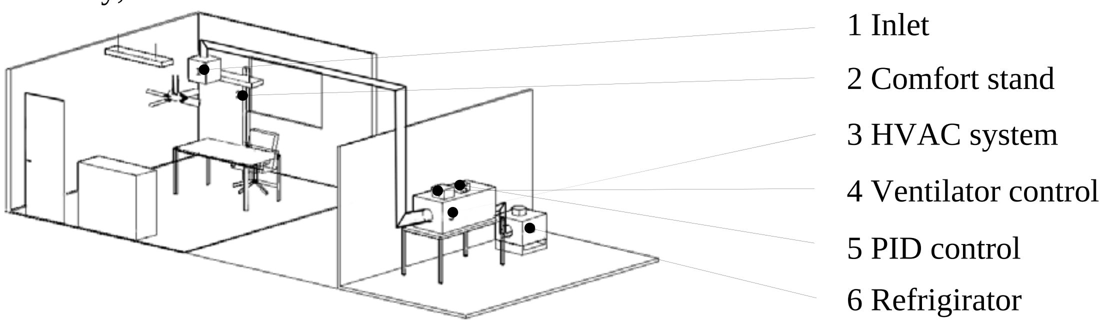

Figure 1. Schematic drawing of the climate room.

Measurements

During the experiments both physical and physiological measurements were carried out continuously. The environmental parameters (air temperature, relative humidity, air velocity, mean radiant temperate and illuminance) were measured according to ISO 7726 (1998). Mean skin temperature was calculated on the basis of the 14 point weighing as proposed by ISO 9886 (2004). To obtain more insight into the extent of vasomotion three measurement sites were added: top of the middle right toe, left forearm and top of left forefinger. Vasomotion can be determined through the temperature difference between forearm and forefinger and between the lower leg and toe. Besides, the rectal temperature of every subject was measured.

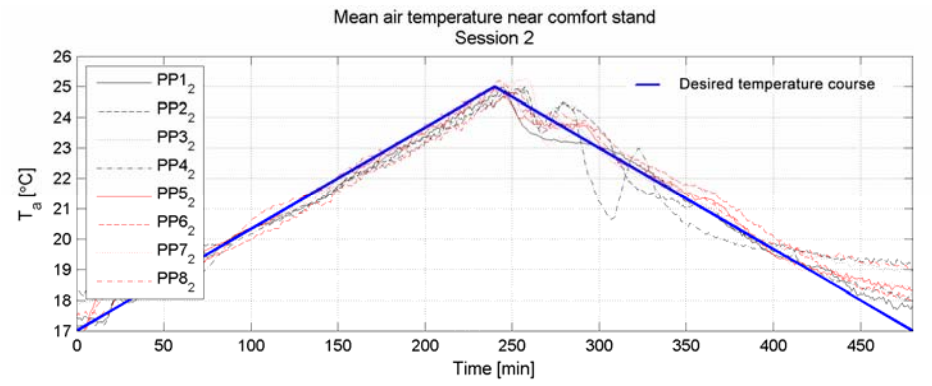

Figure 2. Desired and measured temperature course during experiment.

Questionnaires

Two times per hour, the test subjects filled in a questionnaire that included a 7-point thermal sensation interval scale (each point on the line could be marked), scales to asses the acceptability of the thermal environment and Visual Analogue Scales (VAS) to assess the perceived indoor environment [Kildesø et al., 1994]. A questionnaire to assess self-estimated performance and a questionnaire to assess perceived stress were included as well. To assess the performance a 'Remote Performance Measurement' (RPM) method was used [Toftum et al., 2005]. Within this method the performance was estimated by two simulated office tasks: text typing and addition. Both questionnaires and office tasks were presented in Dutch to the subjects through an Internet browser. A commercially available statistical software package was used to analyze the data.

Modeling

A dynamic thermophysiological model was used to predict local skin temperatures, core temperature and the dynamic thermal sensation (Figure 3) [Van Marken Lichtenbelt, 2004 and 2007]. The dynamic model consists of passive and active components. The passive components model heat transfer phenomena and heat redistribution within the body, including the thermal effects of blood circulation, heat generation, accumulation and conduction in tissue layers. The human body is subdivided into cylinders and spheres representing the body elements (Figure 3). Every cylinder and sphere is built of several layers that represent different tissue materials. Furthermore, the cylinders are divided spatially into three sectors (anterior, posterior, and interior) by which asymmetric boundary conditions can be modeled. The model interacts with the environment by convection, radiation, respiration, skin evaporation and water vapor diffusion. The active component represents the actual thermoregulatory system. The body responds to temperatures and changes in temperature by extra heat production produced by shivering, sweating and vasomotion. The main advantage of this model is that asymmetric boundary conditions and individual body characteristics (height, weight and fat percentage) can be taken into account (Van Marken Lichtenbelt, 2004; 2007).

