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Experimental Evaluation of Standard Effective Temperature A New Biometeorological Index of Man's Thermal Discomfort

by

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A single temperature index, by which man can predict his comfort, his discomfort and his state of health in any environment, has been for many years the goal of physiologists, engineers, meteorologists and those responsible for our standards for health and safety. The first index with this objective was the Effective Temperature (ET) of Houghten and Yaglou in (1923), which described on a psychrometric chart empirically derived loci of equal temperature sensation in terms of dry bulb temperature and humidity. Their index was modified by Bedford (1948) to include the effect of radiant heat, as measured by a black globe, and of air movement, as measured by a hot katathermometer (Vernon, 1932). The mechanical engineer Missenard (1931) derived a somewhat similar scale, called "Température Résultante," by consideration of the heat and mass transfer coefficients involved. The physiologists Winslow, Herrington and Gagge in 1937, introduced the concept of Operative Temperature (T_o) to describe the sensible heat exchange. T_o was defined as a linear average of the mean radiant ($\bar{T}_r$) and ambient air (T_a) temperatures weighted by their respective heat transfer coefficients. The meteorologist Sibbons (1966) extended Winslow's (T_o) concept to include in a new "operative" temperature the appropriate heat transfer coefficients that related the evaporative heat loss to the gradient of humidity ratio from the skin surface to the environment. Later, the engineers Nishi and Ibamoto (1969) extended the two previous concepts to include in their Humid Operative Temperature (T_{oh}) the associated heat transfer coefficient, the effect of humidity, expressed as a vapor pressure gradient, and of clothing insulation. All the above "equivalent" temperatures, which involve humidity, have been expressed in terms of a "saturated" environment, which numerically has very little relationship to the day-by-day "temperature experience" of man living in a temperate climate. To correct this sensory deficiency for such indices the meteorologist Thom (1957) once suggested that the ET of Houghten and Yaglou could more realistically be expressed in terms of a humidity base of 30% RH rather than at 100% RH; he named this temperature, "sentient", to designate what man feels. More recently Gagge, Stolwijk and Nishi (1971) have used a simple model of man's temperature regulation to simulate man's thermal response in any environment and to estimate the probable sweat secretion present on the skin surface; thus, by using the applicable transfer coefficients for both sensible and insensible heat exchange, the Humid Operative Temperature T_{oh} for any given environmental condition could be predicted in terms of T_o, ambient vapor pressure and skin wettedness. With much the same reasoning suggested by Thom, they proposed a new Effective Temperature index (ET*) with a base of 50% RH that would be equivalent to the predicted T_{oh}.

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In later studies, Gagge, Nishi and Gonzalez (1972) proposed that the 50% RH base be included in a new Index, which was defined as the temperature of an imaginary standard environment with a prefixed transfer coefficient in which the total heat exchange (sensible plus insensible) from the skin surface would be the same as in the actual environment. This standard index was called Standard Effective Temperature (SET*).

Houghten and Yaglou originally described a "Comfortable" environment as one in which man was neither warm nor cold and was one with a neutral temperature sensation. In 1966 the American Society of Heating, Refrigerating and Air-Conditioning Engineers proposed a broader definition of Comfort as "a state of satisfaction with the thermal environment". Fanger (1970) and Nevins et al. (1966) have both demonstrated for sedentary subjects that "Comfort", whether defined as a state of satisfaction or neutral temperature sensation, occurs usually when man is primarily in thermal equilibrium and when man is not regulating his body temperature by sweating and by any vascular change.

Fanger (1970) demonstrated for increasing levels of metabolic activity that mean skin temperature for comfort decreased linearly from 34°C and that the skin evaporative heat loss for comfort increased linearly from a minimum ($\approx 12\,W/m^2$) level, caused by skin diffusion alone. By introducing these comfort criteria in the basic heat balance equation at thermal equilibrium, Fanger was able to predict for any metabolic energy level what combination of environmental variables would produce a comfortable environment.

Finally, the heat stress index (HSI) of Belding-Hatch was introduced in 1956 as an index of environmental thermal strain. This non-dimensional index was defined as the ratio of net heat load on the body to the maximum evaporative heat loss possible from the skin surface to the environment. Values of this ratio less than unity are comparable to the skin wettedness present.

In the present experimental study both the Humid Operative Temperature (T_{oh}) and the new Effective Temperature (ET*) will be evaluated from the heat and mass transfer coefficients associated with the observed dry bulb (T_a), mean radiant ($\overline{T}_r$) and dew point (T_{dp}) temperatures. Based on a specially chosen standard environment, the Standard Effective Temperature (SET*) of the test environment will then be related directly to the magnitude estimates of "discomfort", reported by test subjects when exposed to various levels of ambient temperature, radiant heat and humidity.

