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Developing an Adaptive Model of Thermal Comfort and Preference

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ABSTRACT

The adaptive hypothesis predicts that contextual factors and past thermal history modify building occupants' thermal expectations and preferences. One of the predictions of the adaptive hypothesis is that people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones. This is contrary to the static assumptions underlying the current ASHRAE comfort standard 55-92. To examine the adaptive hypothesis and its implications for Standard 55-92, the ASHRAE RP-884 project assembled a quality-controlled database from thermal comfort field experiments worldwide (circa 21,000 observations from 160 buildings). Our statistical analysis examined the semantics of thermal comfort in terms of thermal sensation, acceptability, and preference, as a function of both indoor and outdoor temperature. Optimum indoor temperatures tracked both prevailing indoor and outdoor temperatures, as predicted by the adaptive hypothesis. The static predicted means vote (PMV) model was shown to be partially adaptive by accounting for behavioral adjustments, and fully explained adaptation occurring in HVAC buildings. Occupants in naturally ventilated buildings were tolerant of a significantly wider range of temperatures, explained by a combination of both behavioral adjustment and psychological adaptation. These results formed the basis of a proposal for a variable indoor temperature standard.

INTRODUCTION

Current comfort standards are intended to optimize the thermal acceptability of indoor environments. Unfortunately, they have tended to require energy-intensive environmental control strategies and often preclude thermally variable solutions, such as many climate-responsive and energy-conserving designs, or innovative mechanical strategies that allow for personal control. These standards (ASHRAE 1992, ISO 1994) prescribe a narrow band of temperature to be applied uniformly through space and time. They are based on a static model of thermal comfort that views occupants as passive recipients of thermal stimuli driven by the physics of the body's thermal balance with its immediate environment, and mediated by autonomic physiological responses. The static model of thermal comfort is represented in contemporary thermal comfort standards such as the current *ANSI/ASHRAE Standard 55-1992* (1992) that prescribe relatively constant indoor design temperatures with, at most, a slight seasonal difference to accommodate differences in summer and winter clothing patterns. These standards have come to be regarded as universally applicable across all building types, climate zones, and populations (e.g., Parsons 1994). But many researchers are beginning to challenge the assumption of universality, arguing that it ignores important cultural, climatic, social, and contextual dimensions of comfort, leading to an exaggeration of the need for air conditioning (Kempton and Lutzenhiser 1992).

Growing dissatisfaction with static comfort temperatures and the ensuing environmental impact caused by mismanagement of energy resources, has prompted interest in a variable indoor temperature standard to supplement the current Standard 55. A variable indoor temperature standard, based on the adaptive model of thermal comfort, would have particular relevance to naturally ventilated buildings and other situations in which building occupants have some degree of indoor climatic control. A variable temperature standard links indoor temperatures to the climatic context of the building and accounts for past thermal experiences and current thermal expectations of their occupants.

Ideally, a variable temperature standard would be based on an alternative to traditional comfort theory, termed the adaptive model of comfort, in which factors beyond fundamental physics and physiology interact with thermal perception. An important premise of the adaptive model is that building occupants are no longer regarded as passive recipi-

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ents of the thermal environment, as in the case of climate chamber experimental subjects, but rather, play an active role in creating their own thermal preferences. Contextual factors and past thermal history are believed to modify expectations and thermal preferences. Satisfaction with an indoor climate results from matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate should be like in that same context (Auliciems 1981, 1989, de Dear 1994a, Nicol 1993). In short, satisfaction occurs through appropriate adaptation to the indoor climatic environment.

The generic term adaptation might be interpreted broadly as the gradual diminution of the organism's response to repeated environmental stimulation. Within this broad definition it is possible to clearly distinguish three categories of thermal adaptation (Folk 1974, 1981, Goldsmith 1974, Prosser 1958, Clark and Edholm 1985):

Behavioral Adjustment. This includes all modifications a person might consciously or unconsciously make that in turn modify heat and mass fluxes governing the body's thermal balance. Adjustment can be further sub-classified into personal (e.g., removing an item of clothing), technological (e.g., turning on an air conditioner), and cultural responses (e.g., having a siesta in the heat of the day).