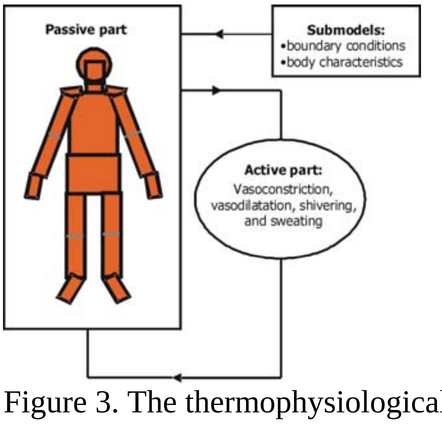

Figure 3. The thermophysiological model.

To predict the thermal sensation, the thermal dynamic sensation (DTS) equation, based on the mean skin temperature, core temperature and the rate of change of mean skin temperature, is used (Fiala, 2003).

RESULTS

Measurements

The results of the physiological measurements, $T_{sk;mean}$ and T_{core} are represented in Table 1. They show that environmental temperature changes resulted in a wider mean skin temperature range (P<0.001).

Table 1. Results of $T_{sk;mean}$ and T_{core} during session 1 and 2, data are averaged for all subjects.

Session	mean ± stdev min - max	
	$T_{sk;mean}$	T_{core}
Session 1	34.62 ± 0.19	36.96 ± 0.08
	34.39 – 35.10	36.83 – 37.32
Session 2	34.28 ± 0.69	36.93 ± 0.10
	33.29 – 35.29	36.80 – 37.19

The results of the questionnaires are represented in Table 2. From the percentiles included in the table, it can be concluded that subjects were able to feel the temperature transients.

Table 2. Thermal sensation session 1 vs session 2 (using 7-point scale).

Session	mean	min	max	25^{th} percentile	75^{th} percentile	median (50^{th} percentile)
Session 1	-0.2	-0.5	0	-0.2	-0.1	-0.1
Session 2	-0.5	-1.3	0.3	-0.9	0.0	-0.7

Based on multiple linear regression analysis a significant relation was found between the measured mean skin temperature, the room temperature and the thermal sensation of the subjects. This is indicated in Figure 4 and 5. The results of the vasomotion measurements for both toe-leg and fingertip-lower arm temperature difference, showed that there was no significant relation between these two parameters and the thermal sensation (p>0.05).

The results of the simulated office tasks indicated no effect of the temperature change on the performance of the subjects. The data of these tests were normalized, the maximum score of each subject was equal to 100% and all other scores were related to this score. After normalizing the data, the scores of the subjects for these tasks were nearly always maximal (ceiling phenomenon), which resulted in minor differences.

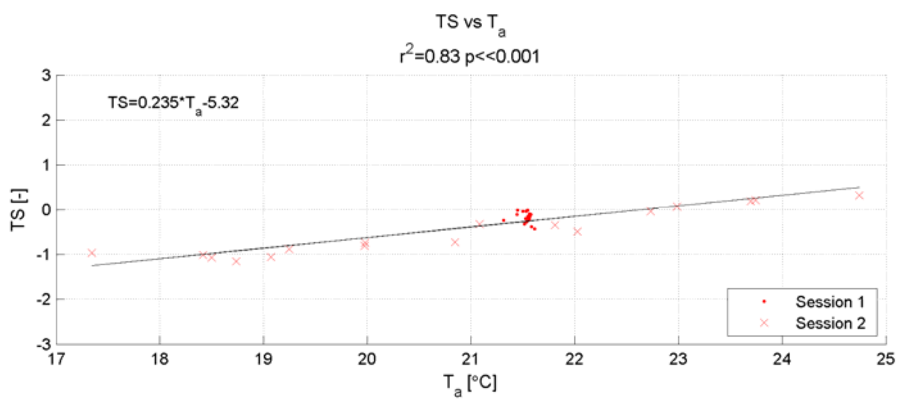

Figure 4. TS vs T_a, each point is an average of TS of all subjects.

