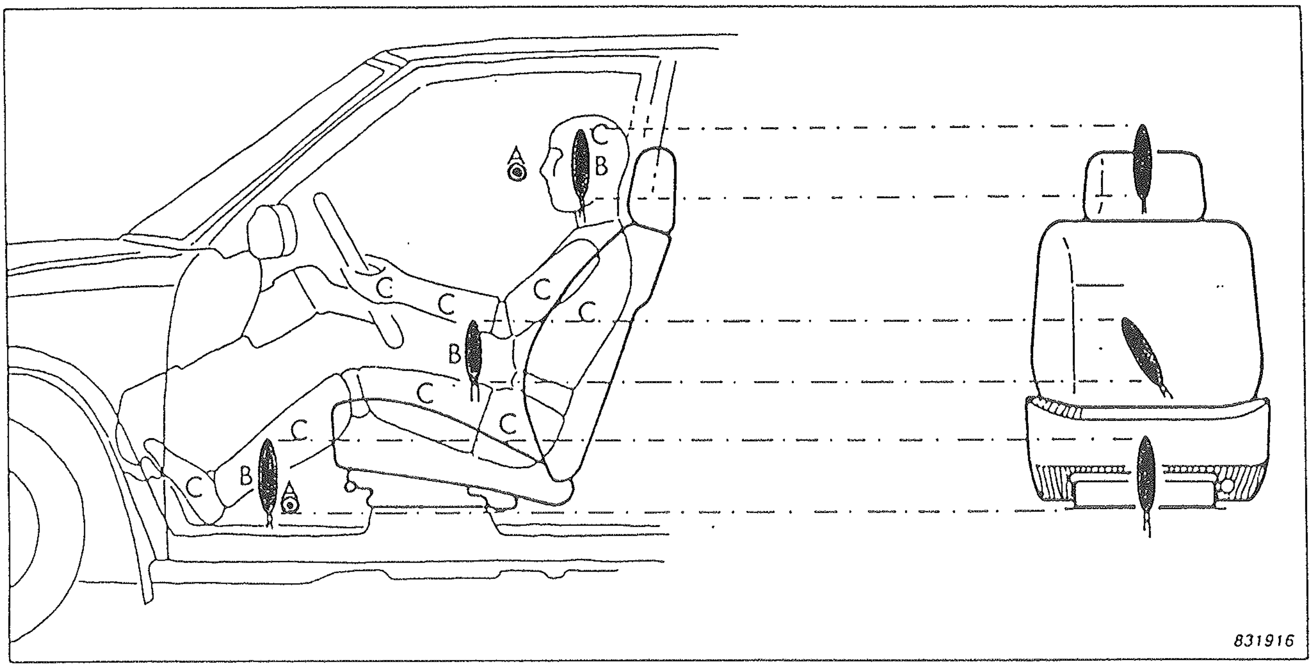
New Methods for Evaluation of the Thermal Environment in Automotive Vehicles

T. L. Madsen, B. Olesen & K. Reid



Report No. 235
January 1986

Thermal Insulation Laboratory
Technical University of Denmark

SF-86-01 No. 4

NEW METHODS FOR EVALUATION OF THE THERMAL ENVIRONMENT IN AUTOMOTIVE VEHICLES

T.L. Madsen *ASHRAE Member*
B. Olesen *ASHRAE Member*
K. Reid

ABSTRACT

A new method for the evaluation of the thermal environment in automobiles has been tested in steady-state conditions and non-steady-state conditions like warm-up periods (as in wintertime) and cool-down periods (as in summertime). The investigation was conducted in a wind tunnel where airspeeds of up to 130 km/h were achievable at temperatures between -18°C and +40°C. A realistic sun load on the car was also simulated during the test.

Three different measuring techniques have been tested at both the driver and front passenger positions, namely: air temperature sensors at feet and head level, thermal comfort sensors that measure the equivalent temperature positioned at three levels, feet, abdomen and head; and finally, a thermal manikin that measures the equivalent temperature or heat-loss for 16 different body segments. The equivalent temperatures used in the two last methods combine the influence from radiation (sun load), air velocity, and air temperature caused by the air-conditioning system. In the test with the thermal manikin, a good simulation of the normal driving situation is created. The thermal manikin is heated and thermally simulates a human being. This is particularly important in a confined space such as a car because the airflow from inlets is nonuniformly distributed and strongly influenced by the presence of driver and passengers. In addition, the sun's radiation through the windows causes an asymmetric thermal load on the persons in the car and the seats thermally insulate some parts of the body, from which the heat loss is greatly reduced. These factors are not taken into account if only air temperature is measured. This paper presents results from all the methods and a comparison is discussed.

T.L. Madsen is assistant professor at the Thermal Insulation Laboratory, Technical University of Denmark, Bjarne W. Olesen, Ph.D, is research assosiate at the Laboratory of Heating and Air Conditioning, Technical University of Denmark and Ken Read is project engineer at General Motors Technical Center, Warren, Michigan.

PROBLEM DESCRIPTION

Recent research into indoor climate has resulted in a fairly good knowledge of the requirements to each of the thermal climate parameters and how to combine the parameters to obtain an acceptable thermal indoor climate. Standards (ASHRAE 81-55, [1], ISO 7730 [2] and ISO 7726 [3]) have been established for both the thermal comfort and the measuring methods for evaluation of the actual degree of thermal comfort.

Research and standards to date have concentrated mainly on the indoor climate in buildings. As people spend a lot of time in cars, the next step is obviously to apply the research methods on the indoor climate to the thermal comfort in cars.