Physiological. The most comprehensive definition of physiological adaptation would include changes in the physiological responses that result from exposure to thermal environmental factors, and which lead to a gradual diminution in the strain induced by such exposure. Physiological adaptation can be broken down into genetic adaptation (intergenerational) and acclimatization (within the individual's lifetime).

Psychological. The psychological dimension of thermal adaptation refers to an altered perception of, and reaction to, sensory information due to past experience and expectations. Personal comfort setpoints are far from thermostatic. Relaxation of expectations can be likened to the notion of habituation in psychophysics (Glaser 1966, Frisancho 1981) where repeated exposure to a stimulus diminishes the magnitude of the evoked response.

In many commentators' minds there is a belief that the static and "adaptive" schools of thought are irreconcilable (e.g., Auliciems 1989, Nicol 1993). The static heat balance models are grounded in a fairly linear, deterministic logic, and are tested with extensive and rigorous laboratory experiments yielding fairly consistent, reproducible results. But the simplistic cause-and-effect approach embodied in the static approach is not so easily applied to the more complex environments within real buildings populated by real occupants as opposed to subjects. Our opinion is that the adaptive perspective complements rather than contradicts the static heat-balance view. The heat-balance model is more correctly regarded as a partially adaptive model, since it acknowledges the effects of behavioral adjustments made by occupants to thermal environmental parameters, clothing, and metabolic rate. We believe that a variable indoor temperature standard can successfully combine features of both the static and adaptive models by incorporating behavioral, physiological, and psychological modes of thermal adaptation.

This paper reports results from the ASHRAE RP-884 project—*Developing an Adaptive Model of Thermal Comfort and Preference*. The research is premised on the development and analysis of a quality-controlled, cumulative database of thermal comfort field experiments worldwide (see de Dear 1998 for more details on the RP-884 database). The specific objectives of RP-884 were to use this global database to:

1. Elaborate and define adaptive processes in the context of indoor climatic perception.
2. Examine the semantics of thermal sensation, acceptability, and preference scales within the context of an adaptive model of thermal comfort.
3. Develop statistical models of thermal comfort based on the various processes of adaptation, including adjustment, acclimatization, and habituation.
4. Compare these adaptive models with predictions of the so-called static models across the database.
5. Propose a variable temperature standard that, in time, might eventually supplement and/or modify Standard 55.

This paper highlights the most significant findings of RP-884, while a more detailed treatment can be found in the project's final report (de Dear et al., 1997).

BACKGROUND

Brager and de Dear (1998) present an extensive literature review on thermal adaptation in the built environment, elaborating the different mechanisms of adaptation, linking the static vs. adaptive comfort theories through a conceptual model with interactive feedback loops, and presenting a wide range of both climate chamber and field evidence for the different modes of adaptation. Many of the highlights of that previous work helped to clarify the conceptual approach and analysis of RP-884, and are presented here for background.

Of the three types of adaptation, behavioral adjustment of the body's heat-balance probably offers the greatest opportunity for people to play an active role in maintaining their own comfort (Nicol and Humphreys 1972, Humphreys 1994a). The extent to which contextual factors offer building occupants scope to behaviorally interact with their indoor climate can be described in terms of adaptive opportunity (Baker and Standeven 1994). This concept helps to differentiate those buildings in which a deterministic relationship between the thermal environment and human response is applicable, and those in which an adaptive feedback loop is fully operational. Adaptive opportunity can be thought of as a continuum—at one extreme is the climate chamber, and at the other extreme we find the single-occupant room with full adaptive possibilities from operable windows through to task-ambient air conditioning.

The evidence for physiological acclimatization is more thoroughly documented for heat exposure than for cold, and for prolonged heat stress induced by a regimen of work in heat (Folk 1974, 1981, Fox 1974, Bruce 1960, Berglund and McNall 1973, Givoni and Goldman 1973). Unlike most behavioral adaptation, where a person consciously takes corrective action when uncomfortable, acclimatization is an unconscious feedback loop mediated by the autonomic nervous system. As shown later in this section, a review of the literature (Brager and de Dear 1998) demonstrated that acclimatization is not likely to be a factor for the moderate range of conditions found in most buildings.

