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The relationship between bioclimatic thermal stress and subjective thermal sensation in pedestrian spaces

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Abstract Outdoor thermal comfort has important implications for urban planning and energy consumption in the built environment. To better understand the relation of subjective thermal experience to bioclimatic thermal stress in such contexts, this study compares micrometeorological and perceptual data from urban spaces in the hot-arid Negev region of Israel. Pedestrians reported on their thermal sensation in these spaces, whereas radiation and convection-related data were used to compute the Index of Thermal Stress (ITS) and physiologically equivalent temperature (PET). The former is a straightforward characterization of energy exchanges between the human body and its surroundings, without any conversion to an "equivalent temperature." Although the relation of ITS to subjective thermal sensation has been analyzed in the past under controlled indoor conditions, this paper offers the first analysis of this relation in an outdoor setting. ITS alone can account for nearly 60 % of the variance in pedestrians' thermal sensation under outdoor conditions, somewhat more than PET. A series of regressions with individual contextual variables and ITS identified those factors which accounted for additional variance in thermal sensation, whereas multivariate analyses indicated the considerable predictive power (R-square=0.74) of models including multiple contextual variables in addition to ITS. Our findings indicate that pedestrians experiencing variable outdoor conditions have a greater tolerance for incremental changes in thermal stress than has been shown previously under controlled indoor conditions, with a tapering of responses at high values of ITS. However, the thresholds of ITS corresponding to thermal "neutrality" and thermal "acceptability" are quite consistent regardless of context.

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Introduction

Urban microclimate and pedestrian thermal stress

Pedestrian thermal comfort is central to the quality of the urban environment. Beyond its direct impact on health and well-being, a thermally stressful outdoor environment can exacerbate the reliance of urban inhabitants on climatically controlled vehicles and interior spaces, increasing energy consumption and related atmospheric emissions (Nicol 1993; Nikolopoulou et al. 2011; Spagnolo and de Dear 2003).

The thermal environment of a city, however, is highly heterogeneous, and the microclimatic conditions that impose thermal stress on a pedestrian within the urban canopy are largely dependent on the physical design of the immediate surroundings. This is especially the case in a hot-arid climate, where exposure to intense solar radiation combined with high daytime temperatures can make thermal stress uncharacteristically harsh and highly dependent on local physical features. At the same time, given the low humidity, sharp diurnal temperature fluctuations, and frequency of strong winds that characterize hot-arid regions, streets and other pedestrian spaces in desert cities may offer exceptional potential for *improving* thermal comfort through responsive urban design. This potential has been underlined by the results of multiple experimental studies (Pearlmutter et al. 1999; Ali-Toudert and Mayer 2005; Pearlmutter et al. 2006; Johansson 2006), which indicate that a compactly built urban environment can have distinct advantages for pedestrian comfort under hot-dry conditions. These advantages are not adequately captured by simple measures such as air temperature but rather are dependent on the complex interchange of radiant energy and heat transfer between the human body and the surrounding environment.

Indices of bioclimatic stress

In previous studies conducted in the arid Negev region of southern Israel (Pearlmutter et al. 2007a, b), these multiple energy fluxes were characterized using the Index of Thermal Stress (ITS), a biophysical model expressing the level of environmental heat stress to which a person is exposed. The value of the index represents the equivalent latent heat of sweat secretion required to maintain equilibrium between the body and environment through evaporative cooling under warm conditions. Thus, the ITS provides a direct quantification of environmental energy exchanges due to radiation and convection, incorporating both internal metabolic heat production and the efficiency of sweat evaporation as limited by factors such as humidity and clothing. Originally developed by Givoni (1963, 1976) as a measure of indoor thermal stress, the ITS was later extended for outdoor use and adapted for the comparative microclimatic assessment of urban spaces (Pearlmutter et al. 2007a). It has been referred to as the most comprehensive index to be developed for gauging human thermal stress under warm conditions (Vogt et al. 1981; Auluciems and Szokolay 1997).

An important advantage of the ITS compared with other comfort indices is that it is based on a straightforward characterization of the *rate* of energy exchanged between the human body and the environment, expressed in watts per square meter of body area, without any conversion to an "equivalent" environmental temperature. In this way, the sensation of thermal stress by an individual is characterized as a process, rather than as a static condition. This index thus accords with a conception that subjective thermal information registers what is happening to the body over time, as the body's thermal endings are not in fact sensors of temperature but rather sensors of heat *flow*, monitoring the rate and duration of heat gain or loss. As expressed by Heschong (1979), "we notice changes, rather than states."

Most other thermal comfort indices in common usage are based on a hypothetical environmental *temperature* that indeed embodies these various energy exchange terms, but expresses them in the familiar form of temperature (°C). Although such indices may be more intuitive, their reliability and explanatory power may be limited in an outdoor environment which is rapidly changing due to the variability of solar exposure and turbulent air flow. One such measure in particular, the physiologically equivalent temperature (PET), has emerged as an especially popular index for urban outdoor comfort studies, and like similar metrics it is heavily reliant on a suitably accurate estimation of the mean radiant temperature T_{mrt} (Matzarakis et al. 2010; Höppe 1999; Andreou 2013). Although this may be a relatively simple descriptor of the radiant field in an enclosed room, in a constantly changing open-air environment its measurement may be challenging (Thorsson et al. 2007b).

A convenient method for estimating T_{mrt} in an actual outdoor setting is to calculate its value based on measurements with a globe thermometer registering the instantaneous difference between the internal temperature of the globe and the surrounding air temperature (as detailed in "Physiologically equivalent temperature"). As the globe temperature is highly sensitive to incident radiation, this calculation is not in fact a direct evaluation of *radiation* exchanges—but rather a measure of the heat exchanged by *convection* between the globe and its surroundings. As such, it is highly sensitive to *wind speed* at the point of measurement, and when accurate measurement of this rapidly changing variable is absent, large errors can accrue in the estimation of convection—and, in turn, of the mean radiant temperature. This is because T_{mrt}—ostensibly a measure of the radiant field—is computed under the assumption that the globe is in thermal equilibrium (i.e., that radiant energy input is exactly balanced by convective heat dissipation). This assumes that the globe thermometer has a negligible heat storage capacity—a potentially crucial limitation of the method. An additional limitation is that the measurement of T_{mrt} at a single point in a space does not allow for the diagnostic analysis of its contributing factors (i.e., the extent to which it is affected by direct or indirect solar radiation, or long-wave radiation emitted by individual surrounding elements).

Perceived thermal sensation

As ITS is formulated in terms of energy exchange rather than as a familiar temperature value, it is both more robust and less intuitive than most other comfort indices. Therefore, the ability to express a given ITS value in terms of actual human sensation is especially useful, and it is thus crucial to test the degree to which the index does, indeed, correlate with the subjective sense of thermal comfort experienced by pedestrians. This importance is underscored by numerous studies which have demonstrated that thermal sensation and the perception of comfort depend on a host of factors beyond the physical conditions of the environment (de Dear and Brager 1998; Höppe 2002; Nikolopoulou and Steemers 2003; Knez and Thorsson 2006; Nikolopoulou and Lykoudis 2006; Knez et al. 2009).

According to Nikolopoulou et al. (2001), the complexity of outdoor thermal comfort devolves not only from multiple causative factors related to the physical qualities of the space but also from the subjective or individual variables people bring to the space. As described by Humphreys (1995), human thermal sensation is a complex, wide-ranging, and intelligent behavioral response to climate, affected not only by heat regulation physiology and clothing insulation but also such elements as mood, culture and other individual, organizational and social peculiarities. Recent evidence for such variations has been given by Knez and Thorsson (2008), who found that different populations may vary in their psychological evaluation of a given thermal environment even when physical conditions are similar. To underscore this point, some have suggested a distinction between thermal "sensation," or the detection of a stimulus in the environment, and the "perception" of thermal comfort, which involves the interpretation of this information (Brager and de Dear 2003; Zhang and Zhao 2009; de Dear 2010). Research on such broader aspects of outdoor thermal comfort has proliferated over the past decade, as reflected in a recently published review by Chen and Ng (2012).