The problems of climate in a car are different and often more difficult to estimate. Normally, a stable and acceptable indoor climate can be established and maintained in a building, but in a car, the controlled indoor climate is only established when the car is started. The thermal environment in a car is more difficult to control and evaluate than in a building. These difficulties are due to external influences, in particular, to direct and varying solar gain on some parts of the body. Other factors are: the inhomogeneous temperature and air velocity field created by the air-conditioning system of the car; that modern car seats give a considerable amount of insulation to the parts of the body in contact with the seat; and that the person, merely by his presence, influences the air movement from the climate and the ventilating system. Last, but not least, neither driver nor passengers are able to change their positions much to make up for the asymmetric climate condition. It is therefore very reasonable to investigate to what degree modern cars are able to create an acceptable thermal indoor climate; how to measure the thermal environment in a car; and to what extent the new international standards for thermal comfort can be used to evaluate the thermal invironment in a car. This paper presents a pilot study designed to compare three different methods of assesment.

Thermal comfort is created when the combined effect of all six thermal climate parameters - activity level, clothing, air temperature, air velocity, air humidity and mean radiation temperature - cause a person to loose the heat produced by metabolism and still maintain an acceptable skin temperature [4]. According to ISO7730 [2], the degree of general thermal comfort can be given by the PMV-index (figure 1). This value can be calculated when the six climate parameters are known. The PMV-index should lie between -0.5 and +0.5, which means that less than 10% will find that the thermal invironment is unacceptable. In addition, the standard includes quidelines for local thermal comfort like radiant assymetry, draft and air temperature gradients.

Measuring Methods

The usual method of evaluating the efficiency of the climate conditioning system in cars is to apply air-temperature sensors to measure the air temperature at feet and head level at all seats, the main purpose being to investigate the ability of the system to raise and lower the temperature to the desired level. However, when using these thermal sensors, only one (air- temperature) of the three main climatic parameters that concerns the thermal comfort sensations (air temperature, mean radiant temperature, air velocity) is measured. This fact is especially unfortunate in cars, as the mean radiant temperature usually differs far more from the air temperature than is the case in buildings and the air velocity is also greater and more nonuniform than in buildings.

Meaurement of thermal comfort can be made by using transducers made specially to make an integrated determination of the influence of the three abovementioned climatic parameters on the thermal comfort. By means of these transducers, when connected to a measuring instrument in which the actual activity clothing and air humidity are also taken into account [7], it is possible to determine the equivalent temperature at the place of the transducers. The equivalent temperature [5, 6] is defined as the uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiation and convection as in the actual environment. By using three transducers per person (figure 2), the equivalent temperatures representing the whole body can be found by weighting the three measured equivalent temperatures in relation to that part of the body they each represent:

$$t_{eq} = 0.23 \cdot A + 0.67 \cdot B + 0.1 \cdot C$$

where A, B and C are the equivalent temperatures measured at feet, abdomen and head level respectively.

By using this mean equivalent temperature, $\bar{t}_{eq}$, the thermal insulation of the clothing and the activity level, the PMV-value may be estimated.

Measurement by Means of Thermal Manikin

The thermal comfort meter is a good instrument for determination of the PMV-values in buildings where the thermal field is fairly homogeneous and the presence of persons is of minor importance for the measuring result. In a car, however, it is more important to simulate the actual conditions and to measure the very nonuniform conditions. This can be done using a thermal manikin as also described by Wyon et al. [8]. Instruments of this kind have been used for measurements of the insulating ability of clothings for several years [9] and, in some cases, for the evaluation of the thermal indoor climate in buildings [10]. The manikin used for the present investigations has been developed at the Technical University of Denmark for measurement of clo-values and for evaluation of the thermal indoor climate [11]. The manikin is fitted with pliable joints so that it can be placed in different positions. Thermally it is divided in 16 sections, each with its own heating system to ensure that each section will maintain exactly the surface temperature that, according to Fanger's comfort equation [4], will give thermal comfort at the actual heat loss. After measuring the energy consumption of each of the 16 sections, the equivalent temperature for each part of the body can be found. By using the total heat loss from the whole body, the PMV-value may be found. For the measurements, the manikin is first clothed in a summer suit with a clo-value of 0.8 and then in a winter suit with a clo-value of 1.4. These clo-values were measured in a pre-test and include the thermal insulation of the seat. It is thus possible to evaluate the general thermal comfort by the PMV-value and any asymmetry of the thermal field by the individual equivalent temperatures for each body segment. These asymmetries will cause differences between the heat losses from any part of the body which is not due to the changing of clothes.

Test Facilities and Procedures

All the tests were performed in a windtunnel where air temperature, wind velocity and radiant sun load would be simulated and controlled at different levels.

As it was not possible to simultaneously measure in the same position with both the comfort transducers and the manikin, measurements were first taken with one placed in the driver's position and the other in the front passenger position. The measurements were then repeated with the positions reversed. The results presented here are mainly those conducted at the driver's seat. The following two test procedures were used.

Cool-down: To simulate summer conditions, the car is heated up in the wind tunnel with simulated sun load to an operative temperature around 60°C. After steady state conditions have been obtained for some time, the engine and air-conditioning system is started. The engine is running under a realistic load during the whole test. During the entire test the air temperature (+40°C) and sun load from above and from the left side of the driver is kept constant. When the car is turned on, the wind speed in the tunnel is increased to a level that is equal to the relative air velocity when driving at 80 km/h. Before the cool-down starts, the air-conditioning system has been set to maximum, the fan speed to high and the outlets set in a fixed position. All measurements are recorded continuously during this transient condition, i.e., thermocouples in two levels, equivalent temperature in three levels and the total heat loss from the manikin, together with the heat loss from the head and feet/lower legs. The clo-values for the thermal manikin and the values set on the comfort meter are given in Table 1. When steady-state conditions are obtained, the heat loss from all 16 parts of the manikin is recorded. By estimating the clo-values for the comfort transducers, it is assured that the thermal insulation of the seat is equivalent to 0.2 clo.