Psychological adaptation encompasses the effects of cognitive and cultural variables, and describes the extent to which habituation and expectation alter thermal perceptions. The role of expectation in thermal comfort research was acknowledged in the earlier work of McIntyre (1980), who stated that "a person's reaction to a temperature, which is less than perfect will depend very much on his expectations, personality, and what else he is doing at the time." Although the least studied of the three adaptive mechanisms, psychological adaptation might actually play the most significant role in explaining the differences between observed and predicted thermal responses. This can be seen particularly in light of different environmental contexts, such as the laboratory vs. home vs. office, or when comparing responses in air-conditioned vs. naturally-ventilated buildings (Fishman and Pimbert 1982, Heijs and Stringer 1988, Busch 1990, de Dear et al. 1991c, Rowe 1995, Oseland 1995).

Climate chamber evidence against the effects of acclimatization on thermal comfort in moderate thermal environments comes from an experimental research design known as the preferred temperature method, in which the temperature within the chamber is directly controlled by its single subject. Using this technique, Fanger (1972 et al., 1977) tested subjects with differing climatic experiences (winter swimmers, workers from a refrigerated storeroom, long-term inhabitants of the tropics, and control groups), and found that their temperature preferences were all approximately the same. de Dear et al. (1991a) replicated Fanger's tropical experiment with heat acclimated students on location in Singapore, and produced similar results. Gonzalez (1979) also studied the role of natural heat acclimatization during a five day humid heat wave in New Haven, Connecticut. He found that for exercising subjects there was a discernible increase in preferred temperature after the heat wave (Gonzalez 1979), but there were no statistically significant differences in resting subjects. In conclusion, on the basis of the majority of experimental evidence published to date, subjective discomfort and thermal acceptability under conditions most typically encountered in residences and office buildings, by resting or lightly active building occupants, appear to be unaffected by the physiological processes of acclimatization.

Although chamber studies have the advantage of careful control, field research is best for assessing the potential impacts of behavioral or psychological adaptations as they occur in realistic settings. Humphreys' (1975) early review of 36 thermal comfort field studies worldwide produced one of the first, and most widely referenced, statistical relationships between indoor thermal neutralities and prevailing indoor temperatures. He found that building occupants were able to find comfort in indoor temperatures covering a broad band of more than 13 K, and attributed this to the adaptive processes, concluding that ". . . the range of recent experience is better regarded as one of the factors that will contribute to the acceptability of the environment to which the respondent is exposed." Subsequent work by both Humphreys (1978) and Auliciems (1981) found convincing evidence for a relationship between indoor thermal neutralities and outdoor climate, particularly in so-called free running buildings that had no centralized heating or cooling plant (i.e., naturally ventilated).

While this work has been widely cited as the first to reveal a strong statistical association between neutralities and outdoor climate, the actual causal mechanisms were left unclear. To more rigorously test the relative influences of behavioral, physiological, and psychological adaptive influences, field researchers have to collect simultaneous measurements of all of the input variables to Fanger's predicted mean vote (PMV) model (ISO 1994). de Dear (1994a) and Brager and de Dear (1998) present a meta-analysis of results from such field experiments conducted in both climate-controlled (air-conditioned) and free-running (naturally ventilated) buildings located in a broad spectrum of climates and seasons (Busch 1990, de Dear and Auliciems 1985, de Dear and Fountain 1994b, de Dear et al. 1991c, Donnini et al. 1996, Schiller et al. 1988). The purpose of the meta-analysis was to compare observed comfort temperatures (based on sensation votes) with those predicted by the static heat balance model (Fanger's PMV index). The PMV model predicted comfort temperatures with reasonable accuracy in most air-conditioned buildings, but failed significantly in the naturally ventilated buildings, with the magnitude of the discrepancy increasing in the more extreme climate zones of the meta-analysis. Since all basic physical parameters governing the body's heat balance were included in PMV's calculations, including the previously ignored contribution of the insulating value of the chair, the mismatch between observation and prediction in naturally ventilated buildings implicate adaptive factors beyond the body's heat-balance.