Although a correlation between the biophysical indicator ITS and subjective thermal sensation was reported by Pearlmutter et al. (2007a) based on experimental data for subjects under the controlled conditions of a climate chamber (Givoni 1963), it has never been investigated in an actual outdoor environment. As outdoor environments are more prone to thermal extremes than enclosed spaces, typically exhibiting far greater fluctuations (i.e., in temperature, air movement, and incident radiation), and as they often entail a quite different suite of human expectations than do indoor settings (Nikolopoulou et al. 2001; Höppe 2002; Stathopoulos et al. 2004; Hwang and Lin 2007), it is critical to examine the validity of and insights offered by the ITS in outdoor contexts.

The primary aim of the research described here was to examine the simultaneous influence of the outdoor urban environment on physiological stress and subjective thermal sensation in a distinctly stressful (hot-arid) climate, in order to validate and/or refine the correlations between biocimatic indices like the ITS and perceived thermal sensation. As in a number of recent studies on thermal comfort (Thorsson et al. 2007a; Lin 2009; Krüger and Rossi 2011; Cheng et al. 2012; Yin et al. 2012; Pantavou et al. 2013), an integrated methodology was used combining micrometeorological measurements and questionnaire surveys—allowing us to explore not only the relationship between physical and subjective aspects of thermal experience but also some of the individual and contextual factors mediating this relationship. We regard this work as part of the broader agenda, expressed by Nicol et al. (1999), of "developing culturally and climatically appropriate opportunities for people to make themselves comfortable."

Methods

The relationship between outdoor bioclimatic thermal stress and subjective thermal sensation was examined by comparing the results of physical environmental measurements and perceptual surveys conducted jointly in a series of urban spaces in a hot-arid climate. Climatic measurements served as input for calculating the ITS in these spaces, while the PET was also derived as a comparative index. Simultaneously with the measurements, questionnaires were distributed to pedestrians in the urban spaces, to gauge human perceptions of varying thermal stimuli. The values of both ITS and PET were then compared with subjective thermal sensation votes, to examine the relationship of perceived comfort with these physical indices. In addition to the direct comparison of thermal sensation with ITS, which reflects the physical basis for comfort, a series of ANCOVA analyses tested the degree to which additional predictive power was provided by models that included ITS as well as additional contextual variables in turn.

Experimental setup

The location of the study is a student dormitory complex located at the Sede-Boqer campus of Ben-Gurion University's Institutes for Desert Research, in the Negev desert of southern Israel (31° N, 30° E; altitude, 475 m). The local climate is typical of the Negev Highlands region, with hot dry summers, cold winters and intense radiation year-round. The study was conducted during the month of July, during which conditions were typical of the summer season—with daytime temperatures ranging from 24 to 36 °C (though dropping to 18 °C at night) and daytime relative humidity averaging 35 %. In this period, skies are consistently clear and prevailing winds are consistently from the northwest, reaching maximum velocity in the late afternoon and evening.

The dormitory complex is comprised primarily of low-rise apartment buildings, along with classrooms, offices and support facilities. The internal design of the complex, with relatively well-defined pedestrian paths between the two-story buildings, provided experimental sites representing small-scale "urban canyons" of varying geometry (Fig. 1). Three locations in the complex were selected for the measurements and administration of questionnaires, with each location having similar material characteristics (concrete-brick paving and surrounding stone-veneer walls) but a different spatial geometry. The measurement spaces consisted of two pedestrian "street" canyons, one with a north–south axis and one with an east–west axis, and an open square adjacent to the classroom buildings located in the center of the complex. Measured micrometeorological data from these locations served as input for the calculation of ITS and PET.

At each of the three locations, air temperature was measured at screen height (1.5–2 m) along with radiant surface temperatures of the ground paving, and in the two canyon spaces, the adjacent walls. All temperatures were measured continuously with ultra-fine copper-constantan thermocouples, which in the case of surface temperatures were attached to the relevant wall or ground elements and protect by small insulating shields. Measured data for global and diffuse radiation and relative humidity were taken from the adjacent meteorological station. Wind speed in the spaces was both

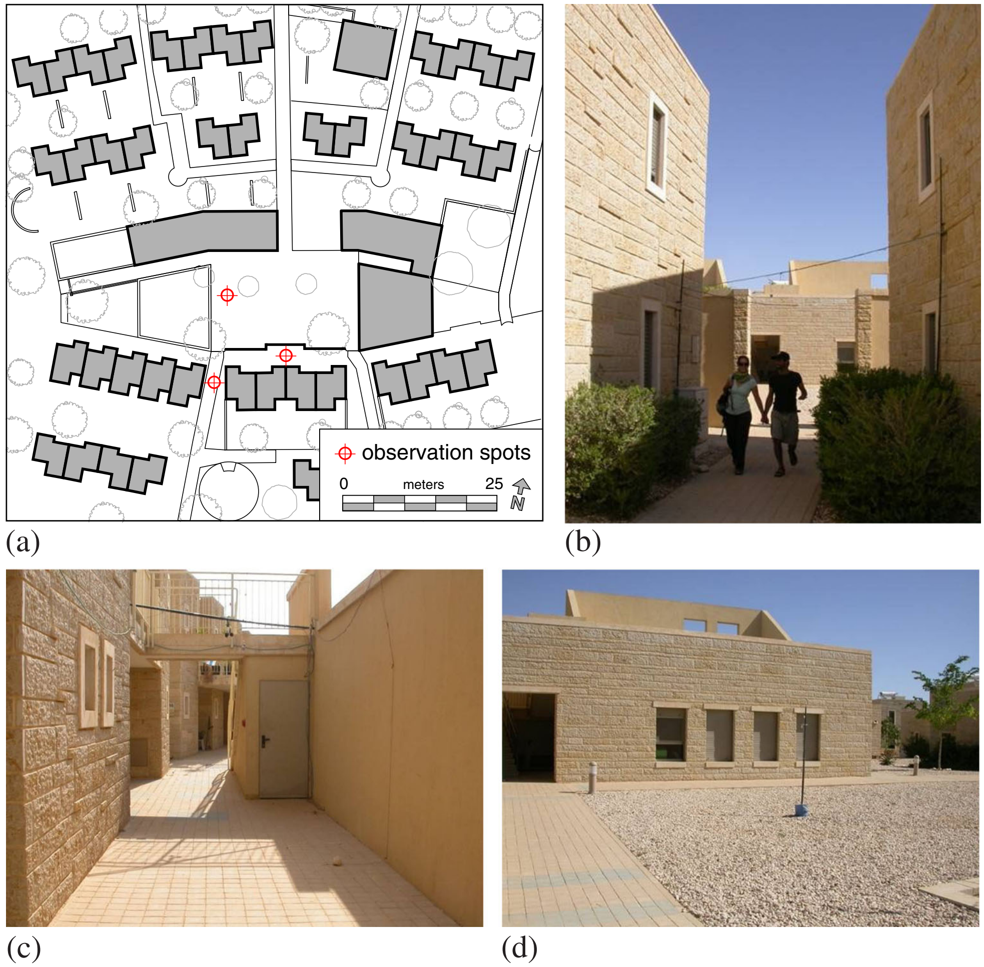


Fig. 1 **a** Site plan of the study area showing measurement locations, and views of **b** N–S pedestrian canyon, **c** E–W canyon, and **d** open square

measured directly by cup anemometer and calculated by applying an attenuation factor (Pearlmutter et al. 2007a) to available meteorological data. Globe temperature, which was used for the calculation of T_{mrt} and in turn PET, was measured with an ultrafine thermocouple housed in a gray painted, 40-mm diameter acrylic sphere (i.e., ping pong ball) following the method described by Thorsson et al. (2007b).

Computation of thermal indices

Index of Thermal Stress

Under warm conditions, the ITS represents the rate of sweat (in terms of its equivalent latent heat, in watts) required for the body to maintain thermal equilibrium with its surroundings through evaporative cooling. It is computed by:

$$\mathrm{ITS} = [R_n + C + (M - W)]/f \quad (1)$$

where R_n and C are the respective energy exchanges between the human body and the environment due to net radiation and convection, M–W is the body's net metabolic heat production, and f is a factor expressing the evaporative cooling efficiency of sweating as limited by the humidity of the air.

