Thermal comfort during continuous and intermittent work

Bodil Nielsen, I. Oddershede, A. Torp, and P. O. Fanger.

August Krogh Institute, Copenhagen University, and Laboratory of Heating and Air Conditioning, Technical University of Denmark.

Abstract

5 women and 5 men each participated in six 2½ hour comfort experiments at six constant activity levels: lying, sitting, and continuous bicycle exercise requiring 2, 3, 4 and 6 times BMR. During each experiment the ambient temperature was adjusted to keep the subject thermally comfortable. The 5 men then each participated in four experiments where the same average metabolic rates (2× BMR and 6×BMR) were established by intermittent work (5 min work/5 min rest, and 5 min work/10 min rest). The ambient temperature was constant at the level felt comfortable during continuous work. Thermal sensation votes were collected.

To maintain comfort the subjects preferred a lower skin temperature and an increased sweat secretion the higher the activity level. Results agree reasonably well with Fanger's comfort criteria up to an activity of 250 W/m^2. Continuous and intermittent work provide the same average thermal sensation.

The comfort equation (1, 2) describing the conditions for thermal comfort has proved to be a useful tool in practice for the design of indoor climates.

By the derivation of the comfort equation Fanger identified the skin temperature and the sweat secretion as physiological parameters closely related to the sensation of comfort. For people feeling thermally comfortable he found regression equations expressing both the skin temperature and the sweat secretion as a function of the activity level. These regression equations were found in experiments with subjects at activities up to 180 W/m^2 (internal heat production). Activities higher than sedentary were established by intermittent work: 5 min constant work followed by rest periods of 5, 10 or 25 min repeated during a 3 hour experimental period (1, 3). The purpose of the present study is a) to study comfort conditions at higher activities than 180 W/m^2 and, b) to compare comfort conditions during continuous and intermittent work.

Experimental method

Ten subjects (5 females and 5 males) participated in the main experiments. Three male subjects were later included in the study, participating in the continuous work experiments at high activities. The subjects were fit students of physical education. All subjects were volunteers who were paid for participating in the experiments. Anthropometric data for the subjects are listed in Table 1.

Table 1.

Anthropometric Data for the Subjects.

		Age	Height	Weight	DuBois Area	Max Oxygen Consumption
		Years	cm	kg	m^2	l/min
Females	mean	22.2	168	59.4	1.67	2.87
n = 5	SD[+)]	2	6	6.2	0.11	0.31
Males	mean	24.8	182	74.8	1.95	4.38
n = 8	SD[+)]	2	7	9.8	0.16	0.70

[+)] Standard Deviation of the sample

The experiments took place in the first environmental chamber (2) of the Laboratory of Heating and Air Conditioning, Technical University of Denmark. In the chamber the air velocity was approx. 0.1 m/s, the mean radiant temperature was kept equal to the air temperature and the relative humidity was 50%.

Each subject participated in six 2½ hour experiments corresponding to six activities: resting on a bed, sitting in a chair, and continuous bicycle exercise requiring approximately 2, 3, 4 and 6 times the basal metabolic rate. The subjects wore shorts or a bikini. The bed was of canvas without a mattress. The chair had a seat and a back of plastic strips. Exercise took place on a Krogh ergometer (60 rev/min).

During each experiment the same procedure was applied as in several earlier comfort studies (4, 5, 6). A check was made before beginning the test to ensure that the subject had had sufficient sleep and normal meals, that there was no fever, and that alcohol had not been consumed during the previous 24 hrs. At the start of each experiment the air temperature and the mean radiant temperature were set at a value at which it was estimated that the subject would feel thermally neutral during the actual activity.

Since it was very important that the environment was optimally comfortable for the subject, the ambient temperature was adjusted to his wishes. This was done by asking the subject every 10 min throughout the experiment whether he would prefer the environment to be warmer, cooler, or the same, and then altering the ambient temperature accordingly. The subject was asked to request even very small changes in order to avoid the chamber temperature being kept constant at the limit of that found comfortable by the subject. The ambient temperature in the chamber could be changed quite rapidly (for small temperature changes the time constant was approximately 2 min).