While we have known for a long time that clothing was a key input to the comfort problem (e.g., the clo inputs to Fanger's 1970 PMV model), only a few studies have examined field evidence of behavioral adjustment in the form of clothing changes. Fishman and Pimbert (1982) found that clo values had a strong linear dependence on outdoor weather and season, especially for women. Humphreys (1994b) and Nicol et al. (1994) concluded that as much as one-half the seasonal changes in comfort temperature could be attributed to clothing flexibility. In a longitudinal study, Nicol and Raja (1996) found that clothing changes were more strongly dependent on the succession of outdoor temperatures that occurred prior to the measurement, compared to the instantaneous or daily mean outdoor temperature, or for that matter, the instantaneous indoor temperature, implying that we dress more for outdoor climate than indoor climate. By asking separate questions about availability, use, and effectiveness of a variety of behavioral adaptive mechanisms, Benton and Brager (1994) found that clothing adjustments were given one of the highest effectiveness ratings. These findings all support the hypothesis that the statistical dependence of indoor neutrality on outdoor climate may, in part, be due to behavioral adjustments that directly affect the heat balance, rather than acclimatization or habituation.

Evidence for psychological adaptation examines how contextual factors influence one's perception of control and expectation, which in turn affect thermal response. Paciuk's (1990) analysis of available control (adaptive opportunity), exercised control (behavioral adjustment), and perceived control (expectation) revealed that perceived degree of control was one of the strongest predictors of thermal comfort in office buildings, and had a significant impact in shaping both thermal comfort and satisfaction. This finding was also supported by the work of Williams (1995), in which office workers expressed higher levels of satisfaction when they perceived themselves to have more control over their environment. The effect of air conditioning on perceived control, expectation, and resulting thermal response has been investigated by several other researchers as well (Rowe et al. 1995, Fishman and Pimbert 1982, Black and Milroy 1966, Rohles et al. 1977). Their findings consistently indicate that people have a wider tolerance of variations in indoor thermal conditions if they can exert some control over them, such as in naturally ventilated buildings. In contrast, people in large open-plan air-conditioned buildings, typically devoid of any individualized control, had higher expectations for homogeneity and cool temperatures, and soon became critical if thermal conditions did not match these expectations.

Methods

Our literature review (Brager and de Dear 1998) indicated that the overwhelming weight of evidence supporting human thermal adaptation came from field research, rather than climate chamber laboratory experiments. Therefore, the RP-884 approach focused exclusively on field data, and began the process of assembling a database by sending a three-page questionnaire on field research methods to most of the thermal comfort research community currently or recently active in field research. On the basis of the questionnaire returns, we requested data from researchers whose:

1. methods of measurement, both physical and subjective, came as close as possible to laboratory-grade,
2. data were structured to allow each set of questionnaire responses to be linked to a concurrent set of indoor and outdoor climate observations, and
3. indoor climatic observations were comprehensive enough to enable heat-balance indices (the static model) to be calculated for each questionnaire respondent.

A primary goal was to keep the internal consistency of the database as high as possible. To this end, the RP-884 database was assembled from raw field data files instead of processed or published findings, enabling us to apply a variety of quality controls and standardized data processing techniques. Since the database is described in detail in de Dear 1998, the purpose of the next section is to briefly outline its contents and the basic steps taken to ensure its integrity.

Assembling the World Comfort Database

The raw data comprising the RP-884 database came from four continents and a broad spectrum of climatic zones. Nearly 21,000 sets of raw data were compiled from several locations in England and Wales, Bangkok, Thailand, several Californian locations, Montreal and Ottawa in Canada, six cities across Australia, five cities in Pakistan, Athens in Greece, Singapore, and Grand Rapids in Michigan.

