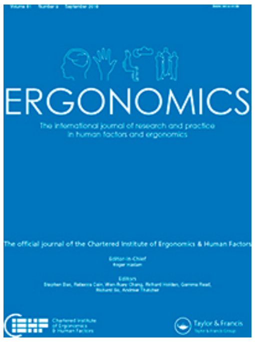

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Thermal sensation of the body as influenced by the thermal microclimate in a face mask

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Keywords: Thermal sensation; Mean body temperature; Face mask climate; Respiratory heat exchange; Brain centres.

Subjective and physiological responses were obtained from six subjects wearing a face mask while exercising (220 W m^{-2}) for 15 min on a bicycle ergometer. Different combinations of ambient air temperatures (7, 16 and 25°C) and mask air temperatures (22, 27 and 33°C) were studied with two different air humidities inside the mask (61 and 86% relative humidity (RH)). Control experiments were performed without the mask at the same ambient temperatures. Skin temperatures, heart rates and skin wettedness were monitored during exercise. The subjects' thermal sensations, sensations of sweating and skin wettedness and their thermal preferences were assessed at the end of the exercise period. Whole body thermal sensation was primarily determined by the ambient air temperature, but was also significantly influenced by the mask air temperature. This could only partly be explained by the change in respiratory heat loss. Other possible avenues of influence are discussed.

1. Introduction

Whole body thermal sensation has been reported to be determined by mean body temperature, and thus body heat content, in both resting (Gagge *et al.* 1967) and exercising (Vokac *et al.* 1971) man. It was proposed that a spatial summation of information from thermal afferents occurs centrally, and that the final integrated signal, reflecting the mean body temperature, determines the whole body thermal sensation (Nielsen and Nielsen 1984). The input from thermal afferents in the core seems most important and determines 80–90% of the resulting thermal sensation. With the core temperature in a steady state, changes in the mean skin temperature are the cause for all changes in whole body thermal sensation.

Some investigators (Vokac *et al.* 1971, Nielsen and Nielsen 1984) have demonstrated that different skin temperature distributions over the body surface do not affect the whole body thermal sensation in situations with equal mean skin temperature. In these studies, the thermal environment around the subject's head did not change. Other studies (e.g. Cabanac and Caputa 1979 b) have indicated that local thermal stimulation of the head may have a larger modifying influence on the whole body thermal sensation than the actual change in the mean skin temperature can explain. Exploratory work in relation to the reduction of heat stress with the use of cooled garments has similarly shown that cooling of the head is more effective than cooling of other body areas in reducing physiological strain (e.g. Nunneley *et al.* 1971).

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Cooling of the head also decreased thermal discomfort (Brown and Williams 1982). Whether a related influence from the thermal environment around the head on whole body thermal sensation exists has not been studied.

The purpose of the present study was to evaluate the significance of the thermal microclimate over the face for the whole body thermal sensation during exercise at different ambient temperatures. Several combinations of air temperature and humidity inside a 'face mask' were used as stimuli.

2. Methods

A plexiglass climate box, 1 m^3 in volume, was constructed for the study to supply separately conditioned air for the mask. The box had its own temperature and humidity control system. A commonly used industrial face mask (Willson Safety Products, Model No. 1200) was modified for the study (figure 1). The outer surface was insulated with neoprene sponge insulation 5 mm thick. The mask was connected by an insulated plastic tube to the climate box. The air inlet in the mask was at the bottom. The two original filters on the sides of the mask were removed, leaving two openings. One of these was completely closed, while the other was left open for an air outlet so the air could pass through the mask without development of increased air pressure in the mask. The air was delivered from the box to the mask at a rate of 21 l min^{-1}. This rate was sufficient to develop a rather uniform environment (spatial variation $< 1°C$) in the mask with only minor fluctuations in air temperature between inspiration and

Figure 1. The modified respiratory protective mask used in the experiments. The direction of the air flow is shown.

expiration. The average temperature of the air in the mask was regulated using a proportional controller. The air humidity in the mask was evaluated by recordings from a resistance-type dew point sensor (Graichen *et al.* 1982) placed inside the mask.

Six healthy subjects who were advised of all aspects of the investigation consented to participate in the study. Prior to the study each subject underwent a graded submaximal exercise test on a cycle ergometer to establish individual relationships between heart rate and measured oxygen consumption. Maximal oxygen consumption ($\dot{V}O_2$ max) was estimated by extrapolation of $\dot{V}O_2$ to the maximal heart rate predicted for that person's age (Åstrand 1960).

The subjects were four men and two women, aged 18–46 years (mean 28 ± 10·9 s.d.). Their physical characteristics were as follows (mean ± standard deviation (s.d.)): height, 174 ± 13·3 cm; weight, 69 ± 9·4 kg; body surface area, 1·83 ± 0·200 m^2; and estimated aerobic capacity, 2·9 ± 0·72 l O_2 min^{-1}. The subjects were familiarized with all the equipment and the testing procedures prior to the sessions involving actual data collection.

Each subject dressed similarly for all experiments. The insulation value of their clothing was evaluated from table values (ASHRAE 1981) and ranged from 0·09 to 0·11 K m^2 W^{-1}. All tests were performed in an environmental chamber (Kjerulf-Jensen *et al.* 1975) under controlled ambient conditions with the radiant temperature equal to the air temperature, T_a. Each subject performed a standardized exercise protocol on a cycle ergometer at three different ambient temperatures: 7°C, 16°C and 25°C. The dew point temperature of the ambient air averaged 2°C, 9°C and 12°C for the three ambient conditions, respectively. The air velocity in the chamber was about 0·05 m s^{-1}. At each ambient air temperature the subjects were exposed to three different mask air temperatures, T_{ma}: 22°C, 27°C and 33°C. At the ambient temperatures of 16°C and 25°C, two different mask air humidity levels were used: a 'dry' condition with an average relative air humidity of 61% (s.d. ± 8·8), and a 'humid' condition with an average relative air humidity of 86% (s.d. ± 7·7). At the 7°C ambient air temperature only 'dry' mask air was tested and the average relative air humidity of this was 58% (s.d. ± 8·1). As a control test, the bicycle exercise was also performed without wearing the mask at all three ambient air temperatures. The relative humidity of the inspired air in these control tests averaged 70% (s.d. ± 5·5), 70% (s.d. ± 12·3) and 46% (s.d. ± 6·7) for an ambient temperature of 7°C, 16°C and 25°C, respectively.