The skin temperature of each subject was measured by means of 14 thermistors taped to the skin by surgical tape. The 14 termistors were distributed evenly over the body surface as reported by Olesen et al.

(4). The rectal temperature was measured by a flexible thermistor rectal probe. All temperatures were registered every 5 min by means of a data-recording system outside the chamber. The weight loss was registered by weighing the subject every 30 min on a balance (SD $\pm$ 2 g). The pause in the exercise necessary for weighing had a duration of 1-2 min. The total weight loss per unit of time was for each experiment determined by means of a linear regression analysis of the 5 weighings, with a half-hour interval, during the last 2 hours of the exposure. The evaporative weight loss was then found by subtracting the difference between CO_2 loss and O_2 gain.

After 100 and 130 min the rate of oxygen consumption was determined by the Douglas bag method. The air volume was measured by a Collin's spirometer and air samples measured on a paramagnetic O_2-analyser (Servomex) and a Beckman infrared CO_2-analyser. The metabolic rate, M (W), was calculated as $M = 341 \times \dot{V}_{O_2}$ where $\dot{V}_{O_2}$ (l/min) is the rate of oxygen uptake. The rate of heat production in the body was calculated as the metabolic rate minus the rate of external work.

During the experiment consumption of water was allowed and measured. All experiments took place in the morning.

Intermittent work

Five male subjects participated furthermore in four 1½ hour experiments with intermittent exercise. In one experiment the subject alternately exercised for 5 min and rested for 5 min sitting on the bicycle ergometer. In another experiment the subject alternately exercised for 5 min and rested for 10 min. In both experiments the average metabolic rate during a cycle was maintained at approximately 2 × BMR.

In two other similar experiments the workload was increased to maintain an average metabolic rate of approximately 6 × BMR.

During each experiment the ambient temperature was kept constant at a value felt neutral by the particular subject during continuous exercise at the same average metabolic rate. Strictly speaking, the chamber was maintained at a slightly lower ambient temperature, the temperature decrement being calculated to compensate for the decreased relative mean air velocity during intermittent work (0.24 m/s during 5 min work/10 min rest and 0.32 m/s during 5 min work/5 min rest, compared to 0.67 m/s at continuous work (7).

The subject indicated his thermal sensation on the usual seven point psycho-physical scale: +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold.

During a work/rest cycle of 10 (15) min the subject voted at 2, 4, 6, 8 (9), (12), (14) min after the beginning of each cycle.

At the same time rectal and skin temperature were registered. During the penultimate work/rest cycle all the expired air was sampled separately from the work and rest period to determine the metabolic rate. The rest of the procedure was the same as in the experiments with continuous exercise.

Results

During continuous work the skin temperatures found comfortable (neutral) by the subjects are plotted in Fig. 1 as a function of the heat production in the body. The skin temperature indicated is the average during the last two hours of each experiment. It is obvious that the skin temperature found comfortable decreases with increasing activity, as established earlier by Fanger (2), up to activities around 180 W/m^2; his regression line, is shown for comparison. At high activities (above 250 W/m^2) the mean skin temperature found neutral seems to level off and no values below approximately 28 ^oC were observed.

Fig. 2 shows the corresponding relation between evaporative heat loss and internal heat production. The subjects prefer to have a certain sweat secretion at moderate and high activities as demonstrated earlier by Fanger (2), and his regression line is shown for comparison. During intermittent work the mean value of the skin temperature and the evaporative