As illustrated in Fig. 2, the instantaneous exchange of energy by radiation and convection is computed in watts per square meter of body surface for a rotationally symmetrical person standing at the center of an urban space (Pearlmutter et al. 1999, 2006). The body's net radiation balance R_n is composed of absorbed short-wave components including direct radiation from the sun (K_{dir}), diffuse radiation from the sky (K_{dif}), and solar radiation reflected from horizontal ground surfaces (K_h) and vertical wall surfaces (K_v), absorbed long-wave components including radiation emitted by the sky and other downward-radiating elements (L_d), horizontal ground surfaces (L_h) and vertical wall surfaces (L_v), and long-wave emission from the body to the environment (L_s):

$$R_n = (K_{\mathrm{dir}} + K_{\mathrm{dif}} + K_h + K_v)(1-\alpha_s) + L_d + L_h + L_v - L_s \quad (2)$$

The absorption of short-wave radiation is based on measured global and diffuse radiation, shading and view factors (which are based in turn on solar and building geometry), and

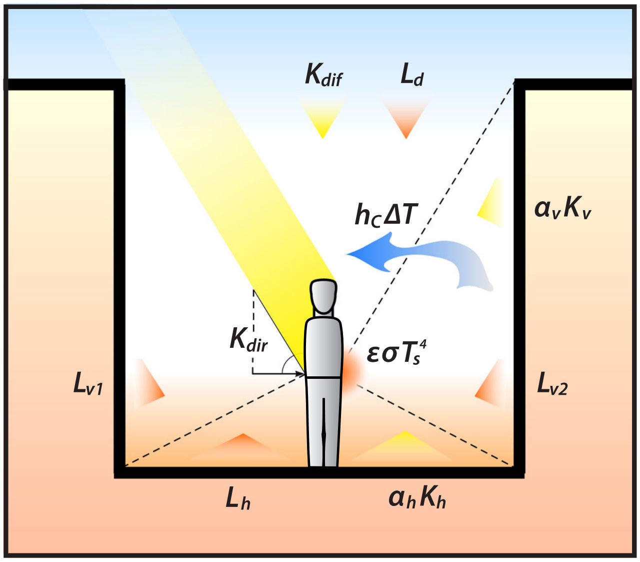


Fig. 2 Diagrammatic representation of energy exchanges between pedestrian and surrounding urban environment, for the calculation of the ITS

the albedo of built surfaces and of the body itself (α_s). Long-wave absorption from surfaces (including the ground and adjacent walls) is calculated on the basis of view factors, measured surface temperatures, and estimated emissivity values for all relevant materials, while emission from the body is based on a constant skin-clothing temperature of 35 °C. Absorption of downward long-wave emission from the sky dome is calculated from measured meteorological values (temperature and humidity), which determine clear-sky emissivity and from relevant sky view factors. A detailed description of the calculation of individual radiation components is given by Pearlmutter et al. (2006).

Convective energy exchange C (also in W m^{-2} of body area) is calculated for a standing pedestrian by:

$$C = h_c(T_s - T_a) \tag{3}$$

in which T_s–T_a is the difference between skin temperature and measured air temperature, respectively, and the empirical heat transfer coefficient h_c is a function of measured wind speed V_a:

$$h_c = 8.3 V_a^{0.6} \tag{4}$$

In most cases, C represents a net dissipation of heat from the body since the air temperature is typically below 35 °C, which was taken as a constant for T_s. To calculate the overall energy balance from the environmental loads R_n and C, component flux densities in watts per square meter are multiplied by the DuBois body surface area to yield fluxes in watts and summed with the body's net metabolic heat gain. The rate of metabolism was initially held constant at 70 W to represent a stationary person, and then adjusted according to the level of previous activity reported by each individual respondent (see "Mediating variables in the relationship between thermal stress and perceived comfort"). The evaporative cooling efficiency f is computed from an empirical relation based on the vapor pressure of the surrounding air (as well as wind speed and a clothing coefficient), as detailed by Pearlmutter et al. (2007a).

Physiologically equivalent temperature

Values of PET were computed using Rayman v1.2 (Matzarakis et al. 2007). As input to the Rayman model, the mean radiant temperature T_{mrt} was calculated from measured data according to an equation given by ASHRAE (2001) with empirical coefficients adjusted by Thorsson et al. (2007b):

$$T_{\mathrm{mrt}} = \left[\left(T_{\mathrm{globe}} + 273.15\right)^4 + \frac{1.335 \times 10^8 V a^{0.71}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273.15 \tag{5}$$

where T_g is globe temperature (°C), T_a is air temperature (°C), V_a is the velocity of air flow in the immediate vicinity of the globe thermometer (m s^{-1}), D is the diameter of the globe thermometer (mm), and ε is the globe emissivity.

For the calculation of PET, metabolic heat was estimated according to pedestrians' reported activity level immediately prior to interviews, based on ISO Standard 8996 (1989).

Questionnaire survey

Subjective thermal sensation was recorded through structured interviews conducted at the same time as which the readings yielding ITS and PET were made. Short questionnaires were administered randomly to pedestrians passing by the three experimental locations (see Fig. 1). The surveys took place during three time periods on summer days: morning (8:00-10:00), afternoon (13:00–15:00) and evening (17:00–19:00). The questionnaire survey spanned nearly the whole month of July, and was conducted on 13 separate days. A total of 319 questionnaire responses from 114 individual subjects were collected and included in the analysis.

Subjective thermal sensation was classified by respondents on a 7-point scale ranging from "very cold" to "very hot," and supplementary questions were used to assess various types of thermal adaptation and ways in which contextual factors might influence people's assessment of the thermal environment. These included (a) demographic and personal variables such as gender, birth date and clothing; (b) short-term thermal history, including previous activity (standing/sitting, walking, or running) and location (indoors/outdoors and sun/shade) prior to arriving at the experimental location, and length of time spent outdoors; (c) assessment of thermal sensation and preference in the particular location; (d) self-judgment of thermal sensitivity, i.e., as being a person who normally feels either hotter/cooler/neither hotter nor cooler than other people; (e) geographic background before living at the Sede-Boqer campus; (f) frequency of presence at the location and reason for being present; and (j) general perception of current thermal conditions in Sede-Boqer (different from the central response variable of thermal sensation in the particular survey location). Table 2 in the following section provides further detail on the questionnaire variables and sample composition, together with a breakdown of responses.

Thermal sensation according to the 7-point scale was modeled as a dependent variable as a function of calculated ITS and PET values in order to examine the respective potential of these indices to describe the actual thermal sensation as experienced by pedestrians in spaces with different micro-climatological characteristics. Next, the additional human factors influencing thermal sensation were added to the physical metric of ITS as covariates in a series of multivariate regression analyses. All analysis was conducted using JMP 8.02 (SAS) statistical software.

