No. 2451

THERMAL COMFORT REQUIREMENTS FOR FLOORS OCCUPIED BY PEOPLE WITH BARE FEET

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INTRODUCTION

The purpose of this paper is to establish thermal comfort limits for the temperature of floors occupied by people with bare feet

A knowledge of these limits is important when choosing flooring materials and in the dimensioning of heated floors in bathrooms, swimming baths, gymnasiums, dressing rooms, bedrooms, etc.

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. It is a necessary condition for thermal comfort that the body as a whole is in thermal neutrality, i.e., that the person cannot say whether he would like a higher or a lower ambient temperature. The conditions for thermal neutrality have been established independent of the environmental parameters in several earlier works (Ref. 7,11,14,8). However, thermal neutrality for the body as a whole is insufficient in itself to ensure thermal comfort. It is a further condition that the thermal influence on the body is not so nonuniform that it gives rise to local discomfort.

Warm or cold discomfort of the feet can occur, for example, due to extremes of heat conduction to the floor. The present paper deals with the question of which surface temperatures floors of different materials should have in order to avoid discomfort for people with bare feet.

Until now very few investigations have been made with barefooted persons. Schüle (Ref. 15) performed an experiment with three persons, and Munro and Chrenko (Ref. 10) performed experiments with two persons. As the number of subjects was so small, it was impossible to determine floor temperature limits which, with reasonable certainty, would satisfy most people. The present paper deals with a series of experiments with 16 persons, the aim being to determine thermal comfort requirements for two characteristic flooring materials (concrete and wood). Moreover, a method is recommended for the characterization of flooring materials and for the determination of comfort requirements for other floors than those investigated. Finally, investigations are made by supplementary experiments of the influence on the comfort requirements of length of occupancy, activity, clothing, and of the general thermal state of the body.

EXPERIMENTS

This section deals with the main experiments (FOOT I), where the influence of the flooring material on the desired floor temperature was determined. The experiments were performed in a climate chamber at the Laboratory of Heating and Air Conditioning at the Technical University of Denmark (Ref. 7).

Sixteen volunteer students took part (8 men and 8 women) who were paid for their participation. The anthropometric data for these persons is given in Table 1. Each person took part in

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two experiments of 4 to 5-hr duration, with a lapse of at most 14 days between the experiments. All persons were in normal good health. In all the experiments the subjects were clothed in the KSU standard uniform (0.6 clo) consisting of undershorts, cotton socks, cotton trousers and cotton shirt (Ref. 11). Before approaching the floor, the socks were removed. The subjects remained in a standing position on the floor for 10 min; while between the part-experiments (when the floor temperature was altered) they were sedentary. The skin temperature was measured at 4 points on the foot, and the heat flow from the ball of the foot to the floor was likewise registered. During all the experiments the air temperature was equal to the mean radiant temperature, the relative air velocity was <0.1 m/s, and the relative air humidity was = 50%.

The air temperature was altered during the course of the experiment according to the wishes of the subjects. As two persons took part simultaneously, the temperature was changed so that these persons on an average were in general thermal neutrality.

Two different test floors were used, one of concrete and one of wood (oak parquet) with a lacquered surface. These materials were chosen partly because they are much used in practice as flooring materials, and partly because they vary from a thermal point of view. Regulation of the floor temperature was made by means of a water-filled plate on which the test floors were placed. The test floors measured 0.5 x 0.6 m and the influence on the mean radiant temperature was negligible.

The subjects evaluated their general thermal state and their foot comfort on a 7-point scale (Fig. 1).

In the course of an experiment day (4-5 hr) the subject was exposed from 4 to 6 different floor temperatures in randomized order. These temperatures were altered so that the person voted within the range -2.0 to +2.0.

For each experiment the following procedure was followed. The two subjects arrived at the climate chamber within a 10 min interval. A check was made to ensure that they met the conditions of participation (a normal night's sleep, no consumption of alcohol during the previous 24 hours, no fever). The subject put on the standard uniform (0.6 clo) and his height was measured. He was then shown into the chamber which was adjusted to the expected comfort temperature calculated on the basis of Fanger's comfort equation (Ref. 7). The subject seated himself and the experimental procedure and the voting scale were explained to him. The next subject entered the chamber approximately 10 min later. During the first half-hour, both subjects were asked individually every 5-10 min about their general thermal state. On the basis of this information, the leader of the experiment tried to regulate the ambient temperature so that the two persons on an average were in thermal neutrality. When the first person had been in the chamber for 30-40 min and the floor had the desired temperature, the socks were removed and the subject stood on the floor.

Before and after each part-experiment the person gave an evaluation of his general state of comfort. While standing on the floor, the subject voted only on foot comfort, as often as he wished, but always after 1,5 and 10 min. During the 10 min the subject could lean against a high table and possibly read at the same time. At the end of 10 min the subject again put on the socks and seated himself. When both subjects had completed the part-experiment, the floor temperature was changed. After a period of 15 to 30 min, depending on the size of the alteration and on the flooring materials, the chamber was ready for a new part-experiment. Each person was tested at 5-6 floor temperature. In the following experiment the subjects repeated the procedure but with the other flooring material.

RESULTS

In the analysis, only measurements after 1 and 10-min occupancy of the floor will be used. The first minute represents the immediate contact, and the tenth minute a state where the rate of change in the physiological parameters was very slow and the person approached a stationary condition.

The analysis of skin temperature and heat flow measurements did not give results which in practice are significant for the determination of thermal comfort limits for the floor temperature. These measurements will not be treated in the present paper; more detailed information can be found in the original thesis (Ref. 13).

Table 2 shows the result of a comparison of the voting after occupancy periods of 1 and 10 min. The comparison is divided into cold (<0) and warm (≥0) votes. For neither type of floor was the difference significant for votings after 1 and 10-min occupancy of cool floors (VOT<0), whereas the voting for warm floors (VOT≥0) was significantly higher after 10-min occupancy. In the following, a division will be made into occupancy periods of 1 and 10 min.

The connection between voting and floor temperature is found by means of a linear regression analysis. A variance analysis showed that this connection was significantly different ($P<0.05$) from person to person, whereas no difference was apparent between males and females. This connection between voting and floor temperature was significantly different ($P<0.05$) for the two flooring materials.