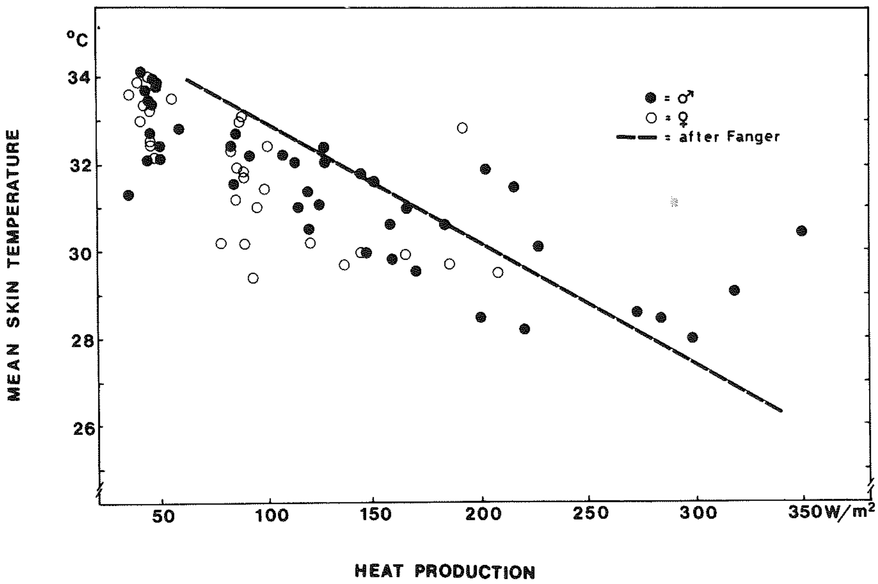


Fig. 1: Mean skin temperature as a function of heat production in the body for subjects feeling thermally neutral during continuous work.

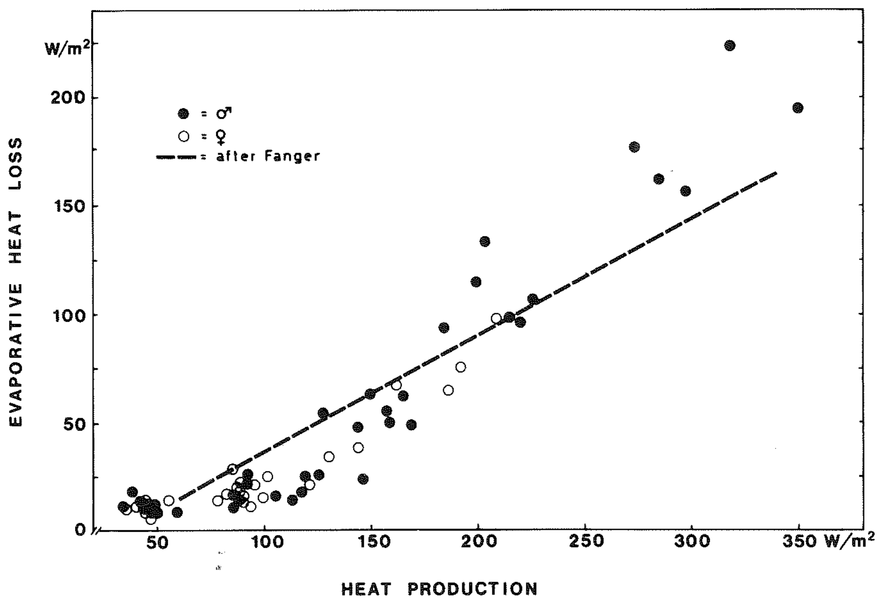


Fig. 2: Evaporative heat loss as a function of heat production in the body for subjects feeling thermally neutral during continuous work.

heat loss during the 1½ hour exposure was found to agree well with the data in Figs. 1 and 2 for continuous work. The rectal temperature increased with increasing activity. When rectal temperature for subjects feeling thermally neutral is plotted against rate of heat production the scatter is great, due to differences in "relative workload" for the different subjects. It increased in average approximately 0.006 K per W/m^2 heat production above BMR.