The definitions of all the above named environmental variables and indices and their derivation will now follow:

THE INDEPENDENT ENVIRONMENTAL TEMPERATURES AFFECTING MAN'S HEAT EXCHANGE

(1) Ambient Air (T_a): the average temperature of man's gaseous environment in °C.
(2) Dew-Point Temperature (T_{dp}): the temperature at which condensation first occurs when an air-water vapor mixture is cooled at constant pressure, (in °C),
or Ambient Water Vapor Pressure (P_{dp}) is the saturated vapor pressure of an air-water mixture at dew point temperature,
or Relative Humidity (RH) or (P_{dp}/P_a) is the ratio of the ambient vapor pressure to the saturated vapor pressure of an air-water mixture at uniform temperature T_a at constant pressure.
(3) Mean Radiant Temperature ($\overline{T}_r$) is the temperature of an imaginary isothermal "black" enclosure in which man would exchange the same radiant heat as in his actual non-uniform environment (in °C).

THE BASIC ENVIRONMENTAL HEAT TRANSFER COEFFICIENTS

(4) Convective Heat Transfer Coefficient (h_c): the ratio of convective heat transfer per unit body surface area from a temperature (T_{surf}) to a moving gas at temperature (T_a) to the gradient ($T_{surf} - T_a$).
(5) Linear Radiative Heat Transfer Coefficient (h_r) is derived from the Stefan-Boltzmann Law, which states that the exchange of radiant heat is proportional to the difference of the fourth power temperatures in degrees K between man's surface and the mean radiant temperature of his environment. The coefficient h_r is given exactly by the term $4\sigma(A_r/A_D)T^3$, where $T = [(T_{surf} + \overline{T}_r)/2 + 273]$ and (A_r/A_D) is the ratio of man's radiating surface area (A_r) to his total skin surface area (A_D) (Dubois, 1936). For a sitting subject (Fanger, 1970) A_r/A_D is 0.70, and A_r increases with clothing worn by a factor $(1 + 0.15\ I_{clo})$, where I_{clo} is insulation of clothing worn in clo units, to be described later. The total skin surface area is given by the Dubois Surface Area formula, namely

$$A_D = 0.202(W)^{0.425}(H)^{0.725} \tag{1}$$

in which W is body weight in kg and H body height in meters.
(6) Evaporative Heat Transfer Coefficient (h_e) is the rate of heat exchange per unit vapor pressure gradient caused by the evaporation of water from a unit area of wet skin surface at mean temperature $\overline{T}_s$ to the ambient vapor pressure P_a or P_{dp}. At sea level, the ratio of $h_e/h_c = 2.2$ (^oC/Torr) known as the Lewis Relation (1922).
(7) Clothing Insulation (I_{clo}), expressed in clo units (1 clo = $0.155^oC \cdot m^2 \cdot W^{-1}$), is always reflected in the body heat transfer coefficients from the skin surface at temperature $\overline{T}_s$ and vapor pressure $\overline{P}_s$ as a non-dimensional factor (F_{cl} or F_{pcl}) defined as follows: for dry heat exchange

$$F_{cl} = 1/\{1 + 0.155(h_r + h_c)I_{clo}\} \tag{2}$$

and for vapor pressure gradient

$$F_{pcl} = 1/(1 + 0.143h_c I_{clo}). \tag{3}$$

Eq. (2) applies for normal porous clothing (Nishi and Gagge, 1970).

The product $(h_r + h_c)F_{cl}$ is the effective combined coefficient that governs the sensible heat exchange from the skin surface through clothing to the environment. The product $h_e F_{pcl}$ is the effective evaporative heat transfer coefficient from the skin surface through clothing to the environment.
(8) Barometric Pressure (P_b) affects sea level values of the convection coefficient (h_c) by the factor $(P_b/760)^{0.55}$ and the Lewis Relation (2.2) by the factor $(760/P_b)$. (Gagge, 1973).

THE BASIC PHYSICAL PROPERTIES OF SKIN SURFACES ARE

(9) Skin Temperature ($\overline{T}_s$) is the mean temperature of the surface of the skin that governs the transfer of the body's heat by radiation, convection, conduction and the evaporation of sweat.
(10) Skin Wettedness (w) is the ratio of the equivalent area of the wet skin surface (A_w) to the total body skin surface area (A_D). A_w is defined as the area (in m^2) of a completely wet skin surface at temperature $\overline{T}_s$ that would result in an observed evaporative heat loss, $\underline{E_s}$. The maximum possible evaporative heat

loss (E_{max}) from the body surface would occur when the entire body surface area is wet. Thus wettedness w is then equal to the ratio A_w/A_D or the ratio E_s/E_{max}.

RATIONAL ENVIRONMENTAL TEMPERATURE INDICES

A rational temperature index is one that can be used in a body heat balance equation, describing the exchange of heat between man and the thermal environment.

Operative Temperature (T_o) is the temperature of an imaginary isothermal "black" enclosure in which man would exchange the same heat by radiation, convection and conduction from his skin surface at temperature ($\overline{T}_s$) as he would in his actual non-uniform environment.
Thus

$$T_o = (h_r\overline{T}_r + h_cT_a)/h \qquad (4)$$

where h is the combined heat transfer coefficient for radiation and convection and equal to $h_r + h_c$. The sensible heat loss from skin surface is always described by $hF_{cl}(\overline{T}_s - T_o)$.