In the steady-state conditions established after cool-down, a series of tests with different levels of fan speed, A/C level and sun load is performed (Table 2).

Warm-up: To simulate winter conditions, the car is cooled down to an operative temperature of approx. -18°C. After steady-state conditions have been reached for some time, the engine is started and the warming-up of the car by the heating system is started. The fan speed has been set in the high position. During the warm-up, similar measurements for cool down are recorded.

In the steady-state conditions, an additional test with low fan speed is performed.

Results and Discussion

Warm-up. figure 3 shows the results from air temperature, comfort meter and thermal manikin measurements taken at the driver's seat during a one hour warm-up test. It is important to remember:

- that the thermocouple curve is the result of only two point measurements of the air temperature

- that the comfort meter curve is a weighted result of three-point measurements of the equivalent temperatures, and

- that the manikin curve is the equivalent temperature calculated on the basis of the dry heat loss from the whole body.

The manikin curve starts at only -11°C corresponding to the maximum possible heat input to the manikin. A new thermal manikin to be used for car investigations may have a higher maximum heat input. The temperature measured by the thermocouples is several degrees higher than that measured by the other methods. The reason is that the air temperature is increasing rapidly while the mean radiant temperature is increasing more slowly because of the thermal capacity in the car. In addition to that, the mean radiant temperature will remain lower than the air temperature because of the poor insulation of normal car walls and ceiling, and, finally, the air velocity caused by the heating system will create an increase in the convective heat loss and thereby a decrease of the equivalent temperature. The rise in temperature is slightly slower when using the manikin than when using the comfort meter; the reason may be the manikin's higher time constant or that the temperature does really increase more slowly when the whole body is taken into account. The time constant of the seat may also have contributed to this difference.

During winter conditions, with an activity level of 1.2 met and a clo-value of 1.4, comfort is obtained at an equivalent temperature equal to 19°C. When using thermocouples, it seems like comfort is obtained after 15 minutes (figure 3). This is a false conclusion because the temperature experienced by the driver is between -5°C and +5°C as measured by the comfort transducers or the thermal manikin. The comfort level is reached after 24 minutes using the comfort meter and after 36 minutes using the thermal manikin. It is, however, important to remember that during the warm-up period the driver will be in a transient state, he will actually feel the thermal environment warmer than indicated by the objective measurements [12]; but the difference found between the thermocouples and the two more sophisticated methods by the end of the warm-up period indicates that the heating system is considerably less efficient than indicated by the simple measurement of air temperature.

Cool-down, figure 4. As neither the comfort meter nor the thermal manikin are able to perspire, they cannot be used at an equivalent temperature higher than the deep body temperature, i.e., 37°C. The heat loss at that temperature is zero and only the operative temperature can be measured, i.e., integrating the air temperature and the mean radiant temperature but not the air velocity. As the manikin has no output for operative temperatures, the starting point of the curve is 36.4°C, which is the temperature at which heat loss begins. The correlation between the three measuring results is better than for the warm-up situation. The reason is that the increase in convective heat loss is partly compensated for by a decrease in radiant heat loss due to the hot invironment outside the car. That means the mistake of using an air temperature sensor that is not influenced by the radiation is compensated by the fact that the air temperature is also not influenced by the air velocity. The optimum comfort temperature for 1.2 met and 0.8 clo is 23°C. This temperature is reached 30-35 minutes after start-up, but in this case the thermal manikin is first to reach the comfort state.

From figures 3 and 4, it is seen that the "real" warm-up and cool-down times are approximately the same, around 30 minutes.

Steady State After Warm-up. Two situations are tested: maximum outlet air temperature with high fan speed and maximum outlet air temperature with low fan speed. The temperature at feet and head level and the mean temperature for both situations are shown in figure 5. The temperature measurements made with thermocouples are significantly higher than those made with the comfort meter and the manikin, except in the case of the low fan speed situation where the feet of the manikin show three degrees higher equivalent temperature than the air temperature measured by thermocouple. The reason may be that because of the low air velocity, the warm air will not reach the thermocouple that is placed closer to the floor than the feet and lower legs of the manikin. The result from head level shows an equivalent temperature several degrees lower than the traditionally measured air temperature at breath level; the reason is - as already mentioned - the higher air velocity and the low mean radiant temperature; but, nonetheless, the heating system is still able to maintain an equivalent temperature of 19°C, which is the comfort temperature during winter conditions.

Steady State After Cool-down. The six situations shown on table 2 have been tested:

Figure 6 shows the mean temperature at the driver's seat, measured using all three methods, for each of the six test situations. There is fairly good agreement between the three methods in test conditions II and III where there was high or mean fan speed and normal cooling. This is due to higher air velocities compensating for the high solar gain. In situations V and VI, where the solar gain is decreased, the difference between the air temperature measured by thermocouple and the equivalent temperature measured by comfort meter and thermal manikin increases. With no sun load, the temperature at the driver's seat is 4-5 degrees lower when measured with meter/manikin than when measured by thermocouple. By comparing the results from test II and III, it is seen that the difference between high and mean fan speed is insignificant.

The differences between temperatures measured by the three different methods at feet and head level as well as the mean difference are listed in Table 3. On average, the comfort meter measurements are 4-5 degrees lower than the thermocouple measurements at feet and head level, although the weighted mean temperature of the three comfort meter measurements is only slightly lower than the mean temperature of the two thermocouple readings. The reason must be that the cold air is concentrated around the body center where the third comfort sensor is placed. At feet level, measurements made by the thermal manikin and measurements made by the comfort meter are in good agreement, but the manikin measures a higher temperature than indicated by the thermocouple at breath level. The reason for this surprising difference is that the thermal manikin is too tall, 1.84 m, and it cannot be seated in a normal position in a car seat; the face is too close to the ceiling of the car and about 0.2 m higher than the thermocouple at breath level. The manikin's head is, therefore, partly outside the cold airstream and exposed to radiation from the hot car roof.