Table 3 shows the result of the linear regression analysis for all 16 persons together. The connection found can be experessed as follows:

Concrete floor

$$1 \text{ min:} \quad VOTE = 0.234\ (t_f - 28.3) \qquad (1)$$
$$10 \text{ min:} \quad VOTE = 0.339\ (t_f - 27.2) \qquad (2)$$

Wooden floor

$$1 \text{ min:} \quad VOTE = 0.112\ (t_f - 26.6) \qquad (3)$$
$$10 \text{ min:} \quad VOTE = 0.154\ (t_f - 25.5) \qquad (4)$$

t_f = floor temperature

The sensitivity (the regression coefficient), which is defined as the change in the foot comfort vote resulting from a 1 deg C change in the floor temperature, will be seen to be approximately twice as much for a concrete floor as for a wooden one.

The optimal floor temperature (see Table 3), i.e., that temperature which produces a foot comfort vote of 0, is different for the two floors. The optimal temperatures for concrete floors (28.3 deg C and 27.3 deg C) are 1.7 deg C higher than for wooden floors (26.6 deg C and 25.5 deg C).

The standard deviation of the estimated voting (s_y, Table 3) which is included in the calculation of the number of dissatisfied persons, is not significantly different for the two types of floor. However, the standard deviation for 1 and 10-min occupancy does differ significantly ($P<0.05$). In calculating the %-dissatisfied, the values 0.645 and 0.951 for s_y are used after respectively 1 and 10-min occupancy.

Fig. 2 and 3 show the connection between floor temperature and the number of dissatisfied, which is reckoned as the percentage of a group of people which, for a particular floor temperature, will vote outside the comfort interval, defined as votings between -1.5 and +1.5. The same figures show the accuracy with which the percentage is determined, as the 95% confidence interval has been calculated. In other words, the probablity that the number of dissatisfied persons will lie outside the interval between the broken curves is less than 5%. It will also be seen that there is no floor temperature at which all persons are satisfied. The smallest number of dissatisfied persons which can be expected is 2% for 1-min occupancy and 11% for 10-min occupancy.

If the floor temperature deviates from the optimal, the increase in the number of dissatisfied persons per degree of deviation will be seen to be greater for concrete floors. For example, after 1 min a deviation of 2 deg C on a concrete floor will increase the number of dissatisfied persons by 4%, whereas the same temperature deviation on a wooden floor increases the number by only 1%.

The influence of the flooring material first becomes apparent with large deviation from the optimal floor temperature. At a floor temperature of 20 deg C there will be 84% dissatisfied after 10-min occupancy of a concrete floor, while on a wooden floor there will be only 25% after the same period. A concrete floor of 24 deg C will cause just as many dissatisfied (approximately 35%) as will a wooden floor of 18 deg C after 10-min occupancy.

The Influence of Other Factors on the Thermal comfort Requirements for Floors

The above-mentioned results are based on experiments where persons standing with bare feet, clothed at 0.6 clo, in general thermal neutrality, occupy for 10 min a concrete floor and a wooden floor. The average ambient temperature in the main experiments (FOOT I) was 24.2 deg C.

In order to investigate the influence of factors such as activity, clothing, the general thermal state and time of occupancy, a further two series of experiments were performed (FOOT II and FOOT III) with 8 and 4 persons respectively. These series are described in more detail in an appendix; only the main results will be mentioned here and compared with the series of experiments described in the previous section (FOOT I).

The two <u>activities</u>, sitting and standing, will dominate in places occupied by people with bare feet. These activities will often be interrupted by walking, but only for shorter periods (less than 1 min). The influence of activity is therefore investigated only for seated and standing persons. In the investigation FOOT III (appendix), a comparison was made of the voting for standing and seated persons with bare feet. It appeared that standing persons voted warmer for the same floor temperature, but the difference between the two activities was significant only in two cases. The difference lay between 0.2 and 0.5 voting units. According to the connection found between floor temperature and foot voting, this corresponds to a floor temperature difference of approximately 1 deg C.

The influence of <u>clothing</u> on the preferred floor temperature was investigated in FOOT III (appendix). The subjects were tested in two sets of clothing: shorts (0.1 clo) and a light cotton shirt and long cotton trousers (0.6 clo). In order to maintain general thermal neutrality, it was necessary to raise the ambient temperature by 2.6 deg C for the light clothing (0.1 clo). The feet, which were bare, were thus surrounded by warmer air, which could be considered to exert an influence on the preferred floor temperature. However, the results from FOOT III showed that the clothing had no significant influence on the preferred floor temperature.

In the same series of experiments the footwear was varied, the persons in some experiments being provided with cotton socks. This change of footwear had no significant influence on the foot comfort voting.

The <u>length of occupancy</u> in the main experiment (FOOT I) was 1 and 10 min, and the voting for foot comfort altered significantly only with regard to warm floors (VOT≥0). Thus, the optimal floor temperature after 10 min occupancy was 1.1 deg C lower than after 1-min occupancy. This applied to both flooring materials. Moreover, an increase in the voting uncertainty became apparent after 10-min occupancy, so that optimally it was not possible to achieve less than 11% dissatisfied in relation to the 2% which could be achieved for 1-min occupancy. The investigation FOOT III (appendix), where the occupancy time was 30 min, showed that for cool floors the voting became significantly higher with time. The greatest rise occurred from 1 to 10-min occupancy (0.5 voting units). For warm floors (VOT>0) there was no significant change.

<u>The thermal state of the feet prior to contact with the floor</u> was almost unchanged from one experiment to another in the main investigations (FOOT I), the persons being in general thermal neutrality between experiments. The variation of the temperature of the ball of the foot before each experiment was for the individual person less than 3 deg C. In order to ascertain the influence of the temperature of the ball of the foot prior to contact with the floor on foot comfort during occupancy of the floor, it was necessary to investigate a wider foot temperature zone for each individual person. This was done in FOOT III (appendix). Two floors were used; a mosaic floor where the temperature was kept constant at 28 deg C and a concrete floor (the same as in FOOT I) where the temperature could be varied from one experiment to another. After 30-min occupancy of the concrete floor the subject shifted to a mosaic floor with a constant temperature. By varying the concrete floor temperature (22 deg C, 25 deg C and 31 deg C), the temperature of the ball of the foot was changed prior to each contact with the mosaic floor. The individual variation in the temperature of the ball of the foot averaged 10.1 deg C. The influence of this variation was found by means of a factor analysis (appendix).

When shifting from a concrete floor of 25 deg C and 31 deg C respectively to a mosaic floor of 28 deg C, the foot comfort voting differed significantly ($P<0.001$) after 1 and 10-min occupancy of the latter. A change from the cool floor (concrete, 25 deg C) to the mosaic floor (28 deg C) gave rise to a higher (warmer) voting than a change from the warm floor (concrete, 31 deg C) to the mosaic floor (28 deg C). After 1 min the difference was 1.3 voting units and after 10 min 0.9 voting units. After 30 min there was no difference at all.