2.1. *Measurements*

Eight thermocouples were taped to representative places on the body surface (Gagge and Nishi 1977). In addition, thermocouples were placed on the skin above the upper lip under the mask, and on the cheek outside the mask.

Dew point sensors were placed under the clothing on the thigh, upper chest and upper arm. Three electrocardiogram (ECG) electrodes were fixed to the chest for continuous monitoring of heart rate during the exercise.

The subjects rated the mask and whole body (environmental) conditions separately, in terms of thermal sensation (Gagge *et al.* 1967) and perception of skin wettedness and sweating, using the rating scales shown in table 1. Each subject also rated thermal preference regarding ambient and mask air temperatures.

2.2. *Protocol*

The air temperature and air humidity inside the mask were coarsely adjusted to the desired levels before each experiment was begun and adjusted finely during the first

Table 1. Rating scales for thermal sensation (A), for thermal preference (B), for sensations of sweating (C) and for skin wettedness (D). Scales A–D were evaluated first for the body/environment, then for the mask area.

How do you feel: (1) in general?	(2) under the mask?
(A) Thermal sensation	(B) Would you prefer
0 Very cold	1 Much cooler
1 Cold	2 Slightly cooler
2 Cool	3 No change
3 Slightly cool	4 Slightly warmer
4 Neutral	5 Much warmer
5 Slightly warm	
6 Warm	
7 Hot	
8 Very hot	
(C) Are you sweating or shivering?	(D) Skin wettedness
1 Not at all	0 Dry
2 Slightly	1 Neutral
3 Moderately	2 Slightly wet
4 Heavily	3 Wet
5 Maximally	4 Very wet
	5 Soaking wet

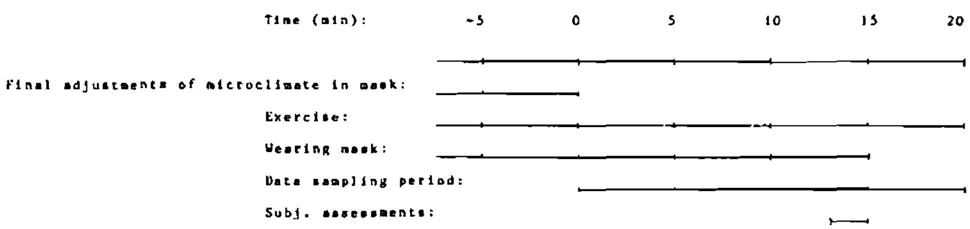

Figure 2. Experimental protocol.

5 min of exercise (figure 2). The subject put on the mask and started exercising. Each subject performed dynamic exercise for approximately 25 min on a cycle ergometer at a work level of 59 W (pedalling frequency 60 rpm). The first 5 min of exercise were considered as the time needed for the subject to reach a quasi steady state. Data collection started after that point. Data on ambient and mask air temperatures, skin temperatures and dew point temperatures of the ambient air, the mask air and the air at the skin surface were collected and stored once every minute on a computer (Radio Shack, TSR-80). The subject continued exercising for 15 min with the mask on. The subjective ratings were collected during the last minute of this period.

2.3. *Calculations*

Data sampled during the eleventh to the fifteenth minute were averaged to obtain a quasi steady-state value for each experimental session.

The heart rates measured during the bicycle work were compared with the individual heart rate/$\dot{V}O_2$-curves established before the experiment to estimate the oxygen consumption during exercise (that is, energy production). Heat production was calculated by subtraction of the energy transformed into external work from the total energy production.

Mean skin temperature, $\bar{T}_{sk}$ was calculated according to the formula of Gagge and Nishi (1977). Vapour pressures at the skin surface, in the mask air and in the ambient air were determined from the dew point temperature recordings.

Local skin wettedness, w, was calculated as:

$$w = (P_{sk} - P_a) \cdot 100/(P_{ssk} - P_a) \quad (\%), \tag{1}$$

where P_{sk} is the water vapour pressure at the skin surface, P_{ssk} is the saturated vapour pressure at the skin surface and P_a is the ambient vapour pressure (Berglund *et al.* 1983). An average skin wettedness under the clothing was estimated using the actual local skin surface area's fraction of the total body surface area:

$$w = 0{\cdot}472 w_{chest} + 0{\cdot}434 w_{leg} + 0{\cdot}094 w_{upper\ arm} \tag{2}$$

Respiratory heat exchange, H_{resp}, was calculated by the following equations from Fanger (1970):

$$H_{resp\ dry} = 0{\cdot}0014 M (34 - T_a) \qquad (\mathrm{W\,m^{-2}}) \tag{3}$$

$$H_{resp\ wet} = 1{\cdot}72 \cdot 10^{-5} M (5867 - P_a) \quad (\mathrm{W\,m^{-2}}) \tag{4}$$

where M is the metabolic rate ($\mathrm{W\,m^{-2}}$).

2.4. *Statistics*

Conventional statistical methods were used to calculate means, their standard deviations (s.d.) and correlation coefficients (r). Linear regressions were computed with a maximal R^2-value.