Results and discussion

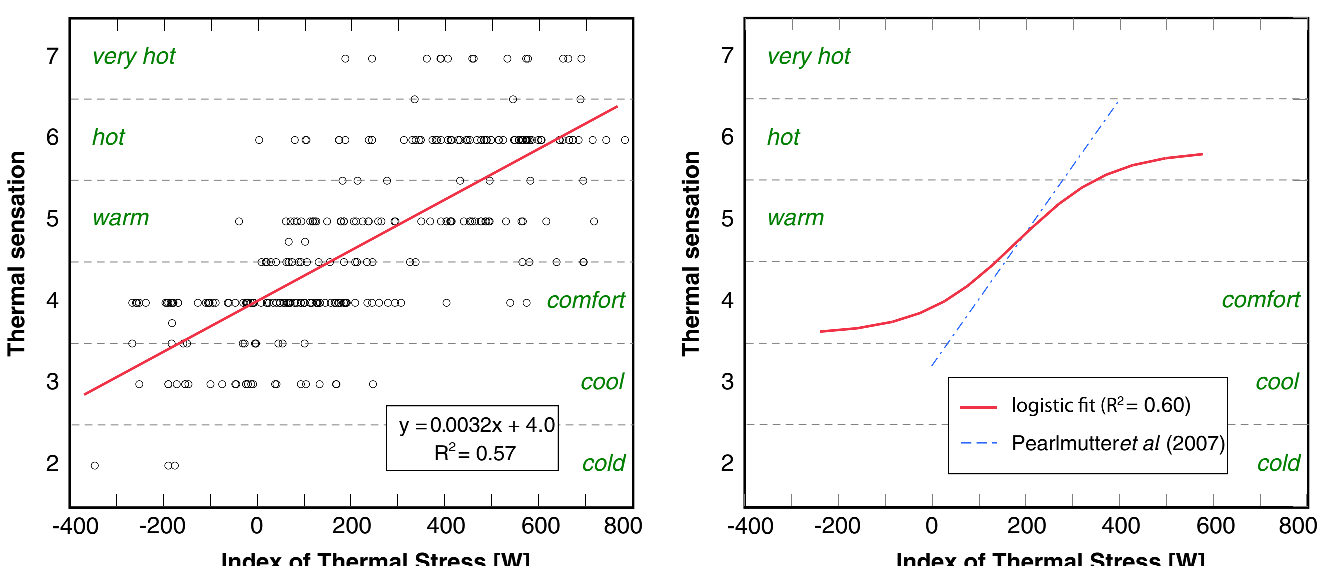
ITS vs. thermal sensation

Figure 3a shows the observed relation between the ITS, as calculated from measured data in the built environment, and simultaneous records of subjective thermal sensation as registered in pedestrian responses. ITS embodies all radiative and convective energy exchanges between the body and environment, with metabolic heat adjusted for previous activity as described in "Mediating variables in the relationship between thermal stress and perceived comfort".

It may be seen that a linear regression fits the data fairly well, with a coefficient of determination (R^2) of 0.57—that is, 57 % of the variability in people's subjective thermal sensation can be accounted for with considerable statistical confidence by the thermal environment, as encapsulated by the biophysical metric ITS. This finding reinforces the value of ITS as a predictor of actual thermal sensation, as it improves upon previous estimates that about 50 % of the variance between objective and subjective comfort evaluations may be explained by physical and physiological conditions (Nikolopoulou and Steemers 2003).

Several additional aspects of the observed relationship are worth noting in more detail. First, the sensitivity of respondents to incremental changes in the thermal environment—which is represented by the slope of the regression line in Fig. 3a—is considerably shallower than that reported previously by Pearlmutter et al. (2007a) on the basis of historical data from climate chamber studies (Givoni 1963). It can be seen that the increment between one thermal sensation category and the next is observed here to be nearly 320 W, whereas the value observed in the climate chamber studies is only 120 W (as seen in Fig. 3b; Table 1).

There are a number of possible explanations for this difference. First, it suggests that pedestrians in an outdoor environment are likely to have a larger tolerance for increases in environmental heat stress than they do under controlled indoor



(a) (b)

Fig. 3 The relationship between reported thermal sensation and the ITS, expressed as **a** a linear regression fit (R^2=0.57; F ratio=414.5; Prob< 0.0001) and **b** a four-parameter logistic fit of experimental data using a sigmoid curve (R^2=0.60), shown together with a linear fit of historical data (R^2=0.76) reported by Pearlmutter et al. (2007a)

Table 1 Thermal sensation thresholds for ITS and PET, as derived from the linear relationship between survey responses and the respective bioclimatic index

Thermal sensation level	ITS (W)	PET (°C)
Cool (3)	≤160	<21
Comfortable (4)	−160 to 160	21 to 33
Warm (5)	160 to 480	33 to 45
Hot (6)	480 to 800	45 to 57
Very hot (7)	>800	>57

conditions. In addition, this may be an expression of short-term climatic adaptation, to the extent that respondents have become acclimated to relatively severe heat stress in the summer season and thus individuals incorporate their expectations into their comfort responses. A final interpretation is the idea that survey respondents maintain a certain hesitancy to vote at the extremes of the scale which is offered, even if the conditions they are experiencing might otherwise warrant it. The latter has been noted as a problem with Likert scales in general (Heine et al. 2002), and in particular those with a low number of named choice points (Cummins and Gullone 2000).

A second notable aspect of the relation shown in Fig. 3a is that despite the difference in the slope of the fit, the transition from an acceptable to an overheated situation—as represented by the ITS value at which the regression line intersects the threshold between the categories of "comfort" and "warm"—is seen to occur here at an ITS level of approximately 160 W, which is nearly identical to what was observed previously for climate chamber results (Pearlmutter et al. 2007a). The implication of this finding, together with the relatively shallow slope of the regression line, is that while people's sensitivity to increasing thermal stress appears to be *context dependent*, the basic definition of thermal acceptability appears to be quite robust regardless of specific circumstances.

A final, remarkable feature of the linearized objective–subjective comfort relationship is that the neutral point on the thermal sensation scale (a vote of 4) corresponds almost precisely to an ITS value of zero watts—that is, thermal equilibrium. Above this point are subjective reports of a condition warmer than comfort, and below it a condition colder than comfort. Thus despite individual variation, an energy-flux definition of thermal stress appears to be extraordinarily capable of predicting neutrality in thermal sensation.

The abovementioned "dampening" effect in the rise of thermal sensation with increasing ITS is given more precise articulation in the fitted curve shown in Fig. 3b, which indicates that the relation between the two is *nonlinear*—with a steeper response in the central portion, and considerably flatter ones below and above this. This nonuniform response is modeled by a sigmoid model, and, specifically, a four-parameter logistic fit, expressed by:

$$y = 3.6 + \frac{2.26}{1 + \exp[-0.01(x-178)]} \tag{6}$$

An information-theoretic model comparison (Burnham and Anderson 2002) of the linear and four-parameter sigmoid models using the second-order Akaike Information Criterion (AICc) suggests that the sigmoid model (AICc=676.3) is considerably better than the linear fit (AICc=697.5), also yielding a slight (<4 %) increase in the portion of variance in subjective thermal sensation explained (R^2=0.60 for the sigmoid model). While sigmoidal responses are evident in the relation between the ASHRAE sensation scale and the percentage of people wanting to be hotter or colder (Hwang and Cheng 2007), and in the cooling or heating actions taken by office inhabitants (Nicol et al. 2007), this nonlinearity has not been studied as a phenomenon in its own right nor demonstrated in a formal model comparison as we do here.

The inflection point of the logistic "S-curve" occurs at an ITS of about 178 W, which is just past its transition from comfortable to warm conditions and just before its intersection with the regression line offered previously by Pearlmutter et al. (2007a). It is understandable that the slight but clear-cut tapering effect which this curve expresses would not have been noticed in the historical data from climate chamber studies, in which the experimental conditions were limited to an ITS range of about 0 to 400 W—where the response is more or less linear. A regression performed on only that central portion of our data yields a linear fit in which the slope approaches that of the historical data, while the intercept (at ITS=0) closely approximates the level expressing neutrality of thermal sensation (level 4).

PET vs. thermal sensation

Thermal sensation was also regressed with simultaneous PET values, as shown in Fig. 4. It can be seen that the linear regression has an R^2 of 0.53, such that just over half of the variance in subjective thermal sensation is explained by PET. The strength of this relationship is just slightly weaker than that found for ITS, reinforcing the validity of both metrics for representing outdoor thermal sensation.

In a sense, the similarity between the two fits (for ITS and for PET) is surprising, given the "noise" introduced into the latter due to significant inaccuracies found in the quantification of its central measure T_{mrt} using a globe thermometer. As it was impractical to precisely measure wind speed in immediate proximity to the globe thermometer for the duration of the study, a sensitivity analysis was performed using short-term measurements of wind speed with a high-precision hot-

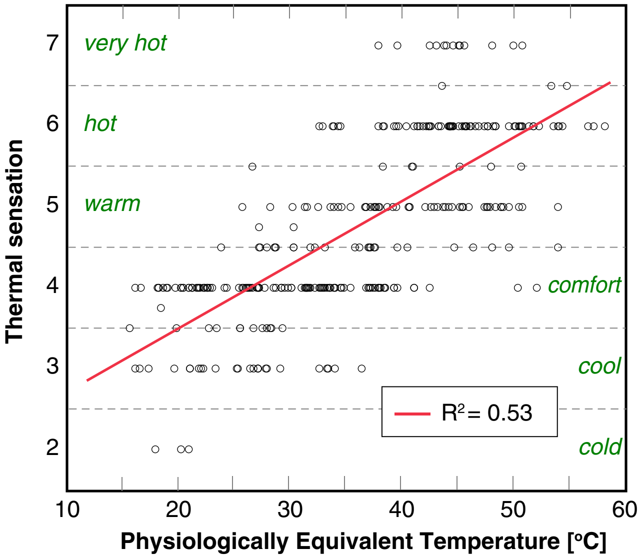


Fig. 4 Scatter plot showing the relationship between subjective thermal sensation and the PET

wire anemometer adjacent to the globe. Given the discrepancies of as much as 1 m s^{-1} between these precise measurements and the general wind speed estimates (based on cup anemometer measurements and attenuation functions), variations of up to 14 °C were found in T_{mrt} values derived by the two methods. Conversely, ITS values were found to be largely insensitive to inaccuracies in wind speed measurement, with maximal deviations of only 5 W m^{-2} in convective heat loss, and in turn in overall energy balance.