<u>The influence of the general thermal state on the preferred floor temperature</u> was investigated in FOOT II (appendix). The experiments were performed with persons clothed in shorts and seated with their feet on a steel sheet, the temperature of which could be altered.

Each person took part in three experiments at different ambient temperatures, neutral environment and 2 deg C over and under respectively. The 2 deg C change in the ambient temperature causes, according to Fanger (Ref. 7), a change in the PMV-value (the voting for the general thermal sensation) of 1 unit.

It appeared that the preferred floor temperature was independent of the person's general thermal state.

Thermal Characterization of Floors

In the German Federal Republic a norm has been established, DIN 52614, (Ref. 3,5,17), for the thermal characterization of flooring materials. According to this norm, the heat loss (kJ/m^2) is measured from an artificial foot to the floor. This artificial foot consists of a water-filled cylinder (15 cm in diameter) with a rubber membrane at the base. The heat loss is determined for 1 and 10-min contact. The standard conditions are an artificial foot at 33 deg C and the floor at 18 deg C. If the floor temperature is other than 18 deg C, the heat loss is converted according to the following expression, which can be applied in the floor temperature zone 10-25 deg C.

$$W = W_1 \frac{15}{33 - t_f} \quad kJ/m^2 \tag{5}$$

where
W_1 = measured heat loss at the floor temperature t_f
W = calculated heat loss at the floor temperature 18 deg C

The two flooring materials which were used in the main experiments (FOOT I) were characterized according to DIN 52614 and the following values were measured:

Concrete: 1 min: 50 kJ/m^2 , 10 min: 293 kJ/m^2
Wood : 1 min: 38 kJ/m^2 , 10 min: 134 kJ/m^2

Relationship Between the Thermal Characterization of the Flooring Material and the Thermal Comfort Requirements for the Floor Temperature

From the investigation in FOOT I, the optimal floor temperature is known for the two floors (concrete and wood) and after 1 and 10-min occupancy for standing persons.

By means of the characterization according to DIN 52614 and the conversion formula, Eq 5, the heat loss at the optimal temperature for the two floors can be found. For both floors, 16 kJ/m^2 was obtained. It is assumed that for any floor the optimal temperature after 1-min occupancy is that which gives a heat loss of 16 kJ/m^2 after characterization according to DIN 52614 and conversion according to the formula (Ref. 5). Thus the optimal floor temperature is determined according to the following expression:

$$t_{opt} = 33 - \frac{16}{W} \times 15 \text{ deg C} \tag{6}$$

where
W = the heat loss (kJ/m^2) after 1 min determined by means of DIN 52614. This connection is shown in Fig. 4.

If a similar reasoning is applied for the temperature limit of the interval where less than 10% are expected to be dissatisfied after 1-min occupancy, the heat loss found is not quite the same for the two floors. Table 4 shows for the two floors, the optimal floor temperature and the 10% interval as well as the calculated heat loss according to the above-mentioned procedure.

A mean value is used for the 10% interval, and the two limit curves can be determined according to the following expression:

$$t_{min} = 33 - \frac{28}{W} \times 15 \text{ deg C} \tag{7}$$

$$t_{max} = 33 - \frac{3.5}{W} \times 15 \text{ deg C} \tag{8}$$

where
t_{min} = the lower limit for the 10% interval (deg C)
t_{max} = the upper limit for the 10% interval (deg C)
W = the heat loss (kJ/m^2) after 1 min determined according to DIN 52614

The curves are indicated in Fig. 4

For 10-min occupancy the conversion formula ,Eq 5, cannot be regarded as valid, as it is based on the case where two semi-infinite bodies with different temperatures are brought into contact (ref. 9). This can presumably apply to the human foot shortly after contact with the floor. After longer contact a heat regulation of the foot will take place and alter the blood supply and thus the inner foot temperature.

If the optimal floor temperature for 1 and 10-min occupancy is compared, it is 1.1 deg C lower after 10-min occupancy for both the flooring materials investigated in FOOT I. This is assumed to be valid for all homogeneous floors. Testing a cork sheet according to DIN 52614 gave the following heat loss: 1 min 33 kJ/m^2 and 10 min 109 kJ/m^2. The optimal temperature for 1-min occupancy, determined according to Fig. 4, is 26 deg C and thus after 10 min, 24.9 deg C. By testing a marble floor (Ref. 16) the values were found to be 75 kJ/m^2 and 511 kJ/m^2, and the corresponding optimal floor temperatures according to the same reasoning as above, were 29.7 deg C and 28.6 deg C.

By means of the optimal floor temperatures found in the experiments after 10-min occupancy of concrete and wooden floors and the optimal temperatures determined above for cork and marble, the curve in Fig. 5 can be drawn. According to the experimental results, 11% dissatisfied can be expected at the optimal floor temperature.

For the two types of floor investigated, concrete and wood, an interval can be determined from Fig. 3 where less than 15% of persons can be expected to be dissatisfied after 10-min occupancy. This interval is given in Table 4. Its width for a concrete floor and a wooden one respectively, is 2.4 deg C and 5.4 deg C. This interval width will depend on the heat loss measured after 10 min (DIN 52614). The relationship between the heat loss from a concrete floor (W_c = 293 kJ/m^2) and that from a wooden floor (W_w = 134 kJ/m^2) is 0.46. In comparison, the opposite relationship between the interval width is 2.4 deg C/5.4 deg C = 0.44. Thus, it can with good approximation be assumed that for any flooring material the relationship between the measured heat loss by characterization (W_1/W_2) is equal to the opposite relationship between the corresponding interval width (I_2/I_1) for a 15% interval. In this way it is possible to calculate the shown interval limits in Fig. 5, depending on the thermal characterization for 10-min occupancy.

DISCUSSION

The floor temperatures found in FOOT I are based on experiments with standing persons with bare feet, clothed at 0.6 clo. The persons were in general thermal neutrality and the thermal state of the foot prior to contact with the floor was neutral. It is apparent from the series of experiments performed (FOOT I) with 16 persons that it is not possible to find a floor temperature where all persons are satisfied. Neither is it possible to achieve less than 2% dissatisfied for short periods of occupancy (1 min) nor less than 11% dissatisfied for longer periods (10 min). These values can be attained when the temperature of the floor is optimal, i.e., that temperature which causes a group of persons occupying the floor on an average to evaluate foot comfort as neutral (voting = 0). If the floor temperature deviates from the optimal, the increase in the number of dissatisfied persons will depend on the flooring material (Fig. 2 and 3). For floors with a small contact coefficient (e.g., cork, wood) the increase in the number of dissatisfied persons will be moderate compared to floors with a large contact coefficient (e.g., concrete, stone).