A two-way analysis of variance (ANOVA) with repeated measures was used to evaluate the effect of ambient temperature and mask air temperature on the physiological and subjective responses. All three ambient temperature conditions were included, but only 'dry' mask air conditions were used. A three-way ANOVA with repeated measures was used to evaluate the effect of the humidity in the mask air on the recorded responses. Ambient and mask temperatures were entered as other causal factors in this ANOVA. Only the tests performed at ambient air temperatures of 16°C and 25°C were included here because 'humid' mask conditions were not tested at an ambient temperature of 7°C. A curve-fitting program (Kolb 1982) for programmable calculators was used to fit the best curve function (with maximal R^2) to paired data of the subjects' thermal preference of either mask or environmental conditions (independent variables) and their thermal sensation (dependent variable). The level of significance was always $p < 0{\cdot}05$.

3. Results

3.1. *Physiological parameters*

Heart rate was influenced by neither ambient air temperature nor mask air temperature. The mean heart rate averaged over the eleventh to the fifteenth minute was $112 \pm 17{\cdot}6$ bpm. The corresponding oxygen consumption was calculated from the previously measured relationship between oxygen consumption and heart rate as $1{\cdot}21\ \mathrm{l\,O_2\,min^{-1}}$ ($220\ \mathrm{W\,m^{-2}}$). This equals 43% (s.d. $\pm 11{\cdot}0$) of the subjects' mean maximal aerobic capacity. Heat production was calculated to be $188\ \mathrm{W\,m^{-2}}$ by

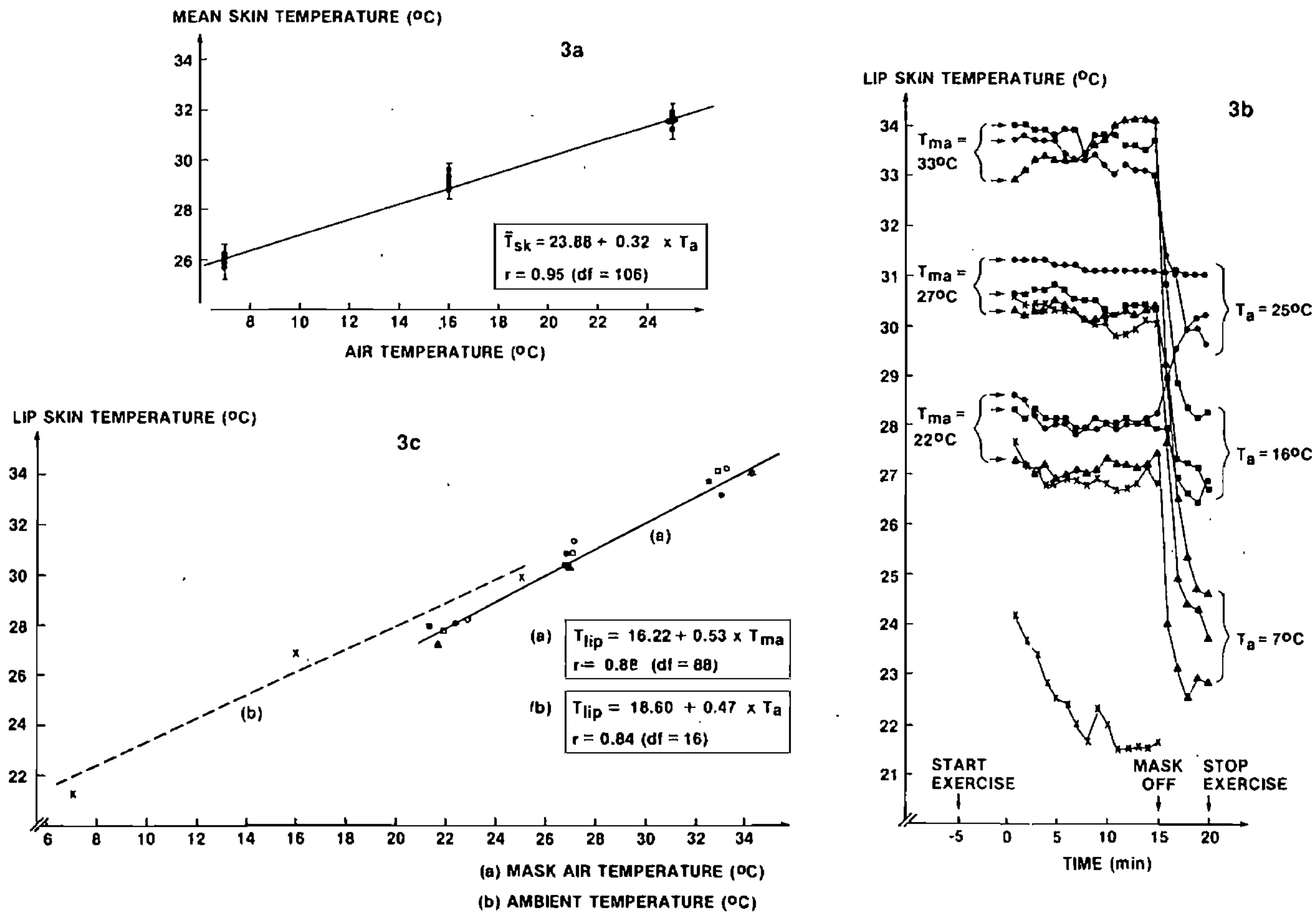

Figure 3. (*a*) Mean skin temperature as a function of ambient air temperature. The mean value ($n = 6$) for each condition is given together with an average standard deviation. (*b*) Average upper lip skin temperature ($n = 6$) measured in each experimental condition as a function of time (symbols used are for sessions without mask (×), and for sessions with mask (▲ = 7°C T_a; ■ = 16°C T_a; ● = 25°C T_a). (*c*) Variation of lip skin temperature ($n = 6$) with mask air temperature (a) and, when no mask was worn with ambient temperature (b). The symbols used are the same as in (*b*). Closed symbols are for session with 'dry' mask air and open symbols for 'humid' mask air sessions.

subtraction of the amount of energy transformed into external work from the total amount of energy produced.