As with the ITS relationship, the slope of the regression line for PET indicates that pedestrians are tolerant of higher environmental stress for a given level of thermal sensation than was found in previously published studies (Matzarakis et al. 1999). As differences in the terminology used for comfort categories on different thermal scales makes a direct comparison inconclusive, in general terms the finding that pedestrians have a considerable thermal tolerance in outdoor settings is in agreement with other studies using PET (Nikolopoulou et al. 2001; Thorsson et al. 2004). The results here indicate that the comfort threshold (transition from "comfort" to "warm" on the thermal sensation scale) corresponds to a PET value of about 33 °C, and the increment between thermal sensation categories is equal to about 12 °C on the PET scale (see Table 1).

Mediating variables in the relationship between thermal stress and perceived comfort

While the above relationships demonstrate that a substantial portion of the variance in subjective thermal sensation can be explained by biophysical indices alone, we also explored the role of additional factors relating to the personal and environmental circumstances in which thermal sensation observations were made. Table 2 summarizes the additional queries which were included in the survey, and in the following section we consider the relationship between each of these variables and thermal sensation, with the main biophysical metric, ITS included as a covariate, as well as in an interaction term with the particular variable. This regression analysis, technically an ANCOVA, allows us to examine if and how these variables might be related to subjective thermal sensation (controlling for ITS), or mediate the relation between ITS and thermal sensation. These analyses are discussed in turn in the sections that follow, and the statistical details are collated in Table 3.

It should be noted that because some individuals contributed multiple responses, the observations are not strictly independent—and it is possible that this "pseudoreplication" (Hurlbert 1984; Machlis et al. 1985) could reduce the statistical power of the analysis by inflating the degrees of freedom in the error term and the likelihood of rejecting a null hypothesis that was true. At the same time, other approaches to the problem of replication (Leger and Didrichsons 1994; Schank and Koehnle 2009) suggest that a more nuanced understanding of the particular questions at hand is needed to determine if and in what way multiple observations may be pooled. The present analysis, which uses observations from a relatively large number of subjects and focuses on the conjunction of thermal stress and other contextual variables which shape subjective thermal experience, ignores the portion of variation due to a subject effect, which is the focus of work now underway using multilevel analysis (mixed effects models).

Previous activity

One group of questions established the nature, location, and duration of respondents' activity immediately preceding the survey. Physical activity, and the setting in which it occurs, influences thermal sensation directly by elevating internal bodily heat production (and therefore ITS itself), and may have indirect effects as well. A regression of thermal sensation on base-metabolism ITS with level of prior activity as a covariate shows that both are significant effects, though their interaction is not (Table 3). Estimates for the intercepts of the three regression lines representing different activity levels—sitting, walking and running—correspond to additions of 15, 75, and 205 W, respectively, above the assumed basal metabolism of 70 W, as summarized in Table 4. These revised metabolic heat inputs to the calculation of ITS are reflected in the relationship with thermal sensation shown above in Fig. 3a.

On average, then, people who had been running would feel the same thermal sensation as those at rest at a much lower environmental ITS value, and people who had been walking would feel the same at an intermediate value. These rates of

Table 2 Contextual and personal variables considered in the regression analysis, in addition to the actual thermal sensation vote and the physical measure of thermal stress (ITS)

Category	Variable	State	Observations	
			n	%
Previous activity	Level	Sitting/standing	187	59
		Walking	125	39
		Running	7	2
	Location	Indoors	98	31
		Outdoors (shade)	140	44
		Outdoors (sun)	80	25
	Duration	<2 min	100	31
		2–10 min	152	48
		>10 min	67	21
Time of day	Period	Morning (08:00–10:00)	93	29
		Afternoon (13:00–15:00)	131	41
		Evening (17:00–19:00)	95	30
Physical context	Location	N–S street	111	35
		E–W street	99	31
		Open square	109	34
	Reason for visitation	Intentional	18	6
		Passing by	300	94
	Frequency of visitation	Rarely	40	13
		Monthly	61	19
		Weekly	78	24
		Daily	140	44
	Clothing	Light summer clothing	246	77
		Other	73	23
Personal characteristics	Gender	Male	172	54
		Female	147	46
	Age (entered as continuous variable)	20–29	208	65
		30–39	96	30
		>39	15	5
	Place of origin	Hotter than local	57	18
		Colder than local	173	54
		Similar to local	89	28
Thermal "sensitivity"	Self-evaluation	Warmer than others	112	35
		Cooler than others	84	26
		Similar to others	123	39
	General impression of current weather	Cool	8	2
		Comfortable	114	36
		Warm	82	26
		Hot	83	26
		Very hot	32	10

metabolic heat production correspond well with the thresholds for moderate and high activity levels given by ISO Standard 8996 (1989), as shown in Table 4.

The time spent in the prior activity was not significant, either by itself (Table 3) or in a further test in which the location of the activity (shade vs. sun) was included. However, in this further test, the interaction term was found to be significant (p=0.04), suggesting that those who came from a prior activity conducted in the sun had a considerably steeper response to ITS. An examination of only the 220 subjects whose prior activity had been outdoors (about 2/3 in the shade and 1/3 in the sun) showed this significance to be stronger (p=0.002), and showed the shade/sun term itself to now be significant (p=0.05). According to this comparison,

Table 3 ANCOVA details for contextual variables found to be significant in separate multivariate regressions, which analyzed their effect on thermal sensation in conjunction with ITS (as computed with fixed internal heat gain)

Source	*df*	Sum of squares	*F* ratio	Prob>*F*
Error	313	158.2		
Prior activity	2	3.61	3.6	0.0288*
Prior activity*ITS	2	0.3	0.3	0.7303
Error	313	147.6		
Time period	2	8.6	9.1	0.0001*
time period*ITS	2	7.7	8.2	0.0003*
Error	313	161.3		
Prior time outdoors	2	1.4	1.3	0.2721
ITS*Prior time outdoors	2	0.57	0.5	0.6177
Error	315	150.4		
N–S street?	1	6.2	13.0	0.0004*
ITS	1	53.2	111.4	<0.0001*
N–S street?*ITS	1	0.380025	0.8	0.3730
Error	314	161.3		
Reason for presence	1	0.0	0.1	0.7816
ITS*reason for presence	1	1.3	2.5	0.1160
Error	311	157.0		
Frequency	3	4.6	3.0	0.0299*
Frequency*ITS	3	1.4	0.9	0.4214
Error	315	158.9		
Gender	1	0.7	1.3	0.2476
ITS*gender	1	3.7	7.3	0.0072*
Error	315	162.9		
Age at survey	1	0.3	0.5	0.4767
ITS*age at survey	1	0.1	0. 1	0.7681
Error	315	160.6		
Clothing long and thick	1	2.1	4.0	0.0454*
ITS*clothing long and thick	1	0.7	1.3	0.2514
Error	313	159.0		
Thermal background of origin	2	2.2	2.1	0.1157
ITS*thermal background of origin	2	1.8	1.8	0.1700
Error	313	158.7		
Usual thermal sensation	2	4.2	4.12	0.0164*
ITS*usual thermal sensation	2	0.4	0.4	0.6776
Error	315	152.72		
General feeling	1	8.6	17.7	<0.0001*
ITS*general feeling	1	1.4	2.8	0.0959

As the covariate term (ITS) and full model evidence an overwhelming effect (Prob>*F* of less than 0.0001), only the error, additional variable, and interaction terms are reported, and additional details are available from the authors. Not included in the table are the tests for a "country of origin" effect using several possible country groupings, none of which showed a significant effect. Effect tests (for all models, total *df*=318 and total SS=376.6)

both those coming from exposed conditions and those coming from the shade report similar sensations within the "warm" zone—but those coming from the sun report sensation levels which rise more rapidly under hotter conditions, and descend more rapidly under cooler conditions. One possible explanation for this divergence is that in the former case, respondents already carry a burden of excess heat, and in the latter they are already acclimated to solar exposure.