Humid Operative Temperature (T_{oh}) is the temperature of an imaginary saturated isothermal enclosure in which man would exchange the same total heat by radiation, convection and evaporation from a skin surface at the same wettedness w as observed in actual non-uniform environment.
By this definition

$$T_{oh} = [AT_o + wB\ \{(P_{dp} + 25.3)/1.92\}]/C \qquad (5)$$

where $A = hF_{cl}$, (5')

$B = (1.92)(2.2)h_cF_{pcl}$, (5")

and $C = A + wB$. (5"')

The sensible plus insensible heat loss from skin surface is always described by $C(\overline{T}_s - T_{oh})$.

The reader should note that the term $(P_{dp} + 25.3)/1.92$ in the T_{dp}-range of 25^o-35^o is numerically equal to T_{dp} itself.

Standard Operative Temperature (T_{so}) is the temperature of an isothermal environment in which man, wearing standard clothing and when exposed to a standard air movement at sea level, would exchange the same heat by radiation and convection with the same skin temperature as he would in the actual environment. If A' is the effective dry heat transfer coefficient in the standard or reference environment,

$$T_{so} = (A/A')T_o + (1 - A/A')\overline{T}_s \qquad (6)$$

The sensible heat loss from skin surface is given by both $A(\overline{T}_s - T_o)$ and $A'(\overline{T}_s - T_{so})$.

Standard Humid Operative Temperature (T_{soh}) is the temperature of a saturated isothermal enclosure in which man, wearing standard clothing, and when exposed to a standard air movement at sea level, would exchange the same heat by radiation, convection and evaporation for the same skin temperature and skin wettedness as in the actual non-uniform unsaturated environment. If A' + wB' or C' are the values for the combined humid transfer coefficients in the standard environment, then

$$T_{soh} = (C/C')T_{oh} + (1 - C/C')\bar{T}_s \tag{7}$$

The sensible plus insensible heat loss from skin surface is also given by $C/(\bar{T}_s - T_{soh})$.

Standard Effective Temperature (SET*) is defined in the same manner as T_{soh} above except that the standard environment is always at 50% RH, rather than being saturated. SET* and T_{soh} are related by equation

$$T_{soh} = [A'SET^* + wB'(0.5P_{set} + 25.3)/1.92]/(A' + wB') \tag{8}$$

where P_{set} is the saturation vapor pressure at temperature SET*.

Analytically SET* is the solution, preferably by iteration on a computer, of the following function when set to zero

$$f(SET) = SET^* + [wh_eF_{pcl}/hF_{cl}]\,(0.5P_{set} - P_a) - T_{so} \tag{9}$$

which is found by combining Eq. (6), (7) and (8).

In general any observed environmental condition (OC) can always be described in terms of T_o and P_a on a psychometric chart (Fig. 1).

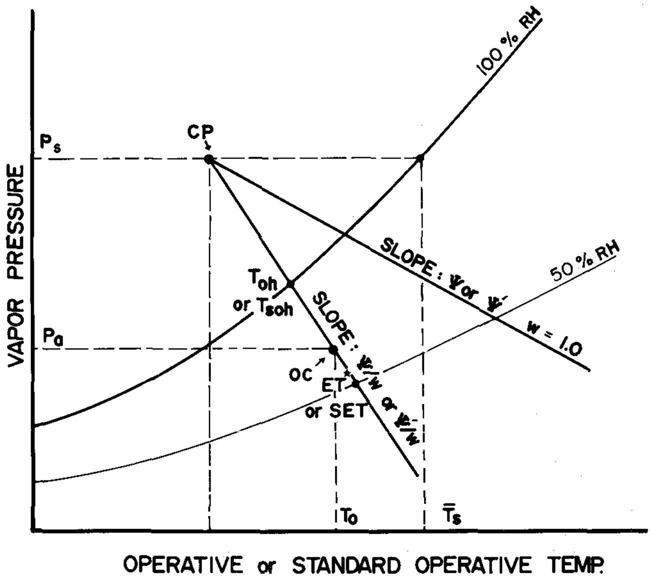

Fig. 1. Graphical relationship between T_o or T_{so}, P_a, T_{oh} or T_{soh}, ET* or SET* and the observed $\bar{T}_s$ and w on a psychrometric chart.

Through (OC) a locus of constant skin wettedness w can be drawn with negative slope Ψ/w in which Ψ equals the ratio $hF_{cl}/(h_eF_{pcl})$. The abscissa at intersection of this slope line with saturation or 100% RH curve is the value of T_{oh}; the abscissa at intersection with 50% RH curve is the value of ET*, which would be the new effective temperature that would correspond to T_{oh}. The point at intersect of locus Ψ/w with a horizontal line through $\bar{P}_s$ and $\bar{T}_s$ is called the Common Point (CP) for any locus of constant wettedness w and has coordinates $[\bar{T}_s - 0.9\underline{M}/(hF_{cl}), \bar{P}_s]$. For a standard environment the abscissa becomes T_{so} and standard coefficients are used for Ψ. By definition the same observed w and $\bar{T}_s$ is used in each case.

THE STANDARD ENVIRONMENT

The standard environment chosen for this study is described by the heat and mass transfer coefficients that apply for a sedentary subject (metabolic energy 58.2 W/m^2) while wearing 0.6 clo and when the air movement is relatively quiet at 0.25–0.3 m/s (or 20–40 fpm). Under these conditions: $h'_r = 4.9$; $h'_c = 3.1$; and $h' = 8.0$ in W/(m^2 . °C) and $I'_{clo} = 0.6$. Thus by Eq. (1) and (2) $F'_{cl} = 0.57$ and $F'_{pcl} = 0.79$. This standard environment is closely comparable to one existing in a centrally heated home located in temperate climates of North America and Europe and is also the basis for the new Comfort Chart of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Handbook, 1972).