Each complete set of raw data was structured within the database using the template developed in previous ASHRAE-funded research projects, particularly RP-462 in a Mediterranean climate (Schiller et al. 1988), RP-702 in a hot-humid climate (de Dear and Fountain 1994c), and RP-821 in a cold climate (Donnini et al. 1996). The data fields included:

- thermal questionnaire responses (sensation, acceptability, and preference),
- clothing and metabolic estimates,
- concurrent indoor climate observations (air and globe temperatures, air velocity, dew point, and plane radiant asymmetry temperature),
- thermal indices (mean radiant temperature, operative temperature, turbulence intensity, ET*, SET*, TSENS, DISC, PMV/PPD, and PD draft risk) were recalculated for each set of observations using the ASHRAE RP-781 software package known as the ASHRAE Thermal Comfort Tool (Fountain and Huizenga 1996),
- outdoor meteorological observations including daily temperatures and relative humidities at 600 hours and 1500 hours, and daily effective temperatures (*ET**) also calculated with the software package (excluding the effects of solar radiation).

Of all these variables, it was the clothing insulation estimate that provided the RP-884 team with the most difficulties, since a variety of estimation methods were used in the various database contributions. To standardize the database, clo unit estimates based on either the Sprague and Munson (1974) method (also described in McIntyre 1980), the ISO Standard 7730 (1984) method, or the ISO Standard 7730 (1994) method were converted into their equivalents under the Standard 55 technique by using a set of conversion coefficients described in de Dear (1998). Accompanying each clothing insulation estimate in the database was an indication of whether or not the subject was seated at the time of their questionnaire response, since McCullough and Olesen (1994) have indicated that this has a significant effect on thermal insulation. An increment of 0.15 clo was added to the overall thermal insulation estimate for all seated subjects to account for the insulating value of a typical office chair.

Once the field experiments supplied by original researchers had been quality controlled and standardized into the RP-884 database template, they were broken down according to season (summer/winter) and building type (centrally-controlled buildings—HVAC), naturally ventilated buildings (NV), and mixed-mode buildings. The classification of buildings largely depended on the judgment of the original researchers supplying raw data, but the main distinction between centrally-controlled HVAC and naturally ventilated buildings was that individual occupants in the former had little or no control over their immediate thermal environment, while occupants in naturally ventilated buildings at least had access to operable windows. It should be pointed out that most of the naturally ventilated buildings were only studied in the summer, and so the type of heating system was irrelevant. The few that were studied in winter may still have had a heating system in operation, but it was of the type that permitted occupant control. The sample included too few mixed-mode buildings to permit meaningful analysis, so the remainder of this paper refers exclusively to NV and HVAC buildings.

Meta-Analysis Methods

The statistical analysis underlying the RP-884 adaptive models was conducted at the scale of individual buildings, of which there were 160 in the database. The main reason for this aggregation was that several parameters critical to the objectives of the project, such as thermal neutrality and preferred temperature, can only sensibly be derived from grouped comfort responses. Therefore, the RP-884 adaptive modeling exercise can be thought of as a meta-analysis of the separate statistical analyses conducted on each of the 160 buildings within the database.

Several basic assumptions were made at the outset of the RP-884 meta-analysis. Field experiments with longitudinal research designs (repeated sampling of a few subjects) were assumed to have independence between observations and were statistically analyzed in the same way as cross-sectional research designs (once-off sampling of many subjects). For all statistical modeling conducted on the meta-file, each building data point was weighted according to the number of questionnaire respondents it represented (i.e., sample size within the building). Derived statistical products such as a building's thermal neutrality and preferred temperature were appended as new variables in the meta-file, but if the model or test in question failed to reach statistical significance at $p < 0.05$, the building registered a missing value code for that particular variable in the meta-file. The effect of this significance criterion was to eliminate from further analysis those buildings that had small sample sizes or that had uniformly hot or cold indoor temperature.