The mean thermal sensation votes for the intermittent experiments are shown on Fig. 3. Both at the

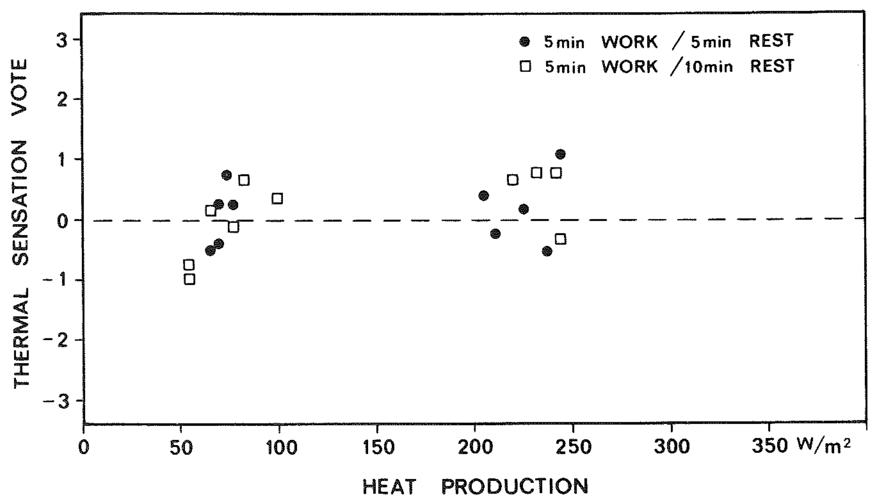


Fig. 3: Mean thermal sensation of male subjects during intermittent work at ambient temperatures felt thermally neutral during continuous work at the same average heat production in the body.

moderate and high activity the mean thermal sensation vote for all the subjects was close to neutral. But the skin temperature and the thermal sensation varied during the work/rest cycle (Fig. 4). The amplitude of the skin temperature was greatest about 2 K at the highest activity and during the 5 min work/10 min rest cycle. The skin temperature was highest during rest and lowest in the work period. The thermal sensation vote increased during the work period while the skin temperature decreased.

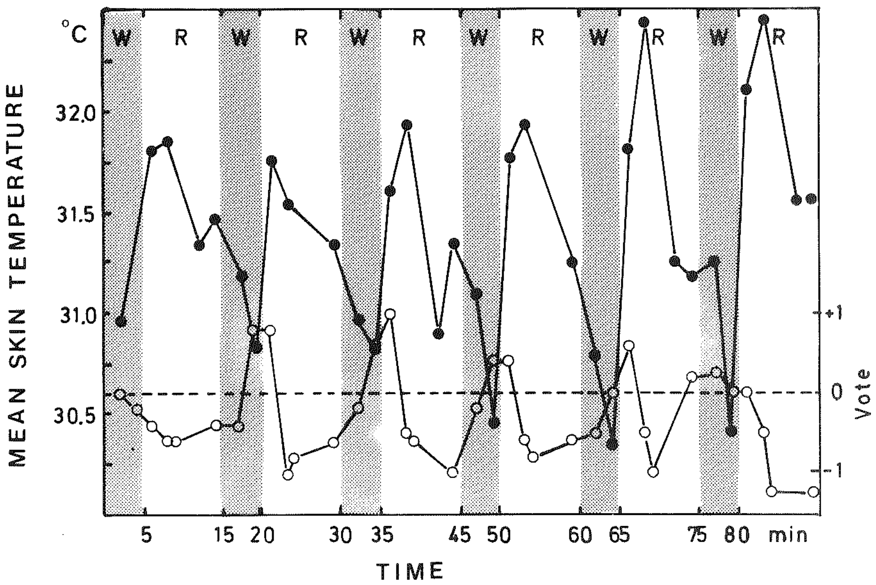


Fig. 4: Mean skin temperature and thermal sensation vote during intermittent work (5 min work/ 10 min rest) at high activity (6 × BMR).

Discussion

Based on studies with normal college-age subjects who worked intermittently at activities up to approximately 180 W/m^2, Fanger (1, 2) derived the comfort equation. From this equation combinations of the environmental parameters can be predicted that will provide thermal neutrality at a given activity and clothing.

The subjects in the present study were fit physical education students who were able to work continuously for 2½ hours at high activities (up to 6 ×BMR). At activities below 250 W/m^2 the results agree reasonably well with the regression line found in earlier experiments. The mean skin temperature felt comfortable decreased with increasing activity (Fig. 1). At high activities there may exist some limit for the skin temperature, around 28°C, below which the skin is felt too cool (Fig. 1). Studies by Gagge et al. (8) gave similar results. Our subjects seemed to prefer an environment that increased their sweat rate rather than decreased their skin temperature at high activities (heat production above 250 W/m^2).