The mean temperature measured by the thermal manikin is 2-5 degrees lower than the mean temperature of the two thermocouples. The thermal manikin will provide a more correct description of the thermal situation at the driver's seat. The description may be even better when using a slightly smaller manikin seated in a normal position.

It is also possible to measure the horizontal asymmetry in all six thermal situations by means of the thermal manikin. The difference between equivalent temperatures for left and right calf plus thigh and for left and right lower plus upper is shown on figure 7. The equivalent temperature for the right leg is, as shown, about two degrees higher than for the left leg, but the equivalent temperature of the right arm is much lower (up to 13 degrees) than that of the left arm. In the two first situations, the reason is a forced cooling from the air inlet of the right arm, and in the last situation, the reason is the forced cooling in combination with the reduced solar gain from the right and front windows. Obviously, this information cannot be obtained from the thermocouple or comfort meter methods.

Measurements have been made both at the driver's seat and at the front passenger seat, and it was interesting to compare the difference between the thermal situation in these two positions when using all three measuring methods. In Table 4, the comparison has been stated.

It can be seen that the thermocouple measures a higher temperature at the passenger seat in all six situations, the comfort meter measures a lower equivalent temperature at the passenger seat, and only the thermal manikin measures the same equivalent temperature at both seats. The reason can be that when measurements are only made at two or three points, it will not be possible to have a correct mean value of a person's thermal situation when the person is exposed to such a nonuniform distribution of air temperature, air velocity and radiation as is typically the case in a car when driving in hot areas. The thermal manikin integrates this complicated exposure over all the body and a representative equivalent temperature can be found.

CONCLUSION

The evaluation of thermal comfort in automotive vehicles is more complicated than in buildings. The reason is partly the transient conditions after start-up in warm or cold environments and partly the intensive and non-uniform influence from solar radiation and from the heating or air conditioning system.

This first investigation indicates that it is insufficient to measure only the air temperature at floor and breath level. During both winter and summer conditions this method indicates a cabin temperature several degrees lower than felt by driver and passenger and gives no measure of the influence from solar radiation or the distribution of hot and cold air over the body surface. It is impossible to correlate these results to guidelines expressed in ASHRAE and ISO standards for indoor climates in buildings.

By means of the comfort meter it will, however, be possible to have this correlation as the influence from all six thermal parameters is considered. The only limitation is that the comfort sensor only measures in one point. Using three comfort sensors, it is possible to get a fairly good impression of the thermal influence on driver and passenger from the complete thermal environment in a car. It will also be possible to evaluate the difference between head and feet level.

The thermal manikin measures the integrated equivalent temperature over the whole body surface as well as over each of the 16 body segments. A manikin is therefore the best instrument for testing the distribution of hot and cold air as well as for testing the influence from solar gain from different directions. While the PMV-index may be used to evaluate the thermal comfort for the body as a whole in steady state conditions, there is a need for additional experimental studies with subjects to establish guidelines for the transient and nonuniform conditions in a car.

REFERENCES

1. ASHRAE 1981. "Thermal invironmental conditions for human occupancy". ANSI/ASHRAE 55-1981. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Inc.

2. ISO 1984. ISO 7730. Moderate Thermal environments. Determination of the PMV and PPD indices and specifications of the conditions for thermal comfort.

3. ISO 1985. ISO 7726. Thermal invironments - Specifications related to appliances and methods for measuring physical characteristics of the environment.

4. Fanger, P.O. 1982. Thermal Comfort Malabar, Fl. Robert E. Krieger Publishing Company.

5. Dufton, A.F. 1932. "The equivalent temperature of a room and its measurement. Bldg. Res. Technical Paper no. 13 London.

6. Madsen, T.L., Olesen, B.W., Kristensen, N.K. 1984. Comparison between Operative and Equivalent Temperature under Typical Indoor Conditions. ASHRAE Trans. 91.1.1984.

7. Madsen, T.L. 1976. Thermal Comfort Measurements. ASHRAE Trans 82.1.1976.

8. Wyon, D.P., Tennstedt, C., Lundgren, I. and Larsson, S. A new Method for the Detailed Assessment of Human Heat Balance in Vehicles - Volvo's Thermal Manikin, VOLTMAN. International Congress & Exposition, Detroit, Michigan. 1985.

9. Umbach, K.H. Comfort of Clothing. Bekleidungs physiologisches Institut Hohenstein. West-Germany.

10. Petersen, L.: Experiments with intermittent Heating and Insulation carried out in a test room. Contribution number 2 from the committee for the study of domestic heating. Copenhagen 1948.

11. Olesen, B.W. and Madsen, T.L.: Measurements of the thermal insulation of clothings by a movable thermal manikin: Proc. of the International Conference "Medical and Biophysical Aspect of Protective Clothing". 1983 Lyon.

12. Rohles, F.H. and Wallis, S.B.: Comfort Criteria for Air Conditioned Automotive Vehicles. Congress and Exposition, Cobo Hall, Detroit. 1979.