METHODS

The present experiments were conducted in a large temperature - humidity controlled chamber. Dry bulb temperature (T_a), dew point temperature (T_{dp}) and mean radiant temperature ($\bar{T}_r$) were held constant or varied independently of each other. Each of ten subjects, while sitting on a chair wearing athletic shorts, were exposed at least twice to the following separate experiments: (1) a humidity series at constant T_a of 32, 36 and 40°C while ambient vapor pressure (P_a, Torr or T_{dp}) was slowly increased toward saturation and then returned to its initial level; (2) an ambient temperature series in which relative humidity was held at approximately 55% RH and constant while T_a rose from 29 to 44°C; (3) a complex environmental series in which unclothed subjects were exposed to rising humidity at constant T_a of 32°C and cycling radiant heat (3 min on, 2 min off) from two shuttered 1600 W T-3 quartz infrared lamps, which were placed 1.8 m away at an angle of 45 degrees above each side of the subject. The radiant heat was equivalent to an effective radiant field (ERF) of 70 W/m^2 and raised the operative temperature (T_o) by 8-9°C above ambient temperature (i.e. by ERF/h); (4) a humidity series using subjects wearing lightweight clothing (jeans and T-shirt) in which ambient vapor pressure was increased towards saturation at constant T_a of 35-36°C; and, (5) a series in which ambient temperature was decreased from 30 to 15°C while subjects were both clothed and unclothed.

Average skin temperature ($\bar{T}_s$) was measured from area weightings of local skin temperature readings by a hand radiometer, when unclothed, and, when clothed, by thermocouples at ten sites (forehead, shoulders, chest, back, thigh, calf, arms and hands). The environmental temperatures observed were dry bulb (T_a) and wet bulb (T_{wet}) by aspiration from which values the ambient vapor pressure and dew point temperature were calculated. The evaporative heat loss from the skin surface ($\underline{E}_s$) was calculated by the observed rate of weight loss while the subject rested on a Potter bed balance. The effective radiant field is linearily proportional to the wattage of the IR heaters and was calibrated by observing the $\Delta\underline{E}_s$ of subject vs wattage when subject was sedentary and exposed to a constant T_a (Gagge and Hardy, 1967). In all series, observations were taken each minute and processed at the end of each experiment by a special computer program. Judgments of warm or cold discomfort were measured by the method of magnitudes estimates (Stevens, Marks and Gagge, 1969). The assessed magnitudes estimates between subjects were averaged geometrically. The combined heat transfer coefficient (h) in the test chamber used was 8.0 W/(m^2 . °C) in which h_c was about 3.0 W/(m^2 . °C) and were close to those for standard condition chosen above.

RESULTS

Figure 2 demonstrates how humidity transients affect the accompanying judgments of discomfort for a typical subject at different constant levels of T_a of 32, 36 and 40°C.

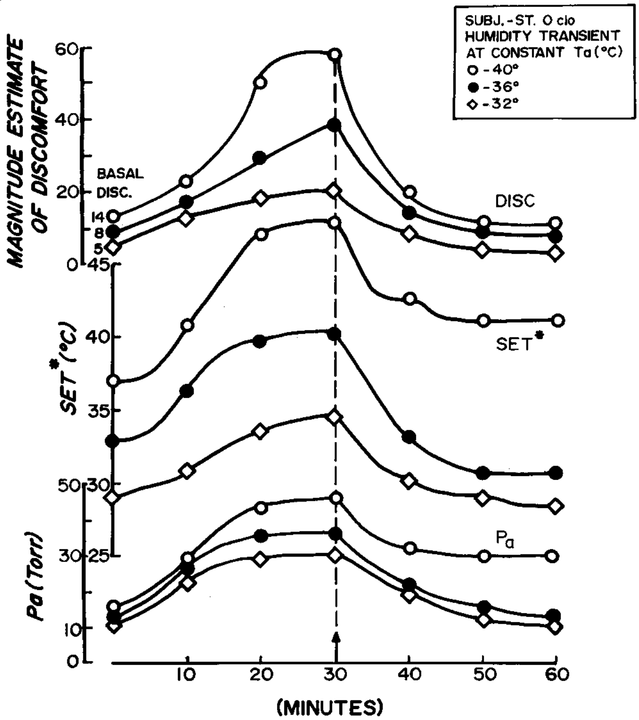

Fig. 2. Magnitude estimates of warm discomfort and corresponding standard effective temperature (SET*) plotted against time for one sedentary subject as humidity (P_a) was altered at different ambient temperatures. Judgment of basal discomfort started at time "0"; termination of the humidity increase is shown by vertical arrow. The pattern of humidity curve was always reproducible for all runs.