In the experiments with bare feet in FOOT I the optimal floor temperature was determined for only two flooring materials (wood and concrete). As the optimal temperature is dependent on the flooring material, it is necessary to find the connection between a characteristic factor for the flooring material and the optimal floor temperature.

As already menteioned, in the German Federal Republic an artificial foot is used to characterize the floor. The trial method is given in the norm DIN 52614. The same method is also used in building research institutes in Scandinavia. The testing can be done partly on existing floors and partly in laboratories.

In sandwich constructions the deeper lying materials will also influence measurements with the artificial foot.

Viewing the results from the two floors investigated, it will be seen that the requirements for 10-min occupancy are more stringent than those for 1-min occupancy. For example, Table 4 shows that the floor temperature interval where less than 15% can be expected to be dissatisfied after 10-min occupancy lies within the floor temperature interval where less than 10% dissatisfied can be expected after 1-min occupancy. For longer periods of occupancy (30 min) the change in the voting for foot comfort was, as mentioned earlier, insignificant.

On the basis of the above observations, and as an occupancy time of approximately 10 min is most usual in rooms occupied by persons with bare feet, it is recommended that the thermal comfort requirements for floors be based on the results for 10-min occupancy. It is also recommended that a floor temperature interval corresponding to 15% dissatisfied be used, this being an increase of approximately 1/3 in relation to the optimal (11%).

According to FOOT III, sedentary persons desired a lower floor temperature (approximately 1 deg C) than standing persons. This difference is so small, however, that it does not warrant special limits for sedentary persons. Moreover, people will be mainly standing in rooms which they occupy with bare feet. For those walking, the occupancy time will be shorter and the requirements thus less stringent than for standing persons. It is therefore recommended that the results for standing persons be used.

As mentioned, the investigations FOOT II and FOOT III (appendix) showed that changing a person's general thermal state by altering the ambient temperature and the amount of clothing has no influence on the preferred floor temperature. This result is not in agreement with earlier studies (Ref. 1,2) on the connection between a change in the general thermal state and the desired temperature for the extremities (hands). According to Cabanac, people desired a higher hand temperature at lower mean skin temperature.

In the present series of experiments (FOOT II) the mean skin temperature for cool-, neutral- and warm environments was 32.4°C, 32.9°C and 33.9°C respectively. Moreover, the heat transfer coefficient between the ball of the foot and the floor is much greater than between the air and the foot, so that a change in the floor temperature will have a relatively important influence on foot comfort.

In practice, the thermal state of the feet prior to contact with a floor is unknown. It is therefore reasonable that the determination of the optimal floor temperature is made on the basis of a thermally comfortable state, which was the case in the main investigation (FOOT I).

CONCLUSION

It is recommended that the thermal properties of a floor be characterized according to DIN 52614, where the heat loss during 1 and 10 min from an artificial foot to the floor is determined. For floors occupied by sedentary, standing or walking persons for less than 30 min it is recommended that a floor temperature be used which lies within the inverval where less than 15% dissatisfied can be expected. This interval is determined from experiments with standing persons after 10-min occupancy. It is dependent on the thermal properties of the floor, and can be obtained from Fig. 5.

Table 5 gives the recommended floor temperatures for a number of typical floor constructions.

The recommended temperatures should be used for persons with bare feet or those wearing light socks.

There is no difference for men or women. Clothing and the general thermal state of the person have no influence on the preferred floor temperature.

APPENDIX

EXPERIMENT FOOT II

An investigation of the influence of the general thermal state on the preferred floor temperature for persons with bare feet was performed with 8 sedentary, male subjects wearing shorts (0.1 clo).

Three temperature levels of the ambient air were investigated. In the first experiment the persons were in general thermal neutrality, the temperature being adjusted according to their wishes. In the following two experiments the ambient temperature was respectively 2 deg C under and over the comfort temperature found in the first experiment. According to Fanger (Ref. 7) the 2 deg C corresponds to a change in the PMV-value of ±1.

The floor was a grey iron plate, 0.3 m^2, the surface temperature of which could be regulated. In addition to the measurements mentioned in FOOT I, the skin temperatures were measured in 14 places (Ref. 12).

In the first experiment with a neutral climate, the subject was asked every 5 min whether he wished the air temperature altered and he was also requested to characterize the surroundings according to the scale in Fig. 6. In the other two experiments the air temperature was not changed, and the general comfort was given according to the scale in Fig. 6. The order of these experiments was randomized.

In each experiment the subject was asked every 5 min whether he preferred the floor to be warmer or cooler and then to give an evaluation of the floor according to the same scale (Fig. 6).

In each experiment the floor temperature was first found where the subject desired no change. It was then changed by step (approximately 2 deg C) up/down, until the upper/lower limit for a comfortable floor temperature was found. The limit was considered to be found when the subject twice in succession for the same temperature had voted "uncomfortable". The floor temperature was then changed stepwise (approximately 2 deg C) over the comfortable zone, until the lower/upper limit was found. Before the experiment was concluded, the floor temperature was changed stepwise until the subject desired no change. In this way the comfort zone was passed from warmer to cooler and the reverse. The order was randomized.

Depending on the size of the interval which the subject found comfortable, the experiment was concluded after 2-3 hr. These limits were found for the three different thermal environments on three different experiment days.

Results

The optimal floor temperature is defined as the mean value of four limits, upper and lower by heating and cooling. In Table 6 this temperature is shown together with the ambient temperature and the mean skin temperature. The influence of the ambient temperature is tested by means of a t-test of the difference between the individual preferred floor temperature at the three different ambient temperatures. Table 7 shows that the ambient temperature (the general thermal state) had no significant influence on the preferred floor temperature.

EXPERIMENT FOOT III

An investigation was made of the influence on the preferred floor temperature of activity, clothing, length of occupancy and the thermal state of the foot prior to contact with the floor, with 4 persons (2 men and 2 women). The thermal measurements were the same as in FOOT II.

Two flooring materials were used. One floor consisted of a concrete slab placed on a water-filled plate, the temperature of which could be regulated. The other floor was a thin sheet of mosaic stone placed on top of electric heating foil. The test floors measured 0.3 m^2.

Two sets of clothing were investigated: shorts or bikini (0.1 clo) and the KSU-standard uniform, 0.6 clo (Ref. 11), consisting of undershorts, cotton shirt, long cotton trousers and cotton socks. Both sets were used with and without socks. Furthermore, both sedentary and standing persons were investigated. The period of occupancy was 30 min at each floor temperature. The investigations were designed as a factorial experiment (Ref. 6). The temperatures used for the concrete floor, 25 and 31 deg C, were chosen so that they lay either side of the expected optimal floor temperature (28 deg C) according to FOOT I. Each person participated in four factor combinations, and all the experiments were repeated, the order of the first floor temperature on the concrete floor (25 or 31 deg C) being randomized.