Time of day

Adding the time of day to ITS in the model, as well as an interaction term between time period and ITS, shows that all three are significant effects—with a small improvement in the overall model (R^2=0.61, see Table 3). As seen in Fig. 5, time of day matters over and beyond its shaping of ITS, as it also influences the slope of the regression line between ITS and thermal sensation: that is, people become less sensitive to

Table 4 Metabolic heat production derived statistically vs. standard rates in ISO 8896 (1989)

Metabolic rate for ITS		Metabolic rate by activity according to ISO 8996 (1989)	
Previous activity	W m^{-2}	Activity	W m^{-2}
Stationary	85	Resting	65
		Sitting/standing	100
Walking	145	Sustained work	165
Running	275	Intense work	230
		Very intense activity	290

incremental rises in ITS as the day progresses. Although all three lines intersect around the theoretically anticipated neutrality point, at which a "comfortable" vote corresponds to zero watts of stress, the shift from category 4 ("comfortable") to category 5 ("warm") requires an increasing addition to ITS as the day progresses: an addition of about 200 W in the morning, more than 300 W in mid-afternoon, and as much as 500 W in the evening. This apparent "desensitization" of the population over the daytime hours in summer could indicate a type of short-term acclimation, in the sense that expectations are modified in the time that elapses between early morning—when conditions are typically cool—and late afternoon, when the heat of the day has reached its maximum extent. In other words, the rate of shift away from perceived comfort differs over the day, even though the basic feeling of thermal neutrality is the same

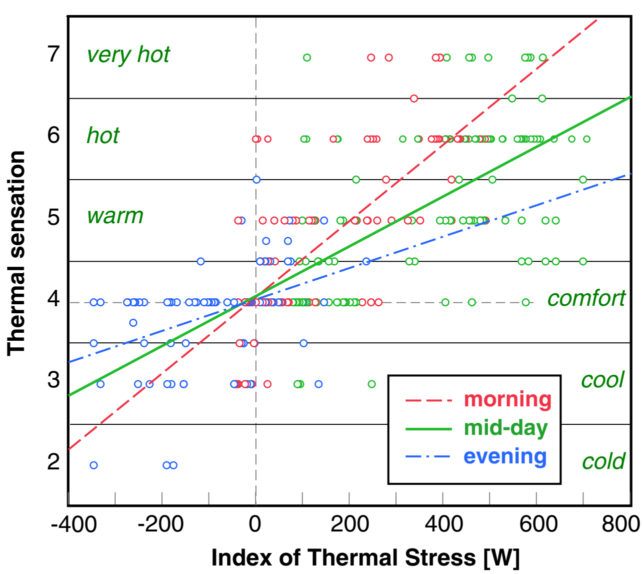


Fig. 5 Scatter plot of ITS vs. thermal sensation with data points separated into subsets corresponding to periods of the day. Note that the slope of the accompanying regression lines declines over time, but all converge around the intersection of ITS=0 (thermal equilibrium) and a thermal sensation vote of "comfortable" (perceived thermal neutrality)

regardless of hour—corresponding in all cases to a situation in which the body is dissipating its internally produced heat without either gaining or losing additional energy.

Separate analyses of the three periods indicate that while there is substantial data in all three periods (see Table 2), ITS has markedly less predictive power later in the day, with R^2 declining from 0.54 in the morning to 0.46 at mid-day and to 0.17 in the evening (all regressions significant at $p<0.0001$). This suggests that over the course of a summer day, thermal sensation becomes both less sensitive to ITS and less *predictably* sensitive—that is, there is more noise around a shallower slope.

Physical context

Variables denoting different aspects of the physical context were analyzed in turn, each in a regression with ITS and an interaction term. The variables denoting reason for visitation and clothing worn were not significant; in the latter case this may be attributed to the observation that almost all pedestrians were wearing light clothes with low thermal resistance. (In winter, of course, differences in clothing insulation would be expected to play a more significant role.) The frequency of visitation had a mild effect on thermal sensation ($p=0.03$), due mainly to the class containing 44 % of subjects who reported that their visits were daily, with the interaction effect not significant (Table 3).

The most marked effect in this cluster of contextual variables was due to whether the measurements were done in the N–S pedestrian street or the other two locations (E–W street and open square). This variable of course has an effect on ITS itself, since the interior of the N–S canyon is shaded from low-angle sun during the morning and afternoon hours, reducing the radiant load on the body and in turn lowering the value of ITS. However, even with ITS as a covariate, this indicator variable was statistically significant (prob>|t|=0.0004) and had a sizeable effect, with people in the N–S street reporting a subjective sensation of almost half a level lower for a given ITS (Table 3).

Although the interaction term with ITS was not significant (that is, the slopes of the two lines were not significantly different from one another), separate regressions on the two groups showed a much better fit for the respondents outside the N–S street ($R^2=0.56$) than for those within it ($R^2=0.30$). In other words, not only did respondents in the deeply shaded canyon report cooler thermal sensations than would be predicted by ITS alone, but ITS also had far less predictive power in the shaded setting. A possible explanation for these findings is that other effects of deep shade, such as visual protection from strong glare, cause some respondents to perceive this location as even cooler than the thermal conditions would suggest—but that this effect is far from universal.

Personal characteristics

While not significant as an independent term ($p=0.25$), the interaction term of gender with ITS was significant ($p=0.0072$) with a moderate effect size: a standard Beta of 0.1 compared with 0.78 for ITS, or, in concrete terms, the rise from "comfort" to "hot" (4 to 6) corresponds to 715 W for men, but only 549 W for women. This finding on the interaction of gender and thermal sensitivity may help refine the growing literature indicating complex interactions between genders and the various dimensions of thermal experience (Karjalainen 2012). Neither age nor country of origin was found to be significant in the current analysis; in the former case this is probably related to the narrow cross-section of ages in the sample, and in the latter case this indicates that the effects of long-term acclimation and climato-cultural factors require further in-depth study. This is also the case with other personal characteristics not investigated here, ranging from health and physical fitness to mood and esthetic perceptions of the environment.

Thermal sensitivity

Three questionnaire items explored broader thermal experiences: respondents were asked about their personal thermal sensitivity relative to others, and their general perception of the local climate, both at the moment and in general relative to their country of origin. The parameter expressing "personal sensitivity" was significant when modeled together with ITS ($p=0.016$), as was the "general feeling" of current local conditions ($p<0.0001$). Also significant ($p=0.04$) was the distinction between the 173 respondents coming from a "cooler" country of origin and the 89 respondents coming from a thermally "similar" one—though there was no significant difference between these and the 57 respondents coming from a "hotter" origin. None of the respective interaction terms were significant.

Multivariable analysis of contextual factors

As noted previously, the direct physical measurements incorporated in ITS can in themselves account for most (57 %) of the variance in thermal sensation. However the preceding series of analyses shows that many of the individual contextual variables, when considered in turn with ITS as a covariate, can help account for an additional portion of this variance both as a main term and through an interaction term.

To build a fuller model, which incorporates more than just ITS and serial consideration of each of these variables, two problems must be considered. Firstly, because of the many colinearities and complex causal relations between the variables, a full-factorial model would not be feasible (the number of terms in a full-factorial model is 2^n, and the subset of nine "significant" variables described above would yield over 500 terms in a regression). In addition, this subset of nine variables was not chosen a priori, but selected based on observed values—thus bringing up the *multiple comparisons* problem (Curran-Everett 2000). In fact, the multiple inferences embodied in this filtering process should be compensated for in any more refined analysis, and we should regard variables whose statistical significance is only marginal as no more than suggestive (though many are significant at levels that would clearly pass more stringent evaluation.)