The magnitude of discomfort at the peak of rising humidity was 4-5 times that present at beginning. For both increasing and decreasing humidity at any given dry bulb temperature, estimates of discomfort by this subject were associated more closely with corresponding values of SET* than with P_a. The initial discomfort at each given level of T_a was also better described by standard effective temperature than by actual ambient vapor pressure measurement. Additionally, for the series in which dry bulb temperature was increased stepwise (not shown in this figure) while relative humidity was between 50-60%, SET* and T_a closely followed warm discomfort. This latter observation would be expected since SET* by definition is the dry bulb temperature T_a at 50% RH in a standard environment.

Figure 3 shows the experimental condition in which dry bulb temperature was set at 36°C and ambient vapor pressure was increased and decreased for a subject clothed in light weight shirt and pants (about 0.4 clo). The corresponding SET* and T_{soh} are drawn.

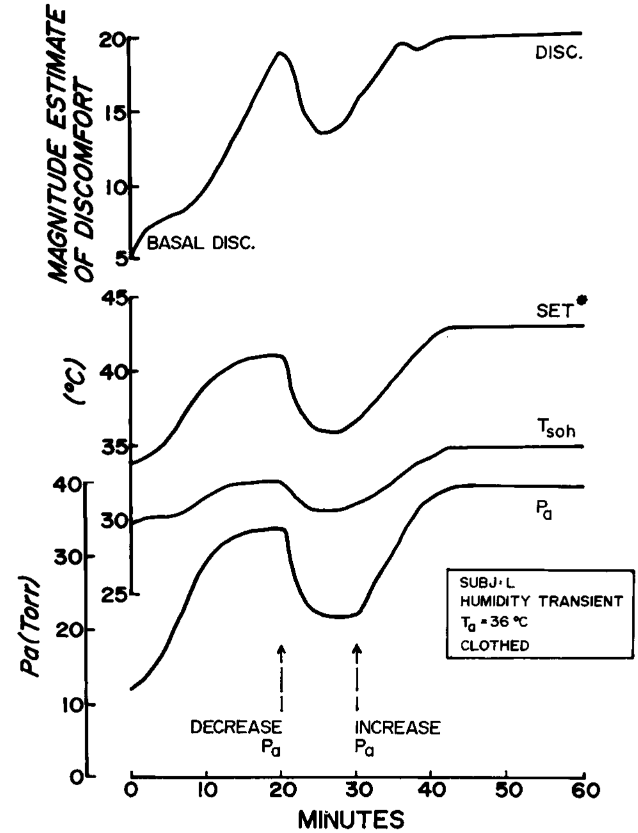

Fig. 3. Warm discomfort in a clothed subject (∿0.4 clo) and standard effective temperature (SET*), standard humid operative temperature (T_{soh}) plotted against time. Arrows indicate time period at which humidity (P_a) was decreased and increased.

During the experiment illustrated, which was also repeated five times in two other subjects, the increasing ambient vapor pressure was suddenly reversed before rising again towards saturation. Variations in SET* and T_{soh} can be seen to follow closely the judgments of discomfort. More important, little hysteresis is seen in discomfort estimates associated with the sudden drop in humidity and thus in SET* and T_{soh}.

In cold environments, SET* would describe a combination of environmental variables resulting in loci of constant mean skin temperature and would be numerically equal to T_{so} since skin sweating is negligible. If exposure time pattern is carefully controlled, the same value of $\overline{T}_s$ would occur in time for all experiments. It is thus possible to relate consistently estimates of cold discomfort to observed skin temperature and, by definition, SET*, which is now derived primarily from T_a and I_{clo}. Figure 4 presents data for a typical subject in which judgments taken at decreasing $\overline{T}_s$ observed every 5 min during an hour's exposure when they are plotted against the corresponding SET*.

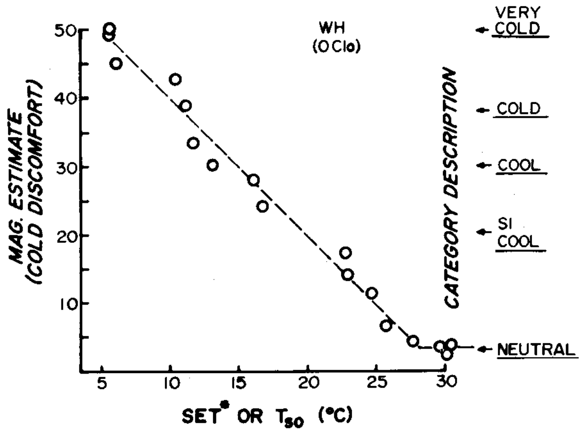

Fig. 4. Magnitude estimates of cold discomfort for one subject plotted against SET* in which ambient temperature was decreased stepwise from 30° to 15°C. Each circle signifies estimate at a respective $\overline{T}_s$ locus and SET*. Category description of discomfort is given on the right ordinate.