The experiments on the mosaic floor had the same factor combination, with the exception of the floor temperature, which was constant at 28 deg C. Instead of this factor, the thermal state of the foot prior to contact with the floor was altered, the persons having occupied a concrete floor of 25 and 31 deg C respectively.

Finally, the experiments with seated persons were supplemented with a floor temperature of 22 deg C. These experiments are not included in the factor analysis, however.

At the commencement of an experiment the subject either sat or stood, depending on which activity was to be investigated, with his feet on the mosaic floor which had a temperature of 28 deg C. Every half-hour the person changed floors, until all floor temperatures had been tested, and the experiment always concluded with a 30-min occupancy of the mosaic floor. Fig. 7 shows the course of an experiment day. In the experiments with standing persons they were seated for 10 min during occupancy of the mosaic floor. One min and 5 min after every shift and every 5 min thereafter, the person voted on foot comfort according to the scale shown in Fig. 6, and every 10 min the air temperature was changed according to the wishes of the person. The experimental time was $2\frac{1}{2}$ hr for standing and $3\frac{1}{2}$ hr for seated persons. Each person completed eight experiment days.

Results

The effects found from the factor analysis of the foot comfort voting are shown in Table 8. It will be seen from this table that the clothing and footwear exerted no influence on the preferred floor temperature. The activity has an influence on approximately 0.2 voting units, as standing persons felt the floor to be warmer than did seated persons. The thermal state of the foot prior to contact with the floor does exert an influence, but this is insignificant after 30 min occupancy.

Table 9 shows the average change in the foot comfort voting from 1 to 10 and 30-min occupancy of the concrete floor. The investigation is divided into occupancy of warm (pos.vot.) and cool (neg. vot.) floors, the sign for the change not necessarily being identical for these cases. It will thus be seen that only for cool floors, was the change of the voting significant in time.

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Table 1. Anthropometric Data for the Subjects

	Age years	Height cm	Weight kg	DuBois area m^2
8 females	21.4 ±0.8+)	168 ± 3	60.4 ±3.3	1.68 ±0.05
8 males	22.5 ±0.9	181 ± 3	69.2 ±1.3	1.89 ±0.03
16 subjects	21.9 ±0.6	175 ± 3	64.8 ±2.0	1.78 ±0.04

+) standard deviation of the sample.

Table 2. Comparison of foot comfort votes after standing 1 and 10 min. on a floor. T-test.

Flooring material	Cold/warm floors	Mean diff. 10 min. - 1 min.	Test quantity t-value/df	Sign. level
Wood	cold , VOT<0	-0.2	1.01/27	
	warm , VOT≥0	0.4	3.25/57	<0.01
Concrete	cold , VOT<0	0.0	0.24/30	
	warm , VOT≥0	0.5	3.58/51	<0.001

Table 3 The result of a linear regression analysis between foot comfort vote and floor temperature

		Concrete floor		Wooden floor	
		Occupancy		Occupancy	
		1 min	10 min	1 min	10 min
Number of experiments		82	82	86	86
Constant (â)	max	-6.49	-9.03	-2.84	-3.71
	mean	-6.63	-9.22	-2.98	-3.92
	min	-6.77	-9.42	-3.12	-4.14
Coefficient (b̂)	max	0.267	0.386	0.131	0.184
	mean	0.234	0.339	0.112	0.154
	min	0.202	0.292	0.092	0.125
St. dev. of calculated vote, s_y		0.624	0.896	0.665	1.002
St. dev. of coefficient		0.016	0.024	0.010	0.015
Multiple correlation coeff. (R)		0.848	0.850	0.781	0.754
Variation due to regression $(100 \cdot R^2)$		72%	72%	61%	57%
Optimal floor temperature ^oC		28.3	27.2	26.6	25.5

Calculated vote is estimated as VOTE = $\hat{a} + \hat{b} \cdot tg$

Max, min. is the 95%-confidence interval for a random subject.

Table 4 The calculated heat loss after characterization of the floor with an artificial foot according to DIN 52614. Optimal floor temperature and temperature limits for 10% dissatisfied for 1 min. and 15% for 10 min. occupancy.

Floor		1 min. Heat Loss kJ/m^2	1 min. Floor Temp. 10% interval ^oC.	10 min. Floor Temp. 15% interval ^oC.
CONCRETE	upper limit	6	31.2	28.4
	optimal	16	28.3	27.2
	lower limit	25	25.5	26.0
WOOD	upper limit	1	32.6	28.2
	optimal	16	26.6	25.5
	lower limit	31	20.6	22.8

Table 5 Comfortable floor temperatures for typical floor constructions.

Floor construction (The underlayer is concrete)		Heat loss estimated according to DIN 52614 1 min kJ/m^2	10 min kJ/m^2	Optimal floor temperature 1 min °C	10 min °C	Recommended floor temp. interval - less than 15% dissatisfied °C
Wooden floor used in the experiment		38	134	26.5	25.5	23 - 28
Concrete floor used in the experiment		50	293	28.5	27	26 - 28.5
Textile layer	1)	17	75	19	24	20 - 28
Wilson-carpet	2)	20	91	21	24.5	21 - 28
Sisal-carpet	2)	24	123	23	25	22.5 - 28
Needled felt sheet	2)	21	111	22	25	22 - 28
5 mm cork	3)	26	145	24	26	23 - 28
Pinewood floor	4)	29	124	25	25	22.5 - 28
Oakwood floor	4)	36	182	26	26	24.5 - 28
Vinyl-asbestos tile	2)	80	485	30	28.5	27.5 - 29
PVC-sheet with felt underlay	2)	49	242	28	27	25.5 - 28
PVC-sheet (2 mm)	2)	60	365	29	27.5	26.5 - 28.5
5 mm tesselated floor on gas concrete	3)	60	301	29	27	26 - 28.5
5 mm tessalated floor on 20 mm cork	3)	63	211	29	26.5	25 - 28
2.5 mm hard linoleum on wood	3)	46	176	28	26	24 - 28
2.5 mm hard linoleum on concrete	3)	45	296	28	27	26 - 28.5
Painted concrete floor	2)	77	487	30	28.5	27.5 - 29
Marble	3)	75	511	30	29	28 - 29.5
Concrete slab finished with steel trowel	3)	63	475	29	28.5	27.5 - 29
Concrete slab finished with wooden float	3)	60	419	29	28	27 - 29

1) Schüle and Monroe (17) 2) Wäänänen and Veijalainen (18)
3) Cammerer (4) 4) Cammerer (3)

Table 6 Mean values of environmental temp., optimal floor temp. and mean skin temp. for 8 subjects

Environment	Environmental temp. °C	Optimal floor temp. °C	Mean skin temp. °C
Cool	24.8	33.1 ±1.22+	32.4 ±0.34
Neutral	26.8 ±0.70	31.8 ±0.76	32.9 ±0.34
Warm	28.8	32.6 ±1.09	33.9 ±0.24

+Stand. dev. of the sample.