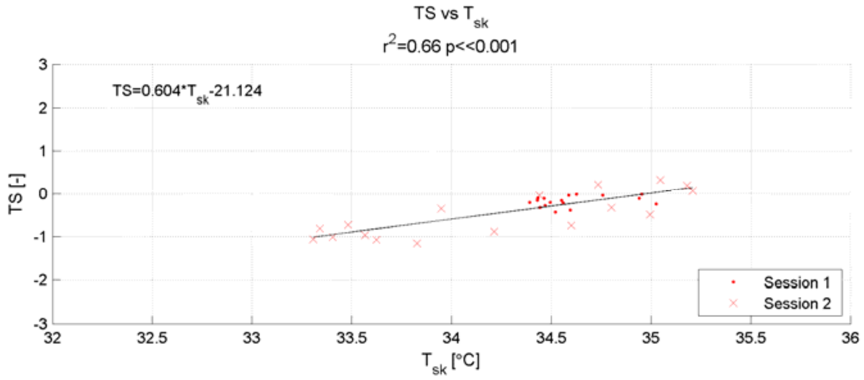

Figure 5. TS vs T_{sk}, each point is an average of TS of all subjects.

The derived multiple regression model based on the room temperature and average skin temperature (equation 1) was compared with the PMV model of Fanger (1970) in Figure 6.

$$TS = 0.204 \cdot T_a + 0.14 \cdot T_{sk} - 9.474 \qquad (1)$$

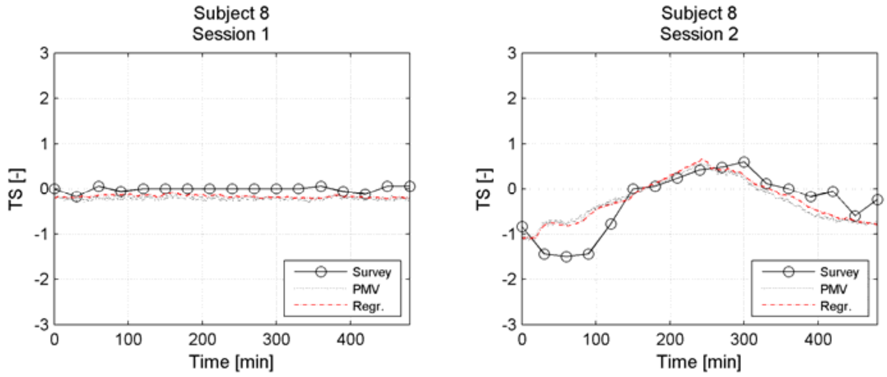

Figure 6. Comparison of observed thermal sensation, PMV (small dotted line) and the derived multiple regression model (large dotted line).

Modeling

Both the measured physical conditions and the body characteristics of the subjects were entered as boundary conditions into the thermophysiological model. The first simulation results assumed that the air flow played an important role in the prediction of the mean skin temperature. A relatively high mean air velocity was measured (about 0.20 m/s, still within the comfort range). Application of this velocity in the model resulted in a significant deviation between the measured and the predicted mean skin temperature (T_{meas} -T_{sim} = 2.97±1.11 K). An overestimation of the heat transfer coefficient may have caused this deviation since the value of the air velocity in the gap between skin and clothing was over predicted. To investigate this assumption, the air velocity between the clothing layers was reduced to a value of 0.05 m/s (T_{meas} -T_{sim} = 1.14±0.10 K). These results are shown in Figure 7.

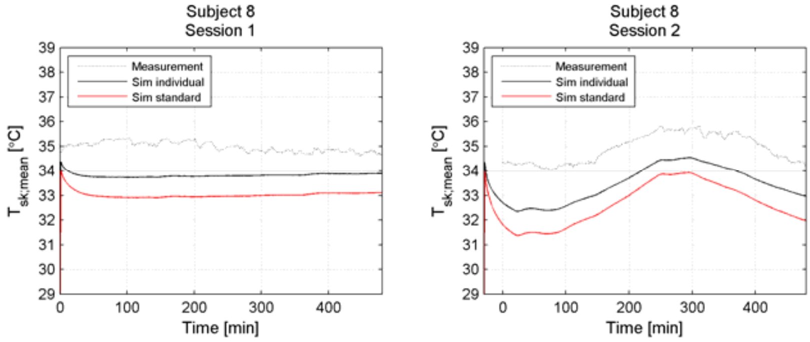

Figure 7. Comparison of measurement and simulation results for T_{sk}, the black line represents the simulation results obtained by simulation with standardized body characteristics (Fiala, 1998), the red line represents the simulation results obtained by simulation with individual body characteristics.