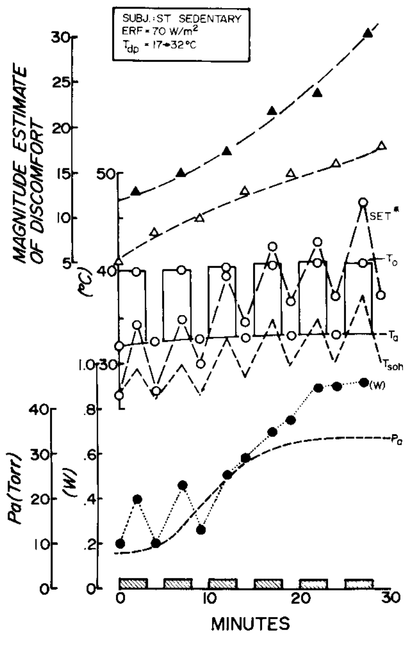

Fig. 5. Estimates of warm discomfort given by one subject exposed to radiant heat intermittently for 3 min and humidity increase. Observed w (or E_s/E_{max}) and SET* and T_{soh} were plotted for the experimental period.

Also shown is the verbal category description by the individual at each particular observation of $\overline{T}_s$ and SET*. As cold discomfort increases, $\overline{T}_s$ values of 33.7°-34.2°C and SET* of 28.5°C correspond to "neutral" temperature sensation; a $\overline{T}_s$ of 32.3°C and SET* of 20°C for "slightly cool"; a $\overline{T}_s$ of 31.2°C and SET* of 15°C for "cool"; and a $\overline{T}_s$ of 28.4°C and SET* of 6°C for "cold".

For subjects exposed to a combination of rising humidity and intermittent radiant heating, SET* again can be used with accuracy as an index of discomfort. Figure 5 illustrates a typical experiment in which dry bulb temperature was held constant at 32°C as ambient vapor pressure was raised from 8 to 35 Torr. Radiant heat (ERF$\sim$70 W/m^2) was varied stepwise every 3 min with a 2 min period without radiant heat. Discomfort estimates for those periods without radiant heat increased as humidity steadily rose and the judgments associated with skin wettedness (by observed E_s/E_{max}) during the period in which ambient vapor pressure was low (< 25 Torr). However, as humidity rose above 30 Torr, skin wettedness rose continuously. During the periods of radiant heating, estimates of warm discomfort reflected both the effect of rising humidity and that of an intermittent rise of 1.5°C in skin temperature.

Figure 6 shows that SET* can be used adequately as a normalizing index to describe the discomfort present in this complex environment. Each simulatneous observation for discomfort and SET* in Fig. 5 have been transferred to Fig. 6.

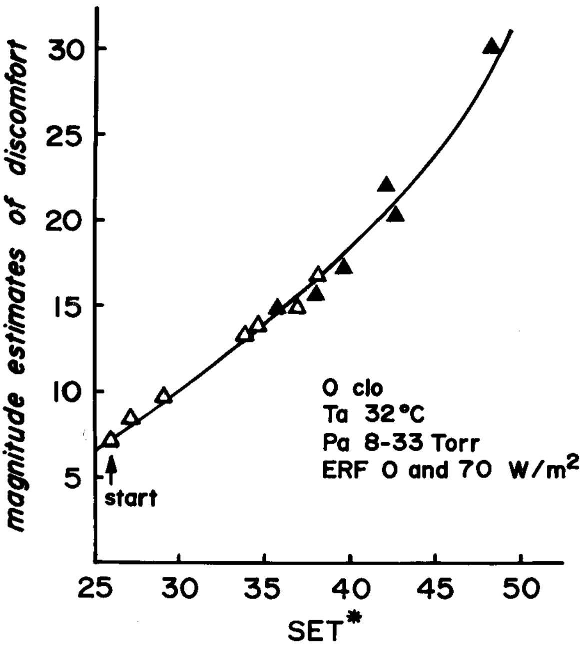

Fig. 6. Discomfort estimates from Fig. 5 plotted as a function of SET*.

Figure 7 relates geometric means of estimates of discomfort to SET* for all different environmental combinations on 10 subjects used a minimum of two times at each environment. The pattern of the curve indicates that warm discomfort for a wide variety of environmental situations may be normalized by the SET* index.

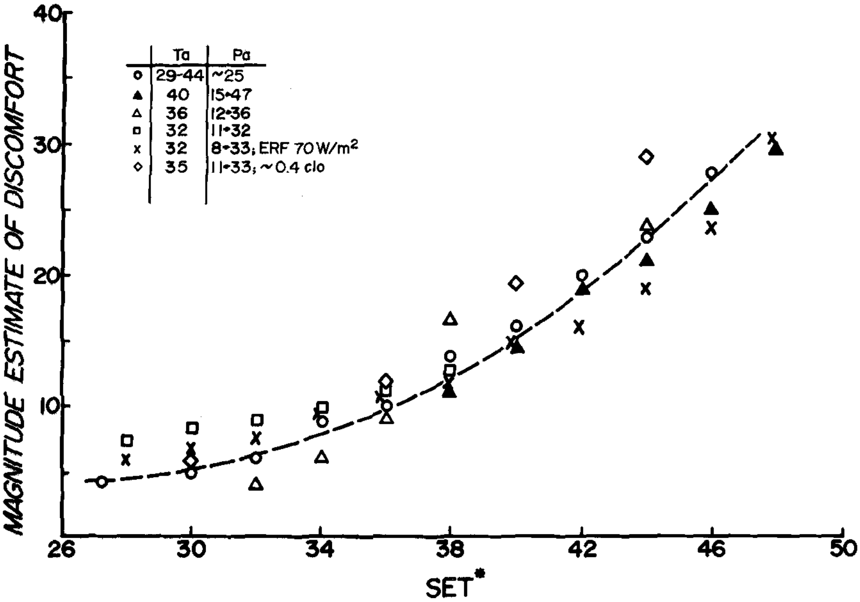

Fig. 7. Geometric means of magnitude estimates of warm discomfort averaged across 10 subjects and repetitions (2-4) as a function of SET* for all environmental variations. β on logplot is 1.8 for the SET* index.