Statistical analysis of subjective thermal sensation votes within each building were used to define thermal neutrality—the operative temperature found to correspond most closely with the scale's central vote of neutral. Neutrality was calculated for each building in the meta-analysis by the following steps:

1. We binned the building's indoor operative temperature observations into half-degree (K) increments, and analysed the bins' mean thermal sensation responses.
2. We fitted a weighted linear regression model between sensations and operative temperature (t_o):

$$\textit{mean thermal sensation} = a + b * (t_o)$$

3. Neutrality was derived by solving each building's regression model for a mean sensation of zero.

Apart from neutrality, other information also was extracted from these regression models. Accepting the statistical assumptions underlying Fanger's PMV/PPD model (1970), our range of t_o corresponding with 80% acceptable thermal sensations was determined by solving each building's regression model for mean thermal sensations of ±0.85 (close to slightly cool or warm). The range of t_o corresponding with 90% acceptable thermal sensations was determined in a similar fashion, by solving for mean thermal sensations of ±0.5.

In addition to observed neutralities for each building, the meta-file also contained neutralities predicted by Fanger's (1970) PMV heat-balance index. Our method consisted of inputting each building's mean values for each of the five PMV variables (t_o, rh, v, I_{cl} + *chair insulation*, *met*) to the ASHRAE Thermal Comfort Tool software (Fountain and Huizenga 1996). The PMV model was then solved iteratively by adjusting t_o (t_a with t_r linked) until the PMV output field equaled zero.

Preferred temperature was assessed directly in a subset of 55 buildings in the RP-884 database with questionnaire items resembling this:

> "At this point in time, would you prefer to feel warmer, cooler, or no change?"

The categorical responses to this question led us to probit analysis (Finney 1971, Ballantyne et al. 1977) rather than linear regression. Separate probit models were then fitted to the want warmer and want cooler percentages within each half-degree (K) operative temperature bin. Our operational definition of the preferred temperature within a particular building is the operative temperature corresponding to the intersection of the two fitted probit curves.

The RP-884 work statement specified separate analyses of thermal comfort (assumed to be associated with specified thermal sensations) and preference. The rationale behind this distinction is known as the "semantic artefact hypothesis," which suggests the preferred temperature in cold climates may, in fact, be described as slightly warm, whereas residents of hot climates may use words like slightly cool to describe their preferred thermal state. The RP-884 meta-file offers an opportunity to examine this hypothesis in detail. To this end, a new variable, semantic discrepancy, was defined in our meta-analysis as the temperature difference between a building's neutrality and its preferred temperature (t_o).

ANALYSIS

Numerous thermal indices have been developed by the comfort research community over the years, ranging from relatively simple air and mean radiant temperatures (t_a, t_r) through to more complex heat-balance indices such as *ET**, *SET*, and PMV. The four indices selected for use in the RP-884 analyses were operative temperature (t_o), *ET**, PMV, and *SET**. While the Final Report presents the full set of these results (de Dear et al. 1997), for brevity the results in this section will be confined to the first of these results since it achieved the best correlations with thermal sensation votes in the largest number of buildings in the database. A possible explanation for this diminution of statistical significance as the thermal index becomes more complex is behavioral adaptation. When occupants use clothing adjustments to compensate for inter-individual differences in thermal preference, the more complex indices that account for these adjustments, such as *SET** and PMV, tend to have a more restricted range than is the case with simpler indices that ignore clo units altogether (e.g., t_o). When used in a regression analysis, a diminished range of the independent thermal index variable might be expected to reduce the statistical significance of any relationship with a dependent variable such as thermal sensation vote.

For the sake of simplicity, the results in this paper are confined just to those buildings that were classified as either having centralized HVAC systems or natural ventilation. Buildings falling outside either of these categories were too few to permit any meaningful statistical analysis.

Behavioral Adaptations

Clothing changes, metabolic rate, and air velocity were all examined as indications of behavioral adaptations. A clear example of behavioral thermal adaptation to indoor climate is illustrated in Figure 1. The dependent variable, weighted by the number of observations within each building, is mean intrinsic thermal insulation, including both clothing and furniture components, and presented in clo values. The error-bars plotted above and below building means represent the buildings' standard deviation.