A curve through the points from our experiments seems to be less steep than that of Fanger (Fig. 1). In his earlier study (1, 2) with intermittent work the subjects were dressed in a 0.6 clo standard uniform, while our subjects only wore shorts. Although the average rate of evaporative heat loss was similar in the present and in the earlier study (Fig. 2), the sweat secretion in the intermittent work periods has been 2 or 3 times higher. The tactile sensation of the wet clothing and the increased skin wettedness due to the resistance to evaporation in the clothing may have caused the subjects in the earlier study to prefer a colder skin and thus a smaller rate of sweating at the higher activity levels.

It may be concluded from the present study that the comfort equation tends to predict too cool environments at high activities. It is recommended that the equation be applied with caution at activities above 250 W/m^2.

There was good agreement between the mean values of the physiological parameters obtained during intermittent work and the corresponding values during continuous work at the same average heat production in the body. The mean thermal sensation votes for the subjects were close to neutral during the intermittent work at an ambient temperature that was felt neutral during continuous work (Fig. 3). This indicates that the comfort equation, originally based on intermittent work experiments, is also applicable for continuous work.

Acknowledgement

The authors wish to thank the Copenhagen General Housing Corporation (KAB) for the financial support given to the present study.

References

1. Fanger, P.O., "Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation", ASHRAE TRANSACTIONS, Vol. 73, part 2, 1967, pp. III.4.1-III.4.20.
2. Fanger, P.O., "Thermal Comfort", Danish Technical Press, Copenhagen, 1970. Republished by McGraw-Hill Book Company, New York, 1973, 244 p.
3. McNall, P.E., Jr., Jaax, J., Rohles, F.H., Nevins R.G., and Springer, W., "Thermal Comfort (Thermally Neutral) conditions for Three Levels of Activity", ASHRAE TRANSACTIONS, Vol. 73, part 1, 1967.
4. Olesen, S., Bassing, J.J., and Fanger, P.O., "Physiological Comfort Conditions at Sixteen Combinations of Activity, Clothing, Air Velocity and Ambient Temperature", ASHRAE TRANSACTIONS, Vol. 78, part 2, 1972, pp. 199-206.
5. Fanger, P.O., and Langkilde, G., "Interindividual Differences in Ambient Temperatures Preferred by Seated Persons", ASHRAE TRANSACTIONS, Vol. 81, part 2, 1975, pp. 140-147.
6. McIntyre, D.A., "Determination of Individual Preferred Temperatures", ASHRAE TRANSACTIONS, Vol. 81, part 2, 1975, pp. 131-139.
7. Nishi, Y., and Gagge, A.P., "Direct Evaluation of Convective Heat Transfer Coefficient by Naphthalene Sublimation", Journal of Applied Physkology, Vol. 29, 1970, pp. 830-838.
8. Gagge, A.P., Stolwijk, J.A.J., and Saltin, B., "Comfort and Thermal Sensations and Associated Physiological Responses During Exercise at Various Ambient Temperatures", Environ. Res., Vol. 2, 1969, pp. 209-229.

DISCUSSION

M.Rolloos
Delft University of Technology, NL

From the paper of Dr. Benzinger we learned that sweat rate is not a function of the skin temperature but of the internal temperature, while you write in your paper "a colder skin and <u>thus</u> a smaller rate of sweating". Is that in agreement with Dr. Benzinger?

B. Nielsen

Yes, Dr. Benzinger's statement holds for high skin temperatures (> 33-34°). At lower skin temperature an inhibition of sweating is elicited from skin receptors, also in Dr. Benzinger's experiments.

E.Rødahl
Technical University of Norway

I am very concerned about relating your results to real work.

1. How far can you extrapolate your results?
2. Are 5 min. work and 10 min. rest equal to 15 min. work and 30 min. rest, etc.?
3. Can you transfer your results for naked persons to persons with working clothing?
4. Can you transfer your results with well trained persons to the average working population?