The subjects' mean skin temperature did not in any condition change from the initial value during the experimental period. It seemed to have stabilized at a steady-state value already before the start of the data sampling. Mean skin temperature, as averaged over the eleventh to fifteenth minute of each experiment, was a linear function of the ambient temperature (figure 3(*a*)). This was also the rule for all local skin temperatures ($p < 0{\cdot}05$ for all correlations), except for the skin temperature in the mask area itself. An ANOVA showed that neither mask air temperature nor mask humidity affected the mean skin temperature and the local skin temperatures outside the mask.

Steady-state values of the skin temperature inside the mask (T_{lip}) were obtained after approximately 5 min of data sampling, and they were always less than 1°C away from the initially monitored values (figure 3(*b*)). Without the mask, the skin temperature above the upper lip was, as with the other skin temperatures, a linear function of ambient temperature (figure 3(*c*)). When the mask was worn, the upper lip temperature was correlated with the temperature of the air blown through the mask ($r = 0{\cdot}88$; df $= 52$); a higher mask air temperature resulted in an increased skin temperature above the upper lip. In that case, the ambient temperature had no influence on T_{lip}. The skin temperature above the upper lip was higher when the mask air was 'humid' than when it was 'dry' ($p < 0{\cdot}05$). After removal of the mask in the sixteenth minute, T_{lip} reached a new steady-state value related to the ambient temperature within 3–4 min (figure 3(*b*)).

The skin wettedness under the clothing increased significantly ($p < 0{\cdot}05$) from its initial value during the exercise period in the 'neutral' (16°C) and the 'warm' (25°C) environment. Exercising in the 'cold' (7°C) environment caused only a small increase in average skin wettedness, and the increase was significant only with the warmest mask air. Steady-state values of average skin wettedness as well as of local skin wettedness on the chest, thigh and arm were correlated with both the dew point temperature of the ambient air ($r = 0{\cdot}55$; df $= 106$) and the ambient temperature ($r = 0{\cdot}55$; df $= 106$). Analysis of variance showed that the air and humidity conditions inside the mask had no significant effect on skin wettedness. However, the highest value of average skin wettedness was found in the 25°C environment with the warmest mask, where it had increased to 65% (s.d. $\pm 8{\cdot}6$).

3.2. *Whole body thermal sensation*

Analysis of variance showed that the ratings of whole body thermal sensation were higher ($p < 0{\cdot}05$) the higher the ambient temperature and the higher the mask air temperature (figure 4). The humidity in the mask has no detectable effect on whole body thermal sensation. At the experimental metabolic rate (220 W m^{-2}) and without the mask over the face, the ratings of whole body thermal sensation (TS) were related to the ambient air temperature (T_a) as follows:

$$TS = 1{\cdot}500 + 0{\cdot}171\,T_a \quad (r = 0{\cdot}84;\ \text{df} = 16) \tag{5}$$

During exercise with the mask on, the different thermal microclimates changed the whole body thermal sensation, thus:

$$TS = -0{\cdot}255 + 0{\cdot}160\,T_a + 0{\cdot}078\,T_{ma} \quad (r = 0{\cdot}78;\ \text{df} = 52) \tag{6}$$

This equation shows that even though the mask air temperature influenced the whole

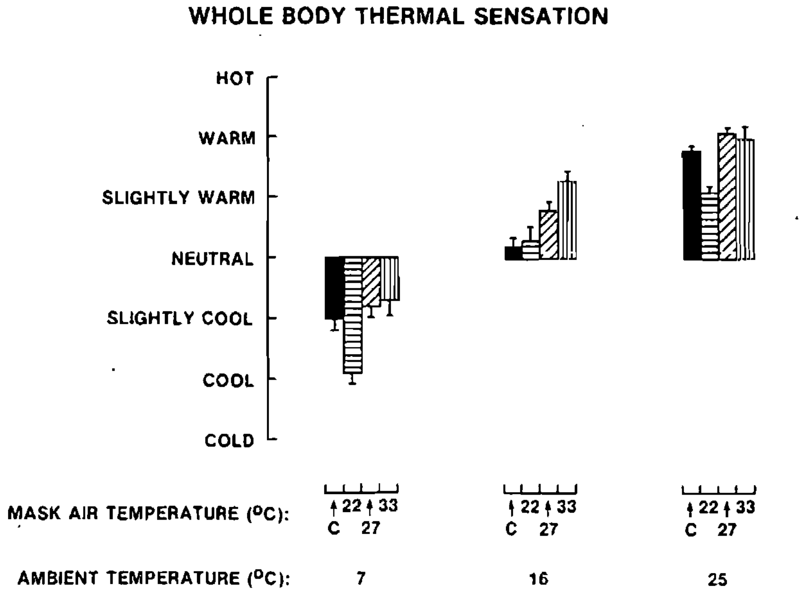

Figure 4. Whole body thermal sensation at the different experimental conditions (mean values ($n = 6$) with standard errors). Only results from 'dry' mask air sessions are shown; C, results from experiment 'without mask'.

body thermal sensation, the ambient temperature was a more important determinant of the thermal sensation.