TABLE 1

Setting of Comfort Meter and Clo-value for the Thermal Manikin during Test

		warm-up winter		cool down summer	
comfort meter	activity level	1.2 met		1.2 met	
	vapour pressure	0.6 pa		0.9 pa	
	clo-value feet	0.8 clo	1.2	0.8 clo	0.7
	clo-value abdomen	1.5 clo		0.8 clo	
	clo-values head	0 clo		0 clo	
thermal manikin clo-value		1.4 clo		0.8 clo	

TABLE 2

Tests Conducted in the Steady-state Conditions established after Cool-down

		I	II	III	IV	V	VI
fan speed	high	x	x				
	mean			x		x	x
	low				x		
air conditioning	max	x					
	normal		x	x	x	x	x
sun load	front	x	x	x	x		
	side	x	x	x	x		
	roof	x	x	x	x	x	

Table 3

Difference between Temperatures Measured by Thermocouple and Equivalent Temperatures Measured by Comfort Meter and Thermal Manikin. (Car speed 80 km. Air temperature outside the car +40°C. Driver's seat)

		$t_{air} - t_{eq.comf.m}$			$t_{air} - t_{eq.manikin}$		
		feet	head	mean	feet	head	mean
max fan speed max AC	I	5.2	11.0	2.3	5.6	-0.2	5.1
- - - norm AC	II	3.9	3.0	-1.2	2.3	0	3.2
mean fan speed norm AC	III	4.1	2.9	-0.5	2.9	-0.6	1.9
low fan speed - -	IV	3.1	-3.5	2.3	2.9	2.9	3.2
mean fan speed norm AC no son sun through side and front pane	V	4.3	3.4	3.0	3.3	-1.2	3.4
mean fan speed norm AC no solar radiation	VI	4.4	5.3	3.9	4.1	-1.4	5.2
mean value		4.2	4.9	1.6	3.5	-0.5	3.7

TABLE 4

Differences between Equivalent Temperature (t_{eq}) Measured at Driver's and Passenger Seat in Six Steady-state Siuations after Cool-down

		t_{eq} (right seat - left seat) ^oK		
		thermo-couple	comfort meter	thermal manikin
max fan speed max cooling	I	3.5	-1.6	-0.3
max fan speed norm cooling	II	3.9	-1.7	0.0
mean - - - -	III	3.0	-0.9	-0.2
low - - - -	IV	3.8	-2.1	0.1
mean fan speed norm cooling no sun through side and front window	V	2.9	-1.1	-1.1
mean fan speed norm cooling no sun radiation	VI	3.5	-3.7	-0.7
mean value		3.4	-1.7	-0.4

ISO(DIS 7730)

PMV=Predicted Mean Vote

+3	hot
+2	warm
+1	slightly warm
0	neutral
−1	slightly cool
−2	cool
−3	cold

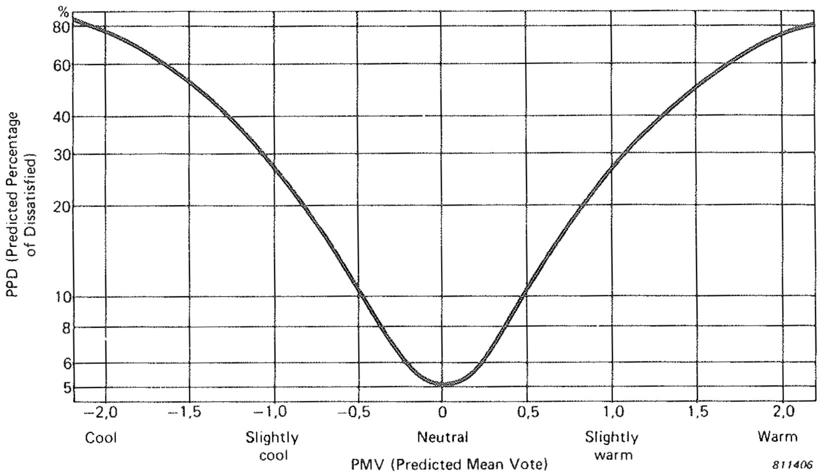


Figure 1. The comfort scale used in the new ISO-standard for mode-rate thermal environment. To the right is the correlation between the PMV-value and the percentage which is voting -3, -2, +2, or +3, which is the thermally dissatisfied (PPD)

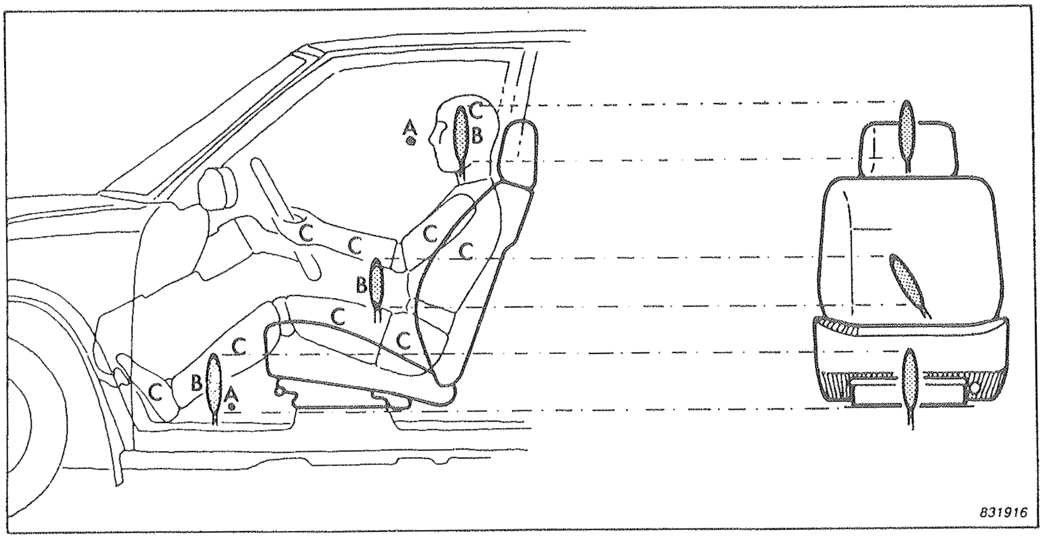


Figure 2. Position of the three different measuring systems in the car. A) Air temperature sensor, B) Comfort sensor, C) Different segments of thermal manikin