Table 7 The influence of the ambient temperature on the preferred mean skin and floor temperatures. Mean differences for 8 subjects. T-test. (FOOT II)

	Floor Temperature			Mean Skin Temperature		
	Difference °C	t-value	sign. level	Difference °C	t-value	sign. level
Cool-neutral	1.3 ±0.75^{+}	1.73	>0.1	−0.54 ±0.14	3.96	<0.001
Cool-warm	0.5 ±0.73	0.69	>0.5	−1.50 ±0.20	7.67	<0.001
Neutral-warm	−0.8 ±0.89	0.89	>0.2	−0.96 ±0.15	6.21	<0.001

Table 8 Factor analysis on the foot comfort vote (FOOT III)

	Floor	Time min	Level	Activity SED/STA	Cloth-ing 0.1/0.6	Foot-wear BARE/SOCK	Floor temp.[1)] 25°C/ 31°C	Least sign. effect (<0.05)
Foot comfort vote	CONCRETE	1	−0.5$^{+)}$	0.1	−0.1	−0.1	1.2$^{+)}$	0.23
		10	−0.2	0.2	0.0	−0.1	1.0$^{+)}$	0.24
		30	0.1	0.2	0.1	0.1	0.9$^{+)}$	0.23
	MOSAIC	1	−0.1	0.3$^{+)}$	−0.1	−0.2	0.6$^{+)}$	0.17
		10	0.0	0.2$^{+)}$	−0.1$^{+)}$	−0.1	0.4$^{+)}$	0.13
		30	0.0	0.1	−0.1	−0.1	0.1	0.18

1) For the mosaic pavement the "floor temp." means that the subjects move from the concrete floor of either 25°C or 31°C to the mosaic pavement of 28°C.

+) Significant at the 5% level.

Table 9 The influence of time of occupancy on the foot comfort vote during contact with the concrete floor. (FOOT III)

	Time	Number of experimts.	Change of vote	Signif. level
Cool floors neg.vote	1 → 10 min	26	0.5	<0.001
	1 → 30 min	26	0.8	<0.001
	10 → 30 min	26	0.3	<0.01
Warm floors pos.vote	1 → 10 min	14	0.1	
	1 → 30 min	14	0.1	
	10 → 30 min	14	0.1	

+ 3 Much too warm
+ 2 Too warm
+ 1 Comfortably warm
0 Neutral
− 1 Comfortably cool
− 2 Too cool
− 3 Much too cool

Fig. 1 Voting scale

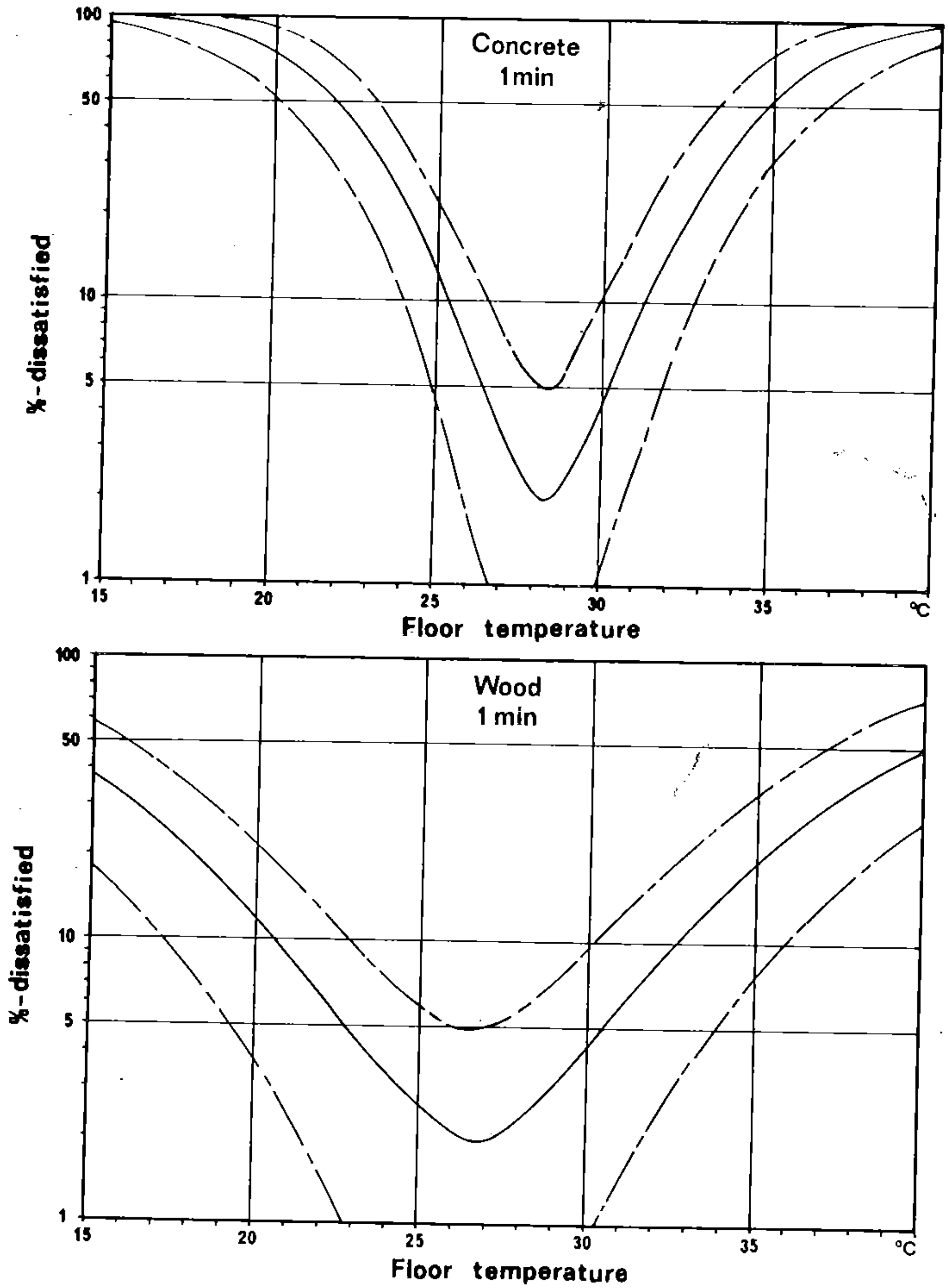
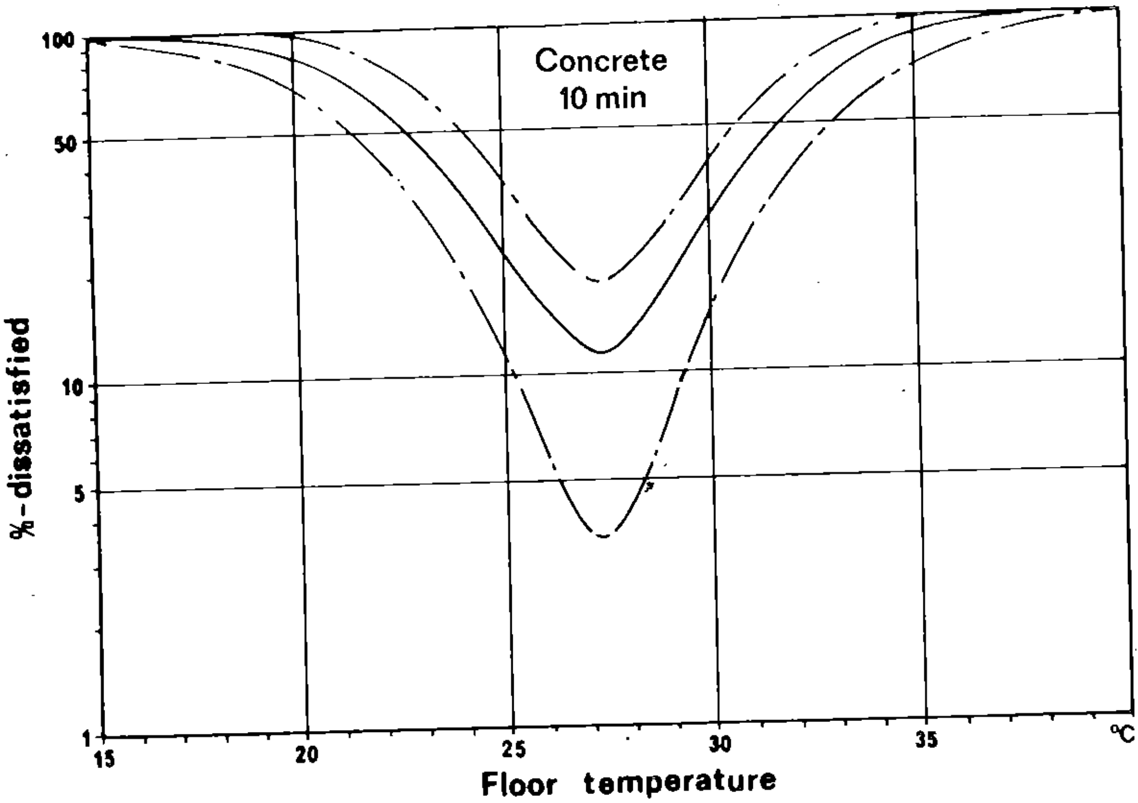