In both the centralized HVAC and naturally ventilated building samples of Figure 1, mean thermal insulation was significantly related to mean operative temperature, but the relationship was stronger in the case of the naturally ventilated buildings, where 66% of the variance in the dependent variable was accounted for by the model ($r = -0.81$, $p < 0.0001$). In such buildings, mean thermal insulation decreased, on average, by 0.1 clo units for every 2 K increase in the building's mean indoor temperature (less than half as sensitive as predicted by the PMV model when adjusting clo units alone).

The metabolic rate of building occupants was another behavioral parameter investigated for possible relationships with indoor temperature, but in both centralized HVAC and naturally ventilated building samples, the regression models were insignificant and ran horizontally through the mean metabolic rate of about 1.2 met units, regardless of indoor temperature.

Mean indoor air speed measured within each building at the same times and locations as subjective thermal questionnaires represents another indication of behavioral adjustment to indoor temperature. Building occupants, particularly in naturally ventilated buildings, might be expected to increase general air movement within their occupied zone, either through operable windows or fans, as air temperatures increased. Figure 2 shows the regression

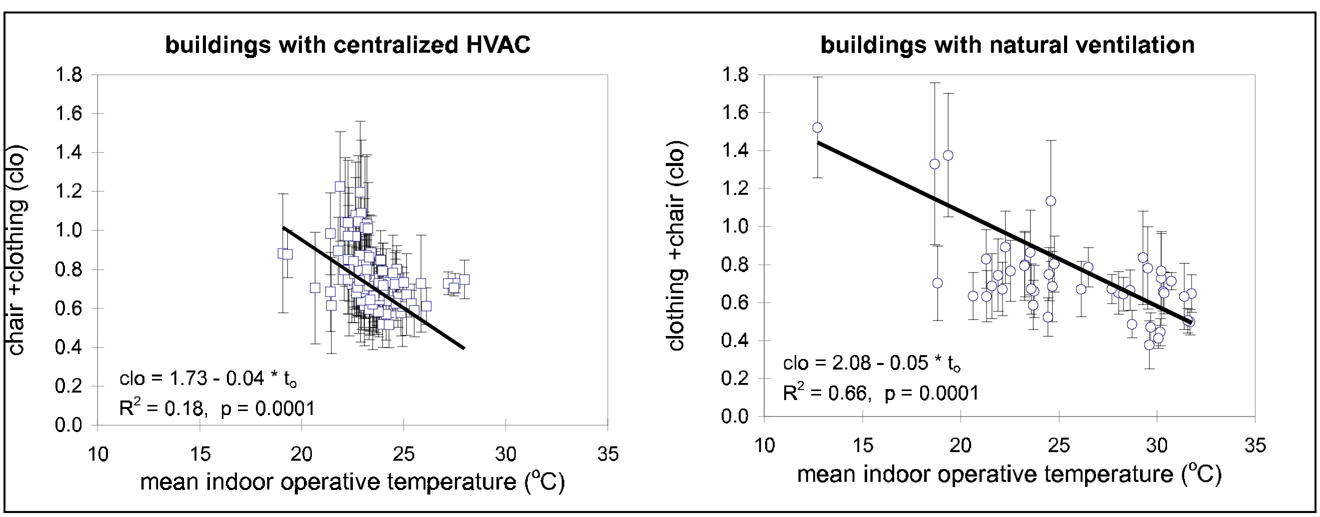

Figure 1 *Clothing as an indicator of behavioral adaptation. Dependence of mean (±stdev) thermal insulation (clothes and chair) on mean indoor operative temperature.*