The ratings of whole body thermal sensation in the sessions with and without a mask were well correlated with the recorded mean skin temperatures (figure 5). In the 'without mask' condition the correlation coefficient, r, was 0·83 (df = 16) and a linear regression on corresponding data pairs gave the following equation:

$$TS = -9{\cdot}822 + 0{\cdot}486\bar{T}_{sk}. \tag{7}$$

The different mask air temperatures significantly modified the relationship between whole body thermal sensation and mean skin temperature. When all observations were included in the analysis the correlation coefficient, r, decreased to 0·65 (df = 106). A multiple linear regression including both the mean skin temperature and the skin temperature above the upper lip as independent variables, gave:

$$TS = -9{\cdot}790 + 0{\cdot}407\bar{T}_{sk} + 0{\cdot}083T_{lip}. \tag{8}$$

An analysis of the data from each mask air temperature condition separately with a curve-fitting program resulted in the maximal R^2 values for the curves shown in figure 5.

The total respiratory heat loss rate without the mask was calculated as 28·3, 23·1 and 19·7 W m^{-2} in environments of 7°C, 16°C and 25°C, respectively, using the equations of Fanger (1970). This corresponds to 10–15% of the total heat production. Respiration of mask air at temperatures of 22°C, 27°C and 33°C changed the estimates of respiratory heat loss to 19·5, 16·5 and 12·1 W m^{-2}, respectively in the 'dry' condition and to 16·7, 12·9 and 6·5 W m^{-2}, respectively when the mask air was 'humid'. The assessments of thermal sensation were given in the fifteenth minute when the subjects had been exercising for approximately 20 min. Over a period of 20 min the total

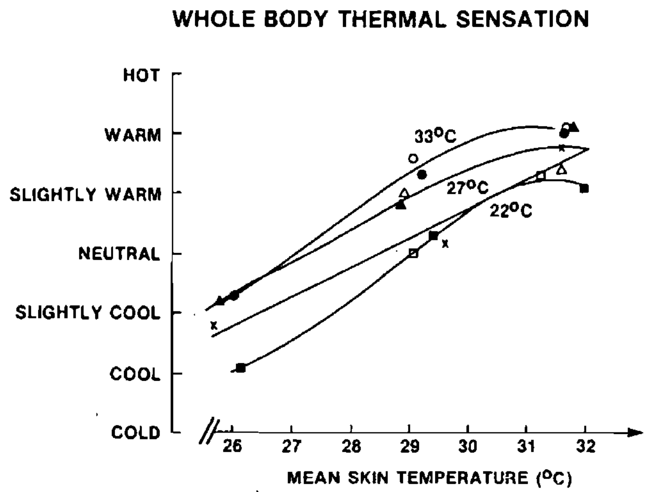

Figure 5. Mean values ($n=6$) of whole body thermal sensation and mean skin temperature for each experimental condition. The best fitting curves (maximal R^2-value) are shown for sessions with mask air temperatures of 22°C (■), 27°C (▲) and 33°C (●) and sessions without the mask (×). Open symbols are for sessions of 'humid' mask air and closed symbols for 'dry' conditions. A linear regression including all data gave the line shown.

respiratory heat loss in the three environments was calculated to be 62, 51 and 43 kJ in the sessions without the mask; 43, 36 and 27 kJ with 22°C, 27°C and 33°C 'dry' mask air and 37, 28 and 14 kJ with 'humid' mask air, respectively. Figure 6 shows the difference in whole body thermal sensation between the 'without mask' and each 'with mask' situation as a function of the corresponding difference in estimates of respiratory heat loss. The correlation was significant ($r=0{\cdot}68$; df$=14$) and the linear regression equation is shown.

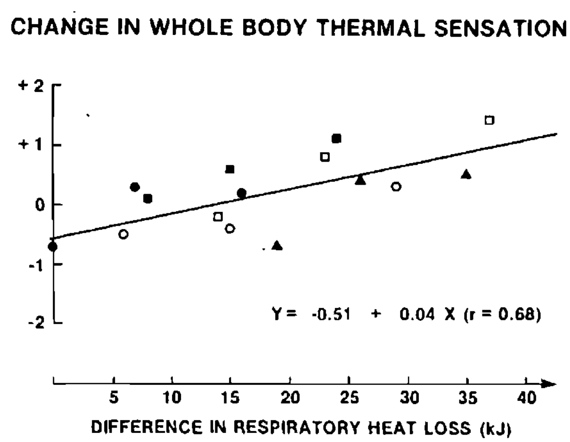

Figure 6. The change in whole body thermal sensation (see table 1 for rating scale) as a function of the calculated difference in respiratory heat loss after 20 min of exercise with and without the mask. (▲ = 7°C T_a; ■ = 16°C T_a; ● = 25°C T_a; open symbols are for sessions with 'humid' mask air and closed symbols are 'dry' mask air sessions).

3.3. Local thermal sensation

The ratings of local thermal sensation under the mask (TS(M)) showed significant ($p<0.05$) augmentation along with increased mask air temperatures:

$$TS(\mathrm{M}) = -0.997 + 0.198T_{ma} \quad (r=0.70;\ \mathrm{df}=89). \tag{9}$$

An increased air humidity inside the mask also increased ($p<0.05$) TS(M), although this augmentation was less than that following increases in mask air temperature. The following relationship between TS(M) and thermal environmental factors was established by a multiple linear regression analysis:

$$TS(\mathrm{M}) = -1.661 + 0.212T_{ma} - 0.012T_a + 0.008\mathrm{RH} \quad (r=0.74;\ \mathrm{df}=87) \tag{10}$$

where RH is the relative humidity (%) in the mask air.

3.4. Thermal preferences

The rating of thermal preference for the body was significantly correlated with the ambient air temperature ($r=-0.77$; df$=106$), while it was independent of the air temperature and humidity inside the mask. There was obviously a highly negative correlation between whole body thermal preference and whole body thermal sensation (figure 7 (*a*)).