B. Nielsen

1+2. We don't know how far the extrapolation holds. This study expanded the range from Fanger's original 180 W/m^2 to about 300 W/m^2 heat production. We found a tendency to a levelling out at the highest activity levels or a slightly lower slope for continuous exercise. Results from our intermittent exercise (5 min work /5 min rest, and 5 min work/10 min rest) agreed very well with the continuous exercise for the same subjects.
3. We don´t know how clothing and especially the wetness of clothing at high working intensities will affect the comfort conditions.
4. I think the results from the well trained subjects can be used for the average working population, since the results agree reasonably well with Fanger's original equation. But the average person cannot work at the highest intensities for so long as 3 hrs.

P.E.McNall
National Bureau of Standards, USA

1. What correlation exists in this study between evaporation heat loss and rectal temperature with heat production variations?
2. How well does the "Fanger" equation predict the preferred environmental conditions for these subjects?

B. Nielsen

1. Rectal temperature T_{re} increased with increasing heat production (approx. 0.006 K per W/m^2 heat production above BMR). Thus, evaporative heat loss and T_{re} both increase with heat production in the comfort condition. But the correlation between T_{re} and activity is rather bad. Exercise core temperature is better correlated with individual relative work work load (percentage of max. oxygen uptake) than with absolute level of heat production (Saltin and Hermansen, J.Appl. Physiol. 21, 1757, 1966. B. Nielsen, Acta physiol. scand. 68, 215, 1966).

2. Fanger's equation predicts preferred skin temperature much better than preferred environmental temperature for these subjects due to the very different sweating capacities of the subjects at high activities.

M.A.Humphreys
Building Research
Station, UK

Could you tell us please the actual air temperatures that the subjects found to be comfortable at the different metabolic rates?

B. Nielsen

Preferred T_a for these subjects scattered much more than the preferred T_{sk}. The following examples at two activities may illustrate this:

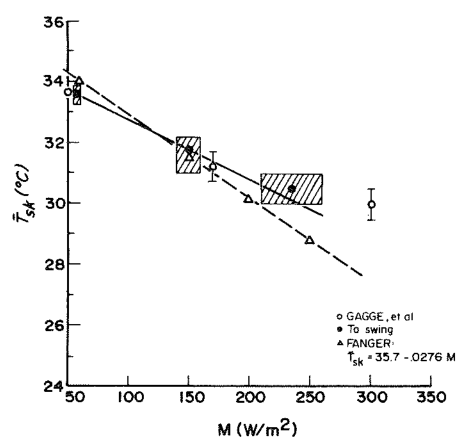
	H W/m^2	T_{sk} ^oC	T_o ^oC
n = 7	152	30.8	19.0
range	(127-184)	(29.8-31.8)	(16.4-22.1)
n = 3	286	28.4	17.9
range	(274-298)	28.0-28.6)	(14.0-21.8)

R.R.Gonzalez
John B.Pierce
Foundation Lab., USA

It is interesting that the authors reached similar conclusions which we also found for continuous exercise during temperature swings. (Gonzalez, R.R., Y.Nishi and A.P.Gagge. Magnitude estimation of thermal comfort during alterations in activity level and ambient temperature. In: Physiological Requirements on the Microclimate in Industry and Problems of their Technical Realization. M.Jokl (ed), Inst. of Hygiene and Epidemiology, Prague, Czechoslovakia, p.p. 62-73, 1975). In the latter study and in the Gagge, Saltin and Stolwijk study, the comfort equation also estimated too cold skin temperatures at exercise levels > 250 Wm^{-2} (see fig.). We found that the multiple regression equation combining operative temperature (T_o) and net metabolic heat flow (M_{sk}) where

$$\bar{T}_{sk} = 0.21(T_o) - 0.006\ (M_{sk}) + 27.5$$

predicted adequately probable $\bar{T}_{sk}$ for comfort during exercise up to 6 mets (350 Wm^{-2}).



B. Nielsen

It is fine that the results support each other. I think we need more experiments at high activity levels, including studies of the effect of clothing during intermittent work of high intensity.