In the model, the thermal sensation (represented on the 7-point scale) was predicted by the DTS. The comparison of the measured and simulated thermal sensation for a typical subject is shown in Figure 8.

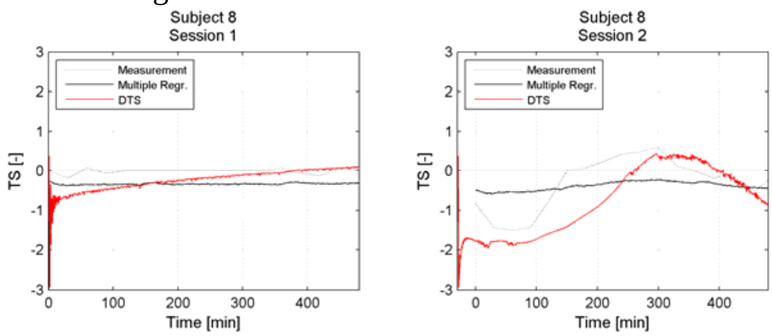

Figure 8. Comparison of measurement and simulation results for TS.

DISCUSSION

Measurements

The studied moderate temperature drifts did not lead to unacceptable thermal conditions. Furthermore, a significant correlation between measured mean skin temperature, room temperature and thermal sensation was found. Both the derived multiple regression model for thermal sensation and Fanger's PMV model showed good agreement with the measurement results. Although a relation in literature was found between the extent of vasomotion and thermal sensation (Wang et al., 2007), in this study no significant correlation was found between these parameters.

From the results of the performance and productivity tests it can be concluded that the exposure in this experiment did not have an effect on subjects' performance. Another conclusion, in line with the study of Fang et al. (2004), could be that the subjects were too motivated which compensated for a possible negative effect of an uncomfortable environment. To obtain more accurate results from the performance and productivity tests, the tests should at least not be too easy. In this study the addition task consisted of the addition of two two-digit numbers.

The prediction of the thermal sensation obtained with the PMV model showed a good agreement with the measurement results. However, it should be noticed that this experiment was conducted under laboratory conditions, which could have influenced the subjects' perception of the environment.

Modeling
Due to relatively high mean air velocities a large deviation was found between the measured and predicted mean skin temperature. An improvement was found when the velocity was reduced to 0.05 m/s. The modified, simulated mean skin temperatures were thus in better agreement with the measured ones (mean deviation in mean skin temperature was 1.14K, Figure 7). The measurement position of the air velocity therefore might not have been characteristic.

Furthermore, the measurements revealed that the temperature difference between lower leg and toe for all subjects stabilized after 120 minutes, most probably as a result of long-term sitting, in spite of the exercise to stimulate the blood flow (derived from the aircraft industry). This effect is not taken in account in the model and therefore results in an inaccurate prediction of the skin temperatures of the feet.

The simulated core temperatures for the experiments with a constant room temperature, showed good agreement with the measured values (mean deviation -0.10K). For the transient conditions the difference between simulated and measured core temperatures was larger (mean deviation was 0.48K). This can be explained by the cyclic temperature course, which occurred in the simulation of session 2 due to the air temperature changes; however this course did not occur during the measurements.

From the results it can be concluded that the prediction of the thermal sensation, during the experiments with a constant room temperature, was in good agreement with the measured thermal sensation (mean deviation 0.20). Also for varying room temperatures, the thermal sensation still can be predicted well. Figure 8 shows that the DTS-model was able to predict the trends correctly (mean deviation 0.39).

CONCLUSION

Based on the experimental results for the control situation it was possible to distinguish between the average room temperature effect and transient effects. In this case temperature changes were significant and noticeable for the subjects. From the results of the performance and productivity tests it can be concluded that the exposure in this experiment did not have an effect on subjects' performance.

The simulation results obtained with the thermo-physiological model indicated that the trend in the varying temperatures were correctly predicted. With respect to the predicted thermal sensation, good agreement was found with the measured thermal sensation for the control situation and for the transient situation. The thermo-physiological model therefore appears promising. Future model developments, amongst others, will concentrate on appropriate definition of the boundary conditions.

ACKNOWLEDGEMENT

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