The thermal preference locally inside the mask was significantly determined by both the ambient temperature and the mask air temperature; an increase in either one of these caused a lower thermal preference. The relationship between the thermal preference in the mask area and the whole body thermal sensation was primarily dependent on the mask air temperature. Though the ambient temperature had a

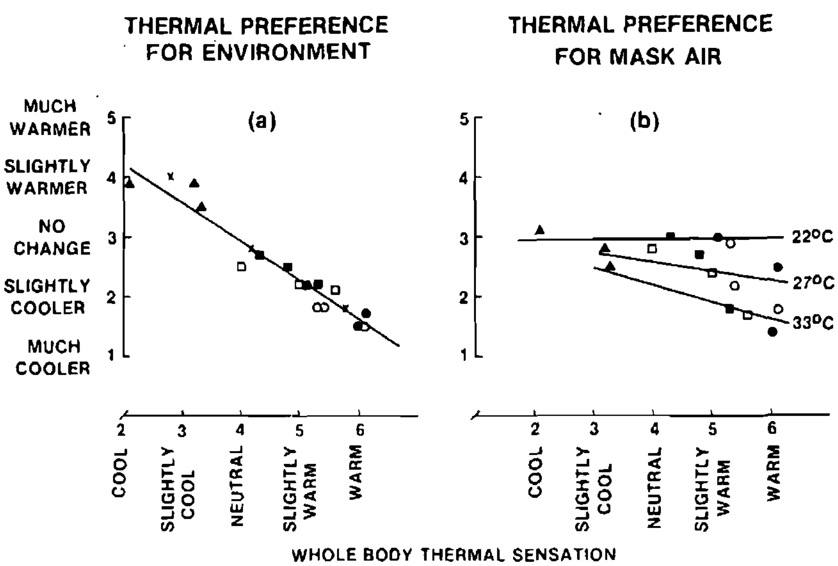

Figure 7. (*a*) Thermal preference for the ambient environment as a function of whole body thermal sensation (mean values for $n=6$). Symbols used: (×), without mask; (▲), $T_{ma}=22°C$; (■), $T_{ma}=27°C$; (●), $T_{ma}=33°C$; open symbols are for 'humid' mask air sessions and closed symbols are for 'dry' mask air sessions. (*b*) Thermal preference for the microclimate in the mask as a function of the whole body thermal sensation. Linear regression curves are shown for each mask air temperature condition.

modifying effect, the difference between mask temperatures grew larger with increasing air temperature (figure 7 (*b*)). The thermal preference inside the mask decreased as a function of increasing thermal sensation under the mask.

3.5. *Sensations of sweating and skin wettedness*

Both an increase in the ambient air temperature and an increase in the mask air temperature had a significant augmenting effect ($p < 0{\cdot}05$) on the sensation of sweating and skin wettedness on the whole body surface. The sensation of sweating and skin wettedness in the mask area was significantly ($p < 0{\cdot}05$) influenced by both ambient and mask air temperature, such that an increase in either one of them increased the rating of both sensations. A high relative humidity in the mask increased ($p < 0{\cdot}05$) the sensation of skin wettedness under the mask.

4. Discussion

The results from the control experiments without the mask are in agreement with results from previous studies (e.g. Vokac *et al.* 1971), showing that at a given metabolic rate and in a given clothing ensemble, the whole body thermal sensation is a linear function of the mean skin temperature, and therefore of the ambient air temperature.

The ambient temperatures used in the present study were selected because they were predicted to result in thermal sensations of 'cool' to 'cold' (7°C), 'neutral' (16°C) and 'slightly warm' to 'warm' (25°C) for subjects exercising at a metabolic rate of $174\,W\,m^{-2}$ with a clothing insulation of $0{\cdot}10\,K\,m^2\,W^{-1}$ (Fanger 1970). The actual metabolic rate was a little higher ($220\,W\,m^{-2}$), which slightly augmented the ratings of thermal sensation.

Whole body thermal sensation is, as mentioned in the Introduction, dependent on mean body temperature. In steady-state conditions, core temperature is a linear function of the relative aerobic strain (Saltin and Hermansen 1966) and largely independent of ambient temperature (Robinson 1963, Nielsen 1970). Owing to the short exercise period in our study, a steady-state core temperature was probably not established during the data sampling period, as it often takes 30–45 min to reach a steady state. However, the work performed was the same in all experiments, and in each subject the core temperature was therefore expected to reach largely identical levels, although the level will vary between subjects. The major variations in mean body temperature between experimental conditions should then have been caused by changes in the temperature of the shell-component of the body (as indicated by $\bar{T}_{sk}$) and a correlation should exist between whole body thermal sensation and mean skin temperature. Considering only the results from the three control conditions without the mask, the correlation between whole body thermal sensation and $\bar{T}_{sk}$ was highly significant. The correlation was still significant when data from the sessions with the mask were included, but the correlation became much looser because the mask with its different thermal microclimates had a modifying effect on the whole body thermal sensation.

The difference in whole body thermal sensation observed between the different mask conditions could not be explained physiologically by differences in either the recorded skin temperatures or the values of skin wettedness. The skin temperature above the upper lip was the only one of the recorded physiological parameters that was changed significantly by the temperature and humidity in the mask. This skin temperature, like other skin temperatures, is dependent on the temperature of the surrounding air. The high air flow rate through the mask increased the convective heat exchange between the skin and the air, resulting in a lower skin temperature above the upper lip than at a corresponding air temperature without the mask.

The edges of the mask were in close contact with the skin, as the mask was fitted tightly on the subject. The material of the mask made a solid contact with the skin, thus changing the dry heat loss underneath it from convective to conductive. At the same time, the insensible heat loss in the contact area was restricted. Some subjects voluntarily reported that they felt cold in the contact area with air of 22°C delivered in the mask. In both the 25°C environment where heavier sweating occurred during the exercise, and in the sessions where humid air was delivered into the mask, the area of contact was reported as wet.