During sweating, and in the heat, discomfort estimates may be described by the power relation

$$\text{Discomfort} \sim (\text{SET}^* - \text{SET}^*_n)^{\beta}$$

in which β is the power function that governs the growth of warm discomfort, and SET^*_n is the standard effective temperature at physiological thermal neutrality. The value of β for the combined series of experiments is 1.8 when SET^*_n is 25°C. The exponent of 1.8 required to fit these data indicates that the growth of warm discomfort with respect to SET* alone is non-linear but increases markedly above SET* value of 41.5°C.

The advantage of using magnitude estimation is that one is then able to transform the value by dividing by a constant without altering the value of the exponent (e.g. growth of warm discomfort). Such a transformation was done in Fig. 8 in which we have plotted warm discomfort estimates from Fig. 7 on a relative scale against SET* and have included estimates in which cold discomfort was taken. This figure also compares numerically temperature sensation and thermal discomfort to SET* garnered from other laboratories (Fanger, 1970) and described by a range of predicted discomfort votes (PDV)(0-4.7) derived by the analytical model from Gagge, Stolwijk and Nishi (1971).

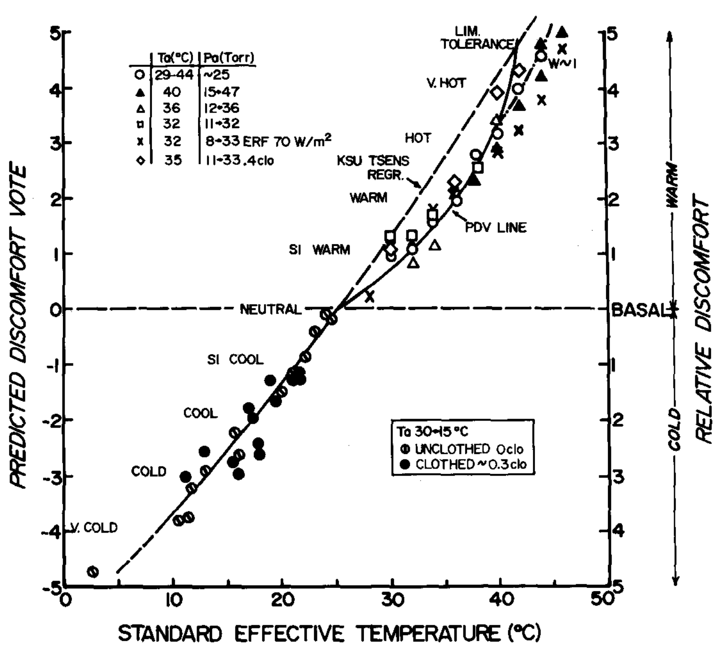

Fig. 8. The relation of predicted discomfort vote curve (Gagge, 1973) to SET*. The solid line indicates the predicted discomfort vote; the dashed lines represent the temperature sensation regression line from Kansas State University study (Rohles and Nevins, 1971). Open and closed symbols are from the present study for 10 subjects and represent transformed values from Fig. 7; dashed line interrupted by dots indicates deviation from PDV line of warm discomfort.

The solid line represents the discomfort trend; the broken line represents the temperature sensation regression line from Kansas State University study (Rohles and Nevins, 1971). The present data for both warm and cold discomfort estimates fit closely the analytical curves from these laboratories especially in the zones of evaporative regulation and of body cooling. In range $41.5^{o}C < SET < 45^{o}$ our data deviate slightly from the analytical discomfort trend line (having a β value of 2.0).

DISCUSSION

The definition and derivation of Operative Temperature and Humid Operative Temperature are based on simple physical theory and knowledge of the physiological process of the regulation of body temperature by the evaporation of sweat. Operative and standard operative temperatures describe the sensible heat exchange from the skin surface in terms of a temperature gradient from a skin temperature common in both the actual and reference environments. Humid operative and standard humid operative temperatures describe the sensible and insensible heat exchange from skin surface in terms of a temperature gradient from a common skin temperature and skin wettedness, caused by regulatory sweating.

The latter appears a factor that modifies evaporative heat transfer coefficients in the actual and reference environments. The operative temperatures are a linear measure of the heat stress of the physical environment for any given metabolic energy level. The humid operative temperatures are measures of the heat strain on man's regulatory system caused by the necessary heat loss by evaporation of regulatory sweat as opposed to the heat stress of the environment. All operative temperatures can be used directly in the body heat balance equation. As seen in Fig. 1, all have simple graphical interrelationships on a psychrometric chart both with each other and to skin wettedness and the various heat transfer coefficients involved.