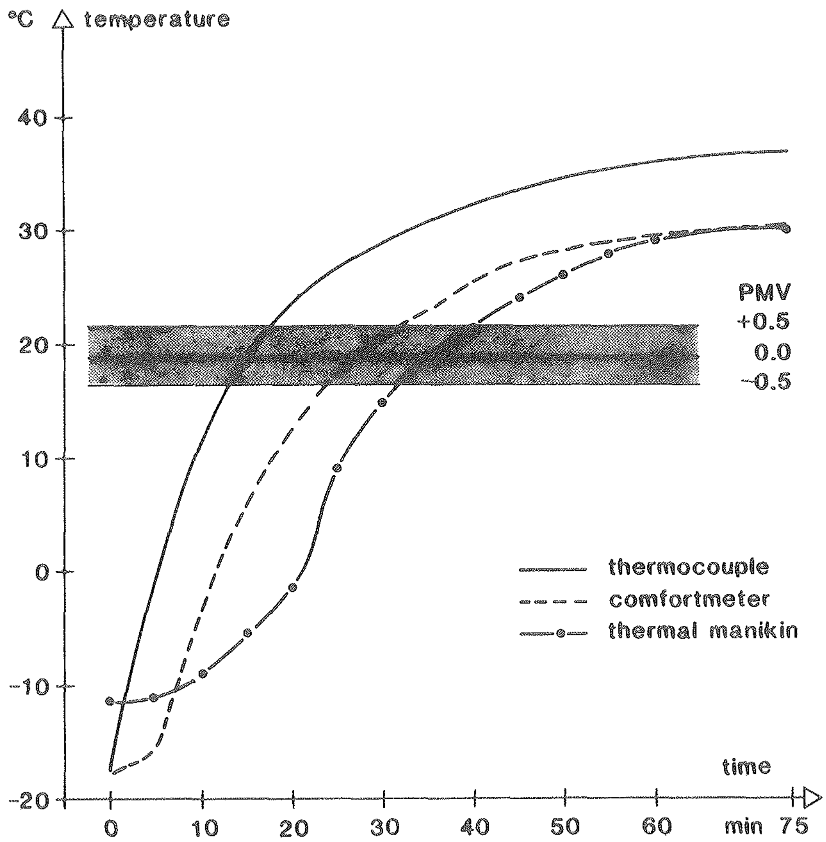


Figure 3. Recording of temperature in driver's seat during warm-up test. I is mean of air temperature at floor and breath level. II is a weighted mean of the equivalent temperature at feet, abdomen, and head leve. III is the mean equivalent temperature measured with thermal manikin. The horizontal lines indicate the comfort zone for 1.2 met and 1.4 clo (winter condition)

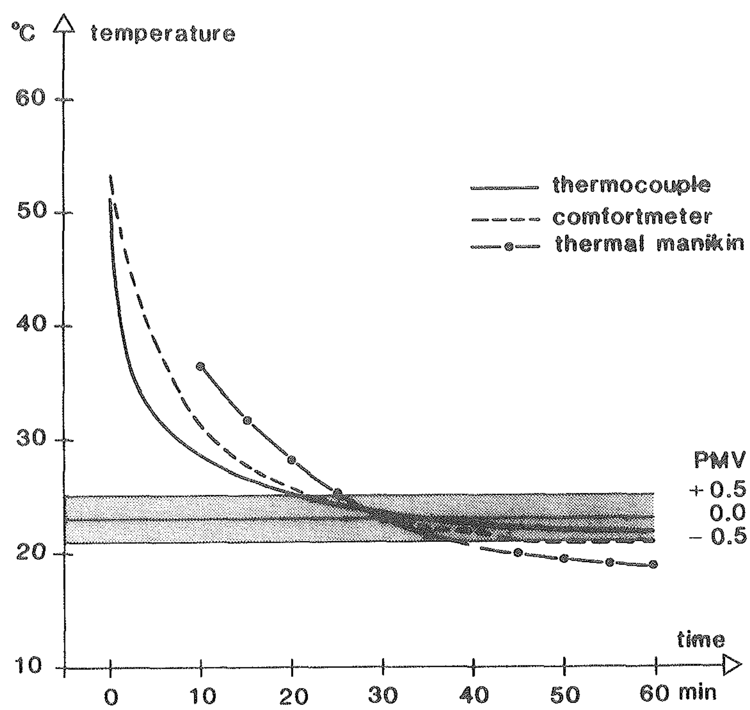


Figure 4. Recording of temperature in driver's seat during cool-down test using the three different measuring systems. The horizontal lines indicate the comfort zone for 1.2 met and 0.8 clo (summer condition)