The skin temperature measured under the mask was not included in the calculation of the mean skin temperature, and a change in the lip skin temperature thus did not change the mean skin temperature. Considering the small skin area covered by the mask and the degree of lip skin temperature change, the actual change of the mean skin temperature caused by incorporation of T_{lip} could not explain the resulting change in whole body thermal sensation. Other possible routes of influence therefore had to be considered.

Respiratory heat loss changes when the temperature and humidity of the inspired air changes (McCutchan and Taylor 1951, McFadden *et al.* 1985) and when the pulmonary ventilation changes (Mitchell *et al.* 1972, McFadden *et al.* 1985). The calculated values of respiratory heat exchange showed that a change in whole body thermal sensation by one unit could be caused by a change in heat loss of 38 kJ. This is a much lower change in heat loss than that normally required to produce such a change in thermal sensation. This indicates that although the change in respiratory heat loss is of importance, other influences on thermal sensation must be taken into account.

Delivery of air of different temperature into a face mask corresponds to the application of a local thermal stimulus to the skin surface around the mouth, nose and cheek. However, in our case this local thermal stimulus also affected the heat exchange in the respiratory tract. An influence on thermal sensation through both a cutaneous and a respiratory pathway are therefore possible.

Cabanac and co-workers (1979 a, b, 1985) hypothesized that the change in whole body thermal sensation following thermal stimulation of the face is mediated through a change in the temperature of the blood bathing the thermosensitive centres of the brain, that is, cooling/heating of the brain itself (Cabanac and Caputa 1979 b, Cabanac and Brinnel 1985). Cabanac and Caputa (1979 a) proposed that a selective temperature influence of cool air, via the face of a hyperthermic individual, on human brain temperature could be attributed to cool venous blood perfusing the cavernous sinus and possibly cooling the blood of the internal carotid artery. However, for obvious reasons, it is not possible to obtain direct temperature readings of human brain temperature so the respective roles of peripheral and central temperature influence is not determinable.

An alternative neurological explanation can be hypothesized. The relative sensitivities to thermal stimuli of individual skin areas are different. Crawshaw *et al.* (1975) showed that the forehead has a greater thermal sensitivity per unit area than other skin areas. They did not consider whole body thermal sensation. However, it may be proposed from our knowledge of the representation area of different senses on the sensory and motor cortex that afferent input from the face may be weighted more than that from other areas in a spatial summation of the total sensory input.

The change in whole body thermal sensation caused by the thermal microclimate in a mask may well be mediated either neurologically or by blood temperature. However, it is possible that an influence via the heat exchange in the respiratory tract is more important. Inspired air is warmed effectively to body temperature by turbulent convection in the upper airways. As the inspired air is warmed, water is simultaneously transferred to the inspired air by evaporation from the mucosa. This heat exchange between respired air and the tissue in the respiratory tract determines the final temperature of the tissue. A changed nasal tissue temperature may affect the temperature of the venous blood returning from the nasal cavities to the thermosensitive structures in the brain, and thus directly influence whole body thermal sensation.

Whether a thermal influence on returning blood from the respiratory tract or from the facial skin surface is more important is difficult to evaluate from the present study. Results from Buguet *et al.* (1976) showing that shivering could be provoked by exposing solely the face, while inspiration of cold air did not have the same effect, may indicate that an influence on facial tissue is most important. However, this needs further investigation.

5. Conclusion

Results of this study show that mean body temperature is not always the determinant of whole body thermal sensation. Stimulation with different thermal microclimates in a face mask caused significant changes in ratings of thermal sensation. This is only partly explained by changes in respiratory heat loss. However, an influence on the brain centres either by increased neural input from the face area compared to other skin areas, or via a change in the temperature of the blood perfusing them, should be considered.

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References

ASHRAE. ANSI/ASHRAE Standard 55-1981, 1981, Thermal environmental conditions for human occupancy. (American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, Georgia).

Åstrand, I., 1960, Aerobic work capacity in men and women with special reference to age. *Acta Physiologica Scandinavica*, **49**, supplement 169.

Berglund, L. G., Cunningham, D. J., and Stolwijk, J. A. J., 1983, The resistance type dew point sensor for moisture measurements on sweating humans. In *Proceedings of the 6th Conference on Biometerology and Aerobiology and the 16th Conference on Agriculture and Forest Meteorology* (Scottsdale), pp. 6–9.

Brown, G. A., and Williams, G. M., 1982, The effect of head cooling on deep body temperature and thermal comfort in man. *Aviation, Space and Environmental Medicine*, **53**, 583–586.

Buguet, A. G. C., Livingstone, S. D., Reed, L. D., and Limmer, R. E., 1976, Cold-induced shivering in men with thermoneutral skin temperatures. *Journal of Applied Physiology*, **41**, 142–145.

Cabanac, M., and Brinnel, M., 1985, Blood flow in the emissary veins of the human head during hyperthermia. *European Journal of Applied Physiology and Occupational Physiology*, **54**, 172–176.

CABANAC, M., and CAPUTA, M., 1979 a, Natural selective cooling of the human brain: Evidence of its occurrence and magnitude. *Journal of Physiology*, **286**, 255–264.

CABANAC, M., and CAPUTA, M., 1979 b, Open loop increase in trunk temperature produced by face cooling in working humans. *Journal of Physiology*, **289**, 163–174.

CRAWSHAW, L. I., NADEL, E. R., STOLWIJK, J. A. J., and STAMFORD, B. A., 1975, Effect of local cooling on sweating rate and cold sensation. *Pflügers Archives*, **354**, 19–27.

FANGER, P. O., 1970, *Thermal Comfort* (McGraw-Hill: New York).