Fig. 2 The connection between floor temperature and the expected percentage of dissatisfied people. The broken lines indicate the 95%-confidence interval. Standing subjects with bare feet, after 1-min exposure



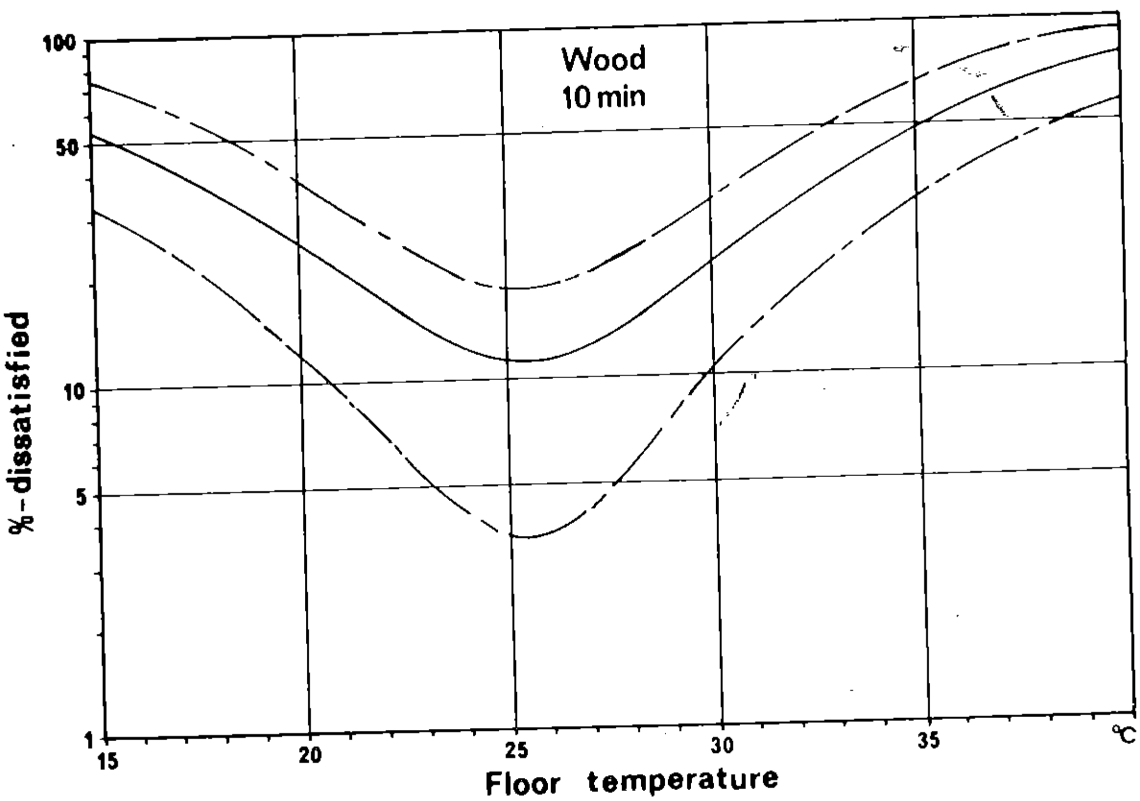


Fig. 3 The connection between floor temperature and the expected percentage of dissatisfied people. The broken lines indicate the 95%-confidence interval. Standing subjects with bare feet, after 10-min exposure