The new Effective and Standard Effective temperature defined and derived here can be described as analytical functions of the ambient vapor pressure and of the operative and standard operative temperatures, which affect the heat stress, and of the combined heat transfer coefficients involved, which now include skin wettedness (see Eq. (9)) as a modifier of the evaporative heat transfer coefficients. Although they are based on valid physical assumptions, the new Effective Temperatures can not be used directly in a heat balance equation but are simple analytical functions of T_o and T_{oh} (or T_{so} and T_{soh}).

The choice of the 50% RH curve on a psychrometric chart as a reference standard for the new Effective Temperature (ET* and SET*) is believed to be more representative of the every day humidities with which average man can more easily identify for his own thermal experience. One could have used the 30% RH curve proposed by Thom or even a constant line at 10 Torr as once proposed by Buettner as a desert equivalent temperature (personal communication).

The experimental evaluation in terms of discomfort presented here is based on SET* as here described. Since the heat transfer conditions for both the test and reference environment are nearly identical as far as h and h_c are concerned, the present SET* scale essentially gives a rational basis for comparing clothed and unclothed subjects used in the present studies.

The use of magnitude estimates rather than category scales of thermal discomfort makes it possible to consider, primarily, relative changes in sensory judgment which are not restricted by the interpretation of scales used in the category description. The use of magnitude estimates has the additional advantage that any series of measurements can all be multiplied (e.g. transformed) by a constant factor without affecting their relative values. The rate of growth of discomfort with the independent variable (in the present case (SET*) is the variable that counts - not the magnitude of the estimate itself.

The validation studies summarized here confirm the observation that, for sedentary subjects, SET* is a unique index of thermal discomfort during a wide variety of thermal transients. As seen in Figs. 2, 3 and 5 for reversible changes in the environment little hysteresis occurs in the sensory response in terms of SET*. For the subjects exposed to step changes in radiant heat the chosen periods of 3-min exposure and 2-min recovery were based on previous experience (Stevens, Marks and Gagge, 1969), which showed that during these short periods skin temperature had reached a relative equilibrium and that a consistent judgment of discomfort was possible. Consistent observations were not possible for shorter exposure periods. Longer periods would have complicated the judgment by introducing severe body heating, which would have raised rapidly skin wettedness (w) to unity. As seen in Figs. 6 and 7, such a rise in w may have occurred for SET* values above 40°C. In general it can be concluded that SET* has proved a unique index of warm discomfort in the heat especially when wettedness falls below unity.

A final point is that in the zone of evaporative regulation (i.e. $25° < \mathrm{SET}^* \lesssim 40°\mathrm{C}$) SET* is a power function of warm discomfort (i.e. $\beta \sim 1.6 - 1.8$), but it may also be a linear function of warm temperature sensation, based on the results from Kansas State University (Rohles and Nevins, 1971). In the cold SET* values are numerically equal to T_{SO} and for controlled times of exposure are also linear with cold discomfort.

In conclusion, a rationally derived temperature index (SET*) has been defined by using a valid physiological basis and developed by use of simple physical theory. The SET* index has been tested experimentally as a measure of warm and cold discomfort for sedentary subjects under varying conditions of radiant heat, and dry and wet bulb temperatures. The reference environment, which is also common to that used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (1972), describes one normally experienced in our daily living (i.e. while wearing 0.6 clo with air movement 0.25-0.3 m/s).

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ABSTRACT.- A rationally derived temperature index (SET*) which can be used as a biometeorological index of man's thermal discomfort has been developed by simple physical theory and has a valid physiological basis. The SET* index, when referred to a standard environment, has been tested experimentally as a measure of warm and cold discomfort for sedentary subjects under varying conditions of radiant heat and dry and wet bulb temperatures. The reference environment is common to one normally experienced in man's daily living while wearing 0.6 clo with an air movement of 0.25-0.3 m/s.

ZUSAMMENFASSUNG.- Über eine einfache physikalische Theorie wurde ein Temperaturindex (SET*) abgeleitet, der als biometeorologischer Index für das Wärmeunbehagen des Menschen benutzt werden kann und auf einer gültigen physiologischen Grundlage beruht. Der SET* Index bezieht sich auf eine Standardumwelt. Er wurde als Mass für Warm- und Kaltunbehagen experimentell an sitzenden Personen unter wechselnden Bedingungen von Strahlungswärme und Trocken- und Feuchttemperaturen geprüft. Die Bezugsumwelt ist gleich der, wie sie im täglichen Leben des Menschen normalerweise gegeben ist bei leichter Bekleidung (0,6 clo) und einer Luftbewegung von 0,25 - 0,3 m/s ist.

RESUME.- On a mis au point un indice de température (SET*), dérivé rationnellement et qui peut être utilisé comme indice biométéorologique d'inconfort thermique pour l'homme. L'indice SET* découle d'une théorie physique simple et a une base physiologique valable. Il a en outre été mis à l'épreuve expérimentalement, par rapport a un environnement standard. Il représente alors une valeur chiffrée de l'inconfort dû aussi bien au froid qu'au chaud et ressenti par des sujets assis soumis à des conditions variables de rayonnement, de température et d'humidité. L'environnement de référence est celui que subit un individu légèrement habillé (clo = 0,6) dans son activité journalière par un courant d'air de 0,25 à 0,3 m/s.