GAGGE, A. P., and NISHI, Y., 1977, Heat exchange between human skin surface and thermal environment. In *Handbook of Physiology, Section 9* (Edited by D. H. LEE) (Waverly Press, Inc; Baltimore), pp. 69–92.

GAGGE, A. P., STOLWIJK, J. A. J., and HARDY, J. D., 1967, Comfort and thermal sensations and associated physiological responses of various ambient temperatures. *Environmental Research*, **1**, 1–20.

GRAICHEN, H., RASCATI, R., and GONZALEZ, R. R., 1982, Automatic dew point temperature sensor. *Journal of Applied Physiology*, **52**, 1658–1660.

KJERULF-JENSEN, P., FANGER, P. O., NISHI, Y., and GAGGE, A. P., 1975, A new type of test chamber in Copenhagen and New Haven for common investigations of man's thermal comfort and physiological reactions. *ASHRAE Journal* (January), 65–68.

KOLB, W. M., 1982, *Curve Fitting for Programmable Calculators* (IMTEC; Bowie).

MCCUTCHAN, J. W., and TAYLOR, C. L., 1951, Respiratory heat exchange with varying temperature and humidity of inspired air. *Journal of Applied Physiology*, **4**, 121–135.

MCFADDEN, E. R., PICHURKO, B. M., BOWMAN, H. F., INGENITO, E., BURNS, S., DOWNING, N., and SOLWAY, T., 1985, Thermal mapping of the airways in humans. *Journal of Applied Physiology*, **58**, 564–570.

MITCHELL, J. W., NADEL, E. R., and STOLWIJK, J. A. J., 1972, Respiratory weight losses during exercise. *Journal of Applied Physiology*, **32**, 474–476.

NIELSEN, M., 1970, Heat production and body temperature during rest and work. In *Physiological and Behavioral Temperature Regulation* (Edited by J. D. HARDY, A. P. GAGGE and J. A. J. STOLWIJK) (Thomas; Springfield), pp. 205–214.

NIELSEN, R., and NIELSEN, B., 1964, Influence of skin temperature distribution on thermal sensation in a cool environment. *European Journal of Applied Physiology and Occupational Physiology*, **53**, 225–230.

NUNNELEY, S. A., TROUTMAN, S. J. Jr., and WEBB, P., 1971, Head cooling in work and heat stress. *Aerospace Medicine*, **42**, 64–68.

ROBINSON, S., 1963, Temperature regulation in exercise. *Pediatrics*, **32**, 691–702.

SALTIN, B., and HERMANSEN, L., 1966, Esophageal, rectal and muscle temperature during exercise. *Journal of Applied Physiology*, **21**, 1757–1762.

VOKAC, Z., KØPKE, V., and KEUL, P., 1971, Effect of cooling of peripheral parts of the body on general thermal comfort. *Textile Research Journal*, **41**, 827–833.

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On a recueilli les réponses physiologiques et subjectives auprès de six sujets portant un masque facial durant un exercice de 15 minutes sur un ergocyle. Diverses combinaisons de températures d'air ambiant (7, 16 et 25°C) et de températures d'air dans le masque (22, 27 et 33°C) ont été étudiées, ainsi que deux humidités d'air intra-masque (61 et 86% H.R.). Les expériences de référence ont été efectuées sans le masque, mais dans les mêmes températures ambiantes. Pendant l'exercice, on a relevé les températures cutanées, la fréquence cardiaque, ainsi que la mouillure de la peau. A la fin de la période de travail, on a relevé les sensations thermiques, les sensations sudorales et de mouillure de la peau, ainsi que les ambiances thermiques préférées des sujets. On a trouvé que la sensation thermique globale du corps était principalement déterminée par la température de l'air ambiant, mais qu'elle était également influencée significativement par la température d'air dans le masque. Ce quid ne s'expliquerait que partiellement par la perte de chaleur par respiration. D'autres causes possibles sont examinées dans la discussion.

An sechs Personen, die eine Gesichtsmaske trugen und 15 min land Fahrradergometerarbeit leisteten (220 $W\,m^{-2}$) wurden subjektive und physiologische Auswirkungen ermittelt. Untersucht wurden verschiedene Kombinationen der Umgebungslufttemperatur (7, 16, 25°C) und der Lufttemperatur in der Maske (22, 27, 33°C), wobei die relative Luftfeuchte innerhalb der Maske verändert wurde (61%, 86%). Bei denselben Umgebungsluftemperaturen wurden Kontrollversuche ohne Maske durchgeführt. Während der Versuche wurden Hauttemperaturen, Herzschlagfrequenzen und Hautbefeuchtung aufgezeichnet. Nach der Arbeitsperiode wurden das thermische Befinden, das Empfinden über Schweißabgabe und Hautbefeuchtung durch die Versuchsperson eingeschätzt. Das thermische Befinden des gesamten Körpers wurde in erster Linie durch die Umgebungslufttemperatur, aber ebenso signifikant durch die Lufttemperatur in der Maske bestimmt. Das konnte nur teilweise durch die Veränderung der respiratorischen Wärmeabgabe erklärt werden. Andere mögliche Einflüsse werden diskutiert.

顔面マスクを着用して自転車エルゴメータで15分間（220 W/㎡で） 運動している6名の被験者から主観的，生理的反応を得た。周囲気温（7，16，25℃）とマスク内気温（22，27，33℃）は異なる組み合せで調査し，マスク内湿度は2水準（61，86%）とした。マスク無しで同一周囲気温で対照実験を実施した。皮膚温，心拍数，皮膚濡れ率を運動中に監視した。被験者の温度感覚，発汗感覚，皮膚濡れ感覚，温度的好みは運動期間の最後に評価した。全身温度感覚は主に周囲気温で決定されるが，マスク内気温にも大きく影響される。これは呼吸熱損失の変化によって部分的にしか説明できなかった。他の考えられる影響要因も考察する。