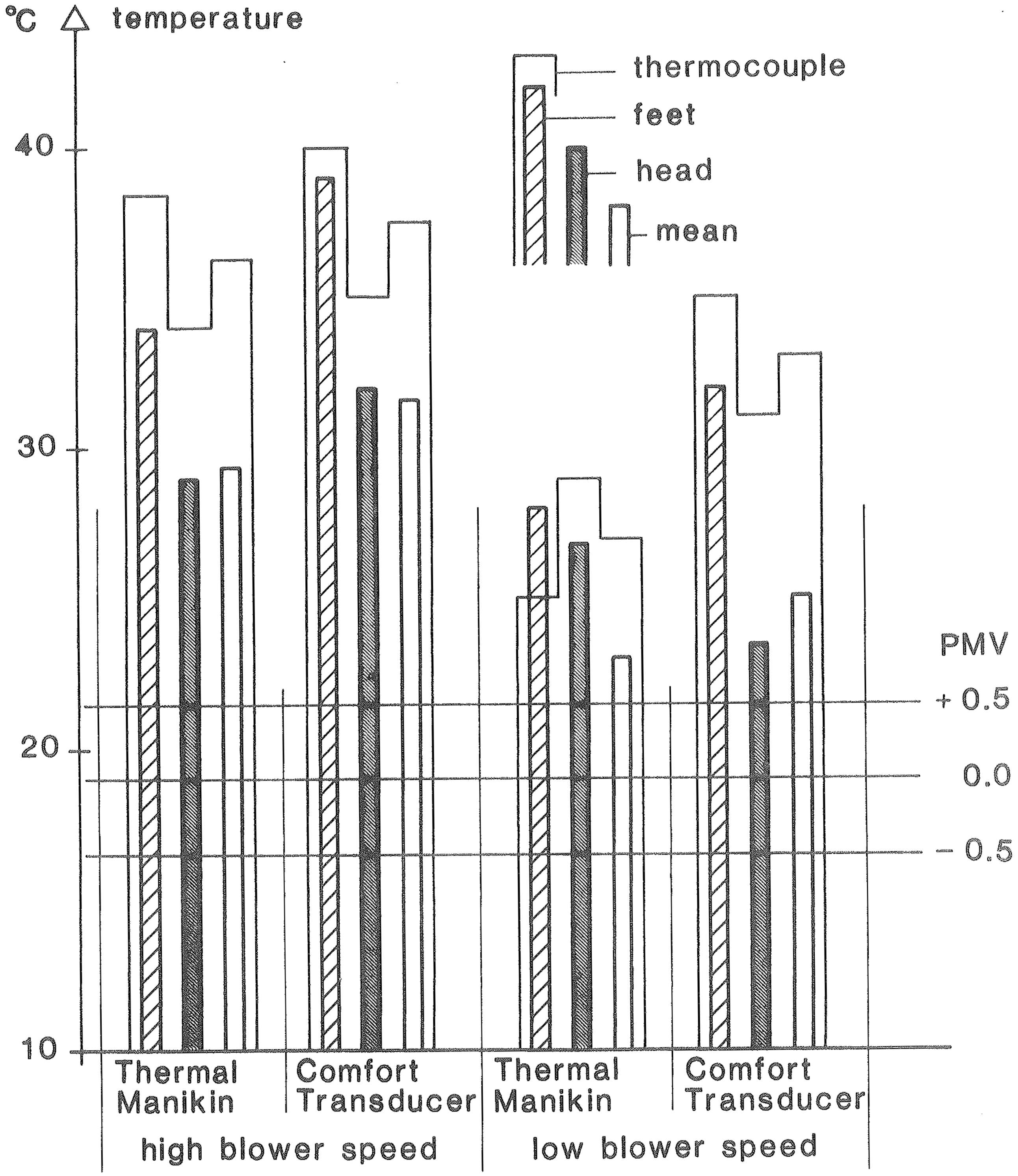


Figure 5. Steady state after warm-up. Comparison between temperature at feet and head level, as well as mean temperature using the three different measuring methods for high and low fan speed