Table 5 Details of multivariable regression analysis (summary of fit)

R-square	0.741834
Root mean square error	0.572805
Mean of response	4.720912
Observations (or sum weights)	318

Given this complexity of factors, we performed here two kinds of analysis. In the first, a conventional regression analysis was done on all the variables (both main factors and interaction terms) that were shown to be significant in the series of ANCOVA procedures described above (Table 3). The second is a partition analysis of all the variables, with the dependent variable being the *residuals* of the parametric sigmoid function of ITS described earlier (see Fig. 3b), performed in order to factor out the main effect of ITS. A common data mining technique, also known as a Classification and Regression Tree (CART) analysis, the partition analysis recursively generates a hierarchical set of cuts or groupings of variable values that best predict a y value—in this case the residual of a univariate fit of thermal sensation and ITS (that is, thermal sensation over and above that predicted on the basis of ITS alone). The results of these two different approaches to multivariable analysis are presented below.

Multivariable regression

The multivariable regression model shows that all factors (except gender) remain significant, yielding an overall model with an R^2 of 0.74 (Tables 5, 6, and 7). Over 99 % of predicted votes are within one level of actual votes, and some 85 % are

Table 6 Details of multivariable regression analysis (analysis of variance)

Source	*df*	Sum of squares	Mean square	*F* ratio
Model	22	278.12729	12.6421	38.5307
Error	295	96.79115	0.3281	Prob>*F*
C. total	317	374.91844		<0.0001*

Table 7 Details of multivariable regression analysis (effect tests)

Source	*df*	Sum of squares	*F* ratio	Prob>*F*
Prior activity	2	3.456761	5.2678	0.0057*
Usual thermal sensation compared with others	2	4.403876	6.7111	0.0014*
Frequency	3	5.963764	6.0588	0.0005*
Time period	2	6.840005	10.4235	<0.0001*
N–S street?	1	7.805932	23.7909	<0.0001*
Gender	1	0.069363	0.2114	0.6460
Geographical background	2	2.180799	3.3233	0.0374*
Setting of prior activity	2	1.059651	1.6148	0.2007
General feeling	1	20.852516	63.5543	<0.0001*
ITS	1	20.352746	62.0311	<0.0001*
ITS*setting of prior activity	2	2.771611	4.2237	0.0155*
Time period*ITS	2	2.378618	3.6248	0.0278*
ITS*gender	1	0.670285	2.0429	0.1540

within half a level. The diagram of scaled estimates (Table 8) underscores those effects that most substantially raise thermal sensation beyond what might be predicted on the basis of ITS itself: general feeling, prior activity and time of day.

Table 8 Multivariable regression analysis: scaled estimates

Term	Scaled estimate	Standard error	*t* ratio	Prob>|t|
Intercept	4.707	0.145	32.54	**<0.0001***
ITS	1.757	0.223	7.88	**<0.0001***
General feeling	0.755	0.095	7.97	**<0.0001***
Prior activity (running)	0.379	0.153	2.48	**0.0137***
(ITS, 185.698)*setting of prior activity (sun)	0.341	0.124	2.74	**0.0065***
Frequency (monthly–rarely)	0.325	0.124	2.62	**0.0092***
Usual thermal sensation (hotter–neither)	0.246	0.079	3.10	**0.0021***
N–S street? (no)	0.239	0.049	4.88	**<0.0001***
Geographical background (hotter–same)	0.220	0.103	2.14	0.0333*
Time period (evening–mid-day)	0.156	0.191	0.82	0.4143
(ITS, 185.698)*gender (female)	0.101	0.071	1.43	0.1540
Time period (evening–mid-day)*(ITS, 185.698)	0.083	0.328	0.25	0.8017
Frequency (weekly–monthly)	0.075	0.102	0.74	0.4624
Setting of prior activity (shade)	0.073	0.052	1.40	0.1616
Frequency (daily–weekly)	0.059	0.088	0.67	0.5034
Usual thermal sensation (neither–cooler)	0.035	0.086	0.41	0.6829
Setting of prior activity (indoor)	0.032	0.054	0.60	0.5483
Gender (female)	0.016	0.036	0.46	0.6460
Gender (male)	−0.016	0.036	−0.46	0.6460
(ITS, 185.698)*gender (male)	−0.101	0.071	−1.43	0.1540
(ITS, 185.698)*setting of prior activity (indoor)	−0.105	0.101	−1.03	0.3026
Prior activity (walking)	−0.105	0.086	−1.22	0.2240
Setting of prior activity (sun)	−0.105	0.061	−1.72	0.0873
Geographical background (same–cooler)	−0.186	0.080	−2.31	0.0215*
(ITS, 185.698)*setting of prior activity (shade)	−0.236	0.097	−2.43	0.0156*
N–S street? (yes)	−0.239	0.049	−4.88	**<0.0001***
Prior activity (sitting)	−0.274	0.086	−3.17	**0.0017***
Time period (mid-day–morning)	−0.486	0.113	−4.31	**<0.0001***
Time period (mid-day–morning)*(ITS, 185.698)	−0.631	0.240	−2.63	**0.0089***

Nominal factors are expanded to all levels. Continuous factors are centered by mean and scaled by range/2. Key effects (large coefficient, small *p* value) are in set in bold

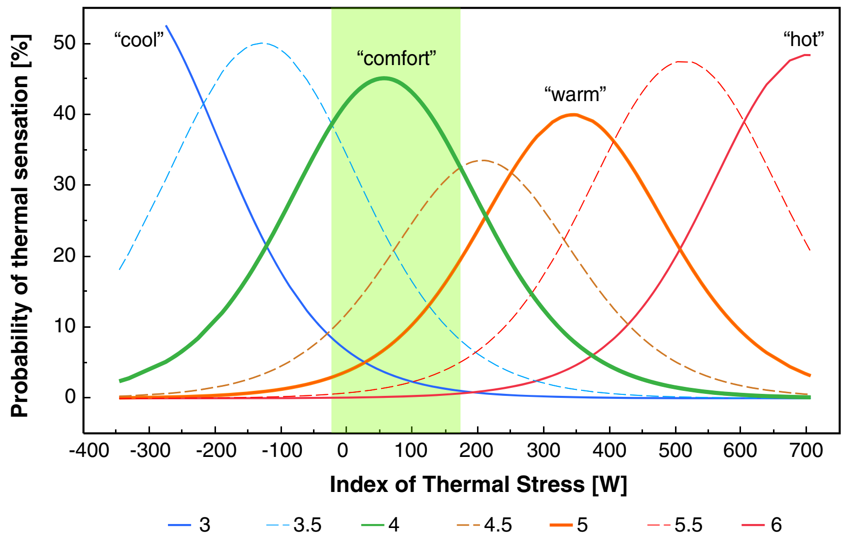


Fig. 6 Ordinal logistic regression of full multivariable model, showing the probability of a given thermal sensation vote being predicted for an observed value of thermal stress, in conjunction with its associated set of contextual variables

In Fig. 6, an ordinal logistic regression of the full multivariable model shows the probability of a given thermal sensation vote being predicted for an observed value of thermal stress, in conjunction with (or "corrected for") the associated set of contextual variables. The shaded area shows that the most probable sensation is "comfortable" when the value of ITS lies in a zone ranging from just under zero watts (thermal equilibrium) to just over 160 W (transition to overheated conditions). It may also be seen that for a given value of ITS (see, for example, 200 W) a very wide range of sensations can be predicted with at least some probability.