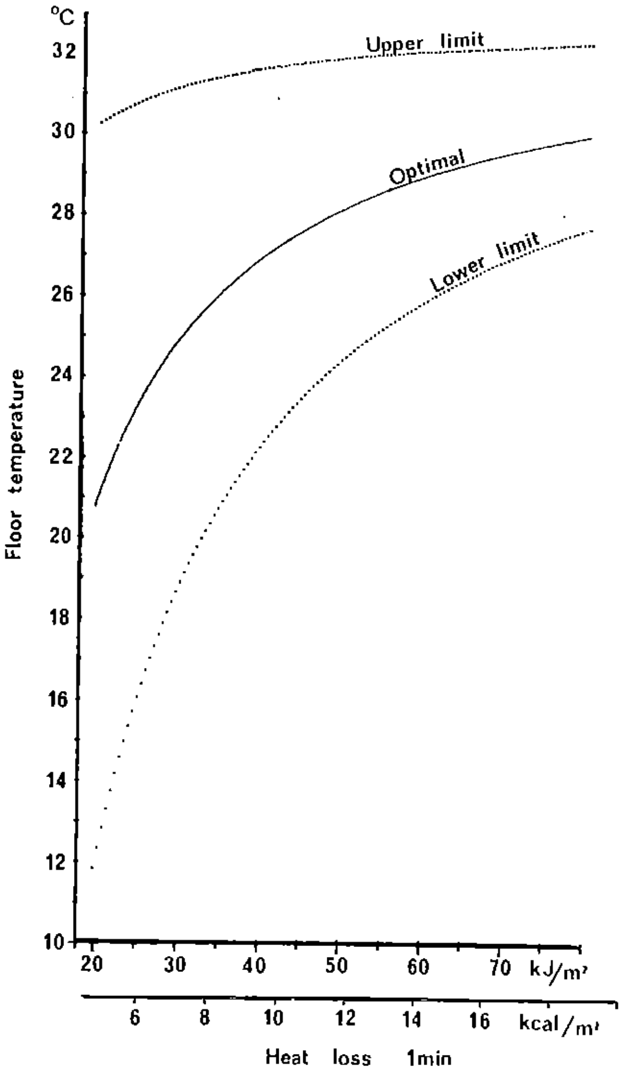


Fig. 4 Connection between measured heat loss from an artificial foot according to DIN 52614 and the optimal floor temperature (2% dissatisfied), together with the limits for the interval within which less than 10% are expected to be dissatisfied. Standing subjects with bare feet, 1-min, occupancy

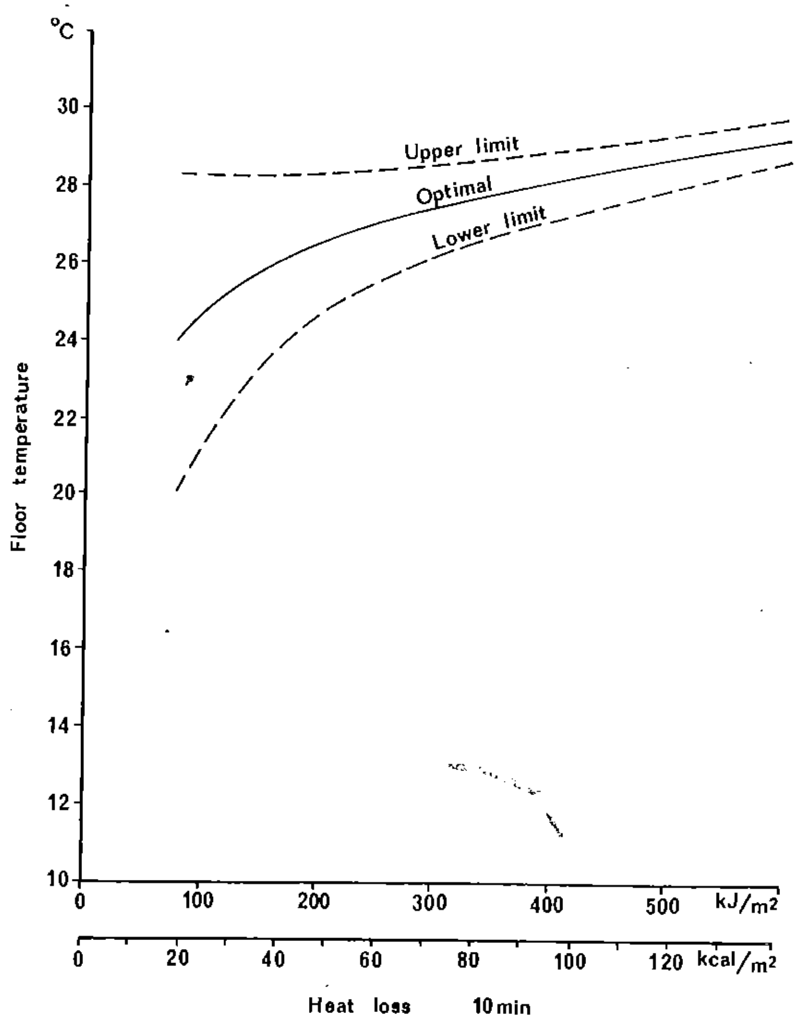


Fig. 5 Connection between measured heat loss from an artificial foot according to DIN 52614 and the optimal floor temperature (11% dissatisfied), together with the limits for the interval within which less than 15% are expected to be dissatisfied. Standing subjects with bare feet, 10-min occupancy.

+ 3	Much too warm
+ 2	Uncomfortably warm
+ 1	Comfortably warm
0	Neutral
− 1	Comfortably cool
− 2	Uncomfortably cool
− 3	Much too cool

Fig. 6 Voting scale (FOOT II, FOOT III).

Time min	Floor material	Floor temp.	
			Start
0 10 20 30	MOSAIC	$28^{o}C$	sedentary during standing experiments
			subject changes floor
0 10 20 30	CONCRETE	$25^{o}C$	
			subject changes floor
0 10 20 30	MOSAIC	$28^{o}C$	sedentary during standing experiments
			subject changes floor
0 10 20 30	CONCRETE	$31^{o}C$	
			subject changes floor
0 10 20 30	MOSAIC	$28^{o}C$	sedentary during standing experiments
			end standing experiments sedentary subjects changes floor
0 10 20 30	CONCRETE	$22^{o}C$	
			subject changes floor
0 10 20 30	MOSAIC	$28^{o}C$	
			end

Fig. 7 Experimental procedure (FOOT III)