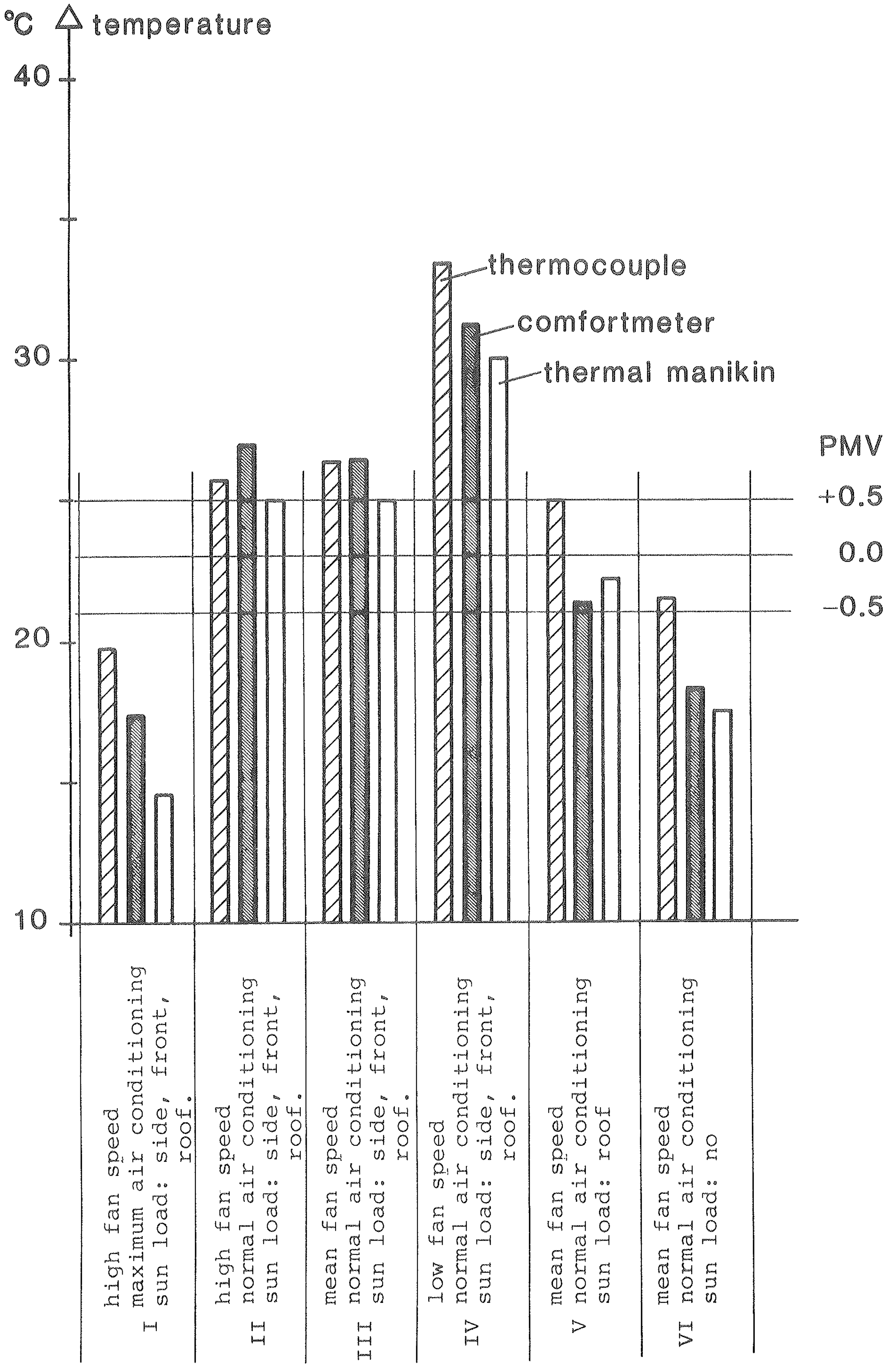


Figure 6. Steady state after cool-down. Comparison between mean temperature measured with the three different methods in six different combinations of air conditioning effect, fan speed and solar gain

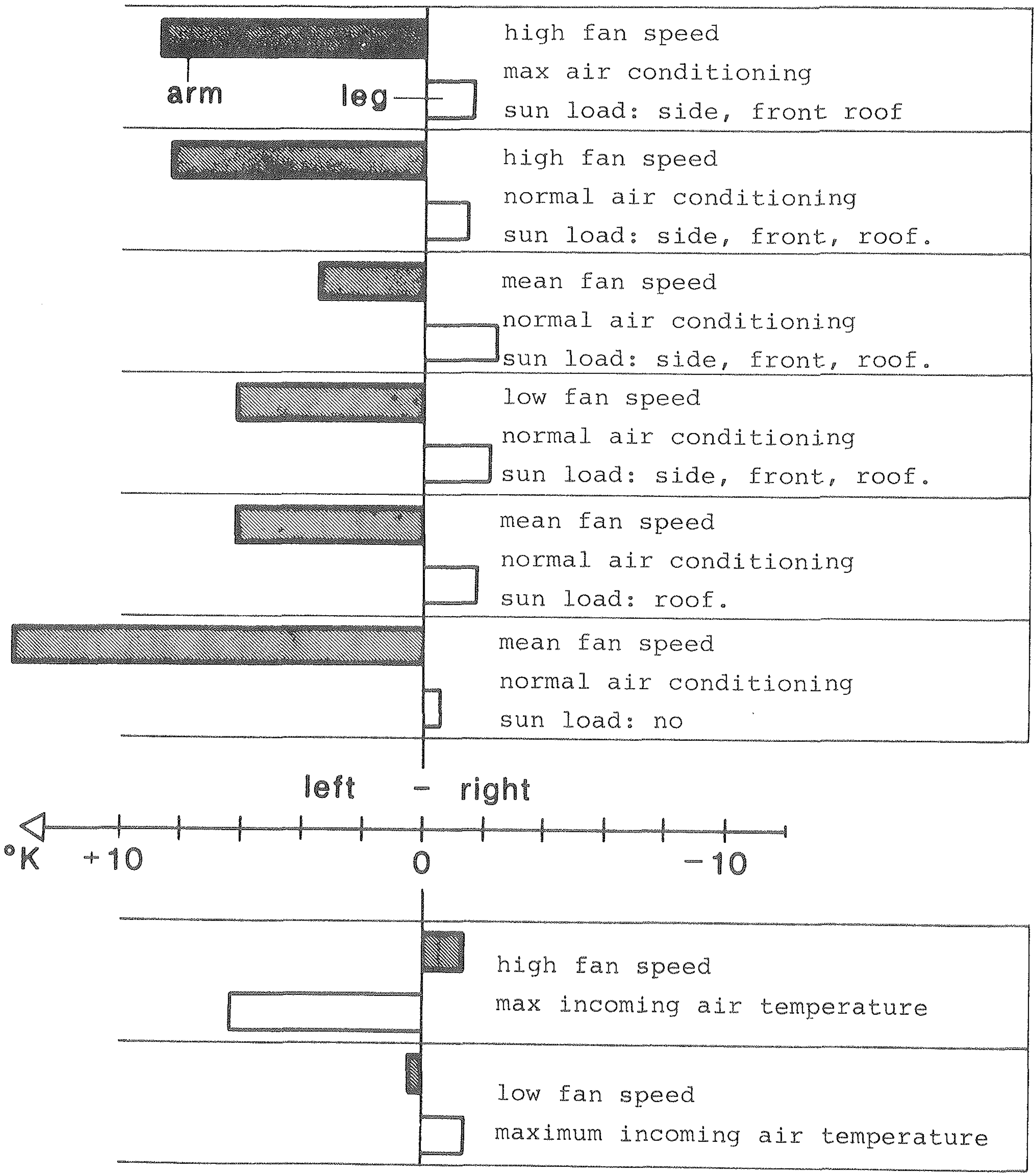


Figure 7. Difference between the equivalent temperatures measured with the thermal manikin's left and right leg and left and right arm. + indicates that the left side is warmer than the right side. At the top the six steady-state conditions after cool-down are shown. At the bottom the two steady-state conditions after warm-up are shown