Partition analysis

The partition analysis on the residuals of the ITS model (Fig. 7) produces a set of "decision rules" that recursively splits the observations (whether through categories or break points in continuous variables) in a way that maximizes the homogeneity of the two resulting groups with respect to the dependent variable (in this case, systematic difference from the predicted thermal sensation based on ITS alone). This analysis identifies the N–S-shaded variable as the most important first cut in predicting remaining variance in subjective

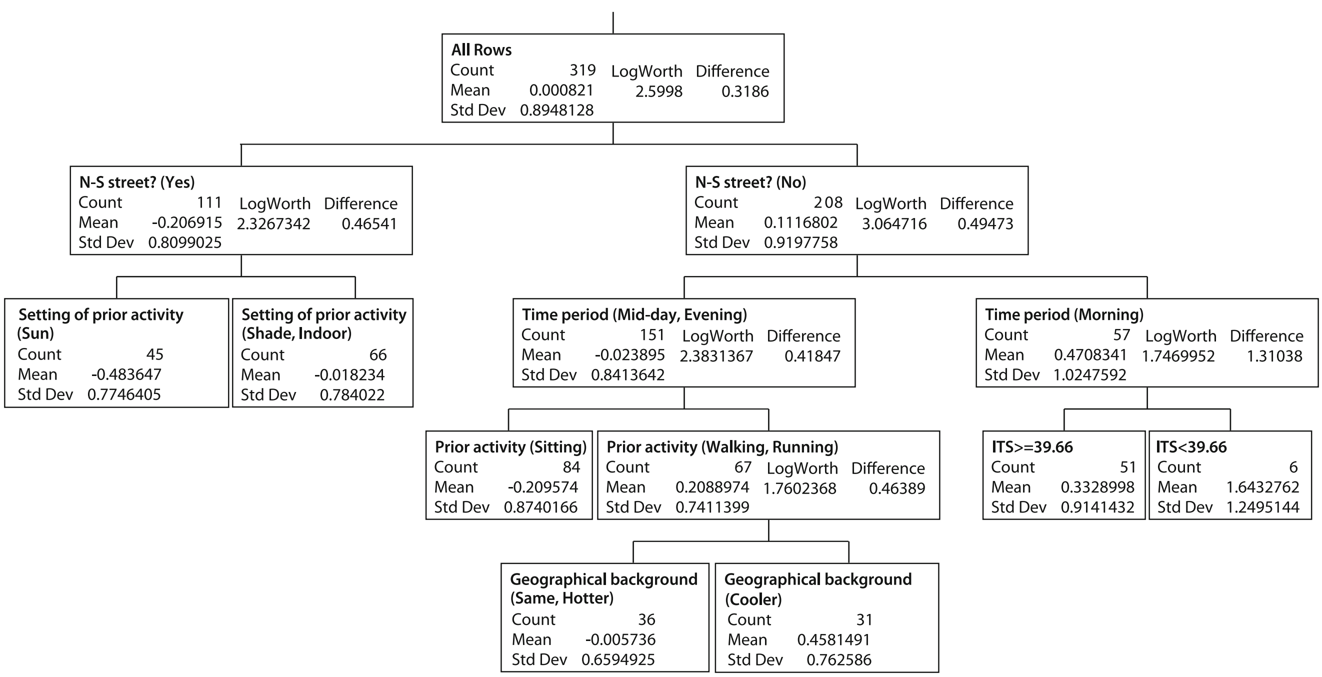


Fig. 7 Partition analysis of all variables, based on the residuals of the ITS model. The count, mean, and standard deviation values are for the number of rows in the branch, with the difference being the difference between the branches of the split in the subsequent level. LogWorth gives the value of the statistic on whose basis the split is made. For details, see SAS Institute (2012)

thermal sensation, with the setting of prior activity being the key second cut in the shaded street, and the morning time period being the next cut for the nonshaded streets. These distinctions reinforce the importance of exposure to the sun, both at the time of response and beforehand, as a factor in thermal perception—and they also highlight the possible changes in people's sensitivity to sunlight over the course of the day. Similar reasoning can be used to explain the next cut, which finds ITS to be important in the morning, and physical exertion in the other periods. Finally, for the 67 non-morning observations made in nonshaded spaces of subjects that had been engaged in some form of physical activity, there was a distinction between those who did or did not come from a cooler country of origin. Thus, while the partition analysis differs in logic from a regression and includes all of the variables, its results concur with the multivariable regression analysis in terms of the variables identified as significant. It too produces a model that is consistent with our expectations, based on physical processes and their subjective perception.

Conclusions

In examining the relationship between physiological thermal stress and subjective thermal sensation in a hot-arid urban environment, a number of conclusions may be drawn regarding the utility and limitations of bioclimatic indices such as the ITS.

First of all, the strength of the statistical relationship between ITS and reported thermal sensation makes it clear that a pedestrian-centered energy balance model can indeed serve as a reliable predictor of the extent to which a population will perceive thermal comfort under real-world outdoor conditions. According to this sampling, well over half of the variance in comfort votes is explained by the physical climatic parameters embodied in ITS (R^2=0.57), and just over half is explained by PET as well (R^2=0.53).

When compared with previous representations of this relation between ITS and thermal sensation, which were derived under controlled indoor conditions, the relationship observed in this study indicates that the basic *limit* of thermal acceptability—i.e., the transition from a situation described as "comfortable" to those described as overheated—is largely confirmed. In both cases, this limit is identified under conditions which lead to a net gain by the body of approximately 160 W, accounting for the full range of environmental energy fluxes as well as the level of metabolic heat production and the efficiency of self-cooling by sweat evaporation.

In addition, the fundamental perception of thermal "neutrality"—as expressed by the midpoint of the "comfortable" category on the thermal sensation scale—was found to correspond closely to the condition of physically based neutrality represented by a net-zero value on the ITS scale. This confirms the basic logic of the approach taken by Givoni (1963) in developing the thermal index, which states that the human body's physiological tendency toward *thermal equilibrium* is the basis for our psychological preference for thermal comfort. This correspondence between objective and subject neutrality appears to be robust, as it finds expression not only in the overall sample but in sub-samples taken over different periods of the day.

As the physical ITS metric demonstrates considerable explanatory power when it comes to describing thermal neutrality and thermal acceptability, our analysis shows that additional factors are able to describe the *deviations* from these thermal norms, and thus allow refined models with further explanatory power. The sensation reported at a given level of ITS and the sensitivity of respondents to incremental changes in the thermal environment are both highly *context dependent* in multiple ways. Most notably, it appears that a more severe level of environmental stress is required for pedestrians in an outdoor setting, perhaps due to a process of local adaptation, to report "hot" or "very hot" sensations than it is for subjects inside a closed room. The indication that people's sensitivity to increasing heat stress may have "diminishing returns" (as represented by a nonlinear response of sensation to ITS) further accentuates the possibility that respondents may be reluctant to express "extreme" values.

The extent to which these levels of discomfort are reported for given physical conditions also tends to vary by time of day, apparently due to changing expectations—rendering the index less reliable for predicting precise levels of discomfort than it is for predicting discomfort itself. In describing the original ITS model, Givoni (1963) suggested that "while comfort sensation may have a clear, well-defined significance, those of the different degrees of discomfort depend on psychological and physiological factors, and may vary between groups of subjects…"

The importance of such considerations can be seen in the systematic contributions made by contextual and personal factors in explaining the variance of comfort votes. The effect of physical activity on thermal perception was found to be directly proportional to the metabolic heat generated in the body, and results also indicated that nonthermal stresses such as visual discomfort may have a non-universal but tangible influence on responses. A subject's self-defined "sensitivity" to heat or cold, as well as his or her "general" impression of the prevailing weather conditions, were also seen to have a significant effect.

When taken together, the combination of environmental and personal variables which could be identified in a definitive way explain a large part of the variance in thermal sensation, beyond what is explained by ITS alone. In separate regression analyses, many of the contextual variables proved to be significant when they were combined with ITS either as a complementary term or through an interaction term. A multivariable regression including all of these significant variables yielded an overall R^2 of 0.74, with results indicating not only that such a model can account for the large majority of variance in subjective thermal sensation, but that nearly all predictions are within one level of the observed response. As seen from an ordinal logistic regression of the full model, the probability of a comfortable vote being cast is highest when the value of ITS lies in a zone ranging from just under zero watts (thermal equilibrium) to just over 160 W (transition to overheated conditions). Finally, a decision-rule approach to partitioning the observations identifies similar variables, and provides additional insights into systematic divergences from the thermal response one might expect on the basis of ITS alone.

In summary, these findings should provide a measure of confidence that the complex phenomenon of thermal comfort can, to a meaningful extent, be understood in a systematic way—and they should also serve as a reminder that many of its "intangible" properties remain to be unraveled.

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