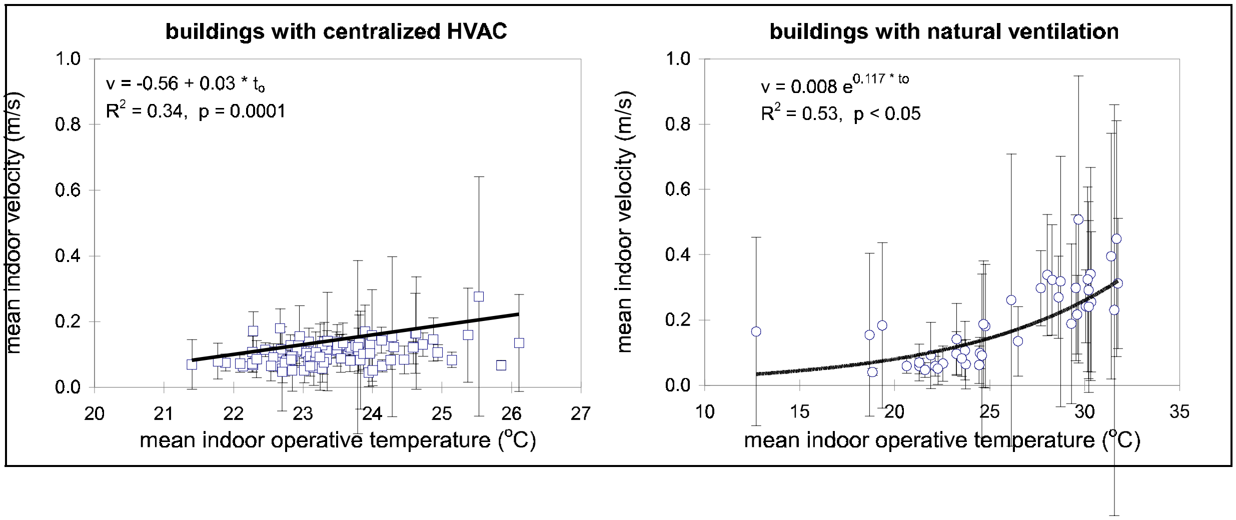

Figure 2 *Air velocity as an indicator of behavioral adaptation. Dependence of mean (±stdev) indoor air speeds on mean indoor operative temperature.*

TABLE 1
Thermal Sensation and Indoor Temperature

	Centrally Heated/ Air-Conditioned Buildings	Naturally Ventilated Buildings
Number of Buildings	109 (2 missing values)	44 (1 missing value)
Number of Buildings with Regression Models Achieving 95% Significance	63 (57.8% of total)	36 (81.8% of total)
Mean (±stdev) Model Constant (a = y-intercept)*	−11.96 (±5.839)	−6.65 (±3.572)
Mean (±stdev) Model Gradient (b)[1]	0.51 (±0.248)	0.27 (±0.134)

Note: Summary of the weighted linear regression of mean thermal sensation on indoor operative temperature.

1. Based on building models ($y = a + b * t_o$) achieving 95% statistical significance or better.

analyses for the two classes of building. Mean air speeds recorded in the HVAC buildings generally were confined to the region below 0.2 m/s, as prescribed in Standard 55. The naturally ventilated buildings, on the other hand, recorded speeds above this draft limit when indoor temperatures extended beyond the upper temperature limit of 26°C in Standard 55. The best-fit regression line for the sample of naturally ventilated buildings was an exponential model that achieved a correlation of $r = +0.73$, ($p<0.05$).

Thermal Sensation, Acceptability, and Preference

Weighted linear regression models were fitted to the relationship between thermal sensation and indoor operative temperature for each building. Table 1 summarizes the models separately for the centralized HVAC and naturally ventilated building samples. Table 1 also indicates that naturally ventilated buildings were more likely than centralized HVAC buildings to achieve a statistically significant regression model for thermal sensation votes, possibly due to the restricted range of temperatures observed in the latter class of buildings. The gradient of the regression model is related to the sensitivity of mean thermal sensation to indoor temperature, and the results in Table 1 suggest that occupants of centralized HVAC buildings were twice as sensitive to temperature deviations away from optimum, compared to their naturally ventilated counterparts, with the difference between the two sub-samples being statistically significant ($T = 5.37$, $df = 97$, $p<0.001$).

Solution of each building's regression model for zero defines thermal neutrality, and the adaptive hypothesis suggests that neutrality should drift toward the mean indoor temperature. Figure 3 shows graphs of the statistical relationship between indoor neutrality and building mean indoor operative temperature, and the statistically significant correlations ($r = +0.5 \sim +0.6$) in both cases lend support to this adaptive hypothesis.

The adaptive hypothesis was noted in the background to predict thermal adaptation to the outdoor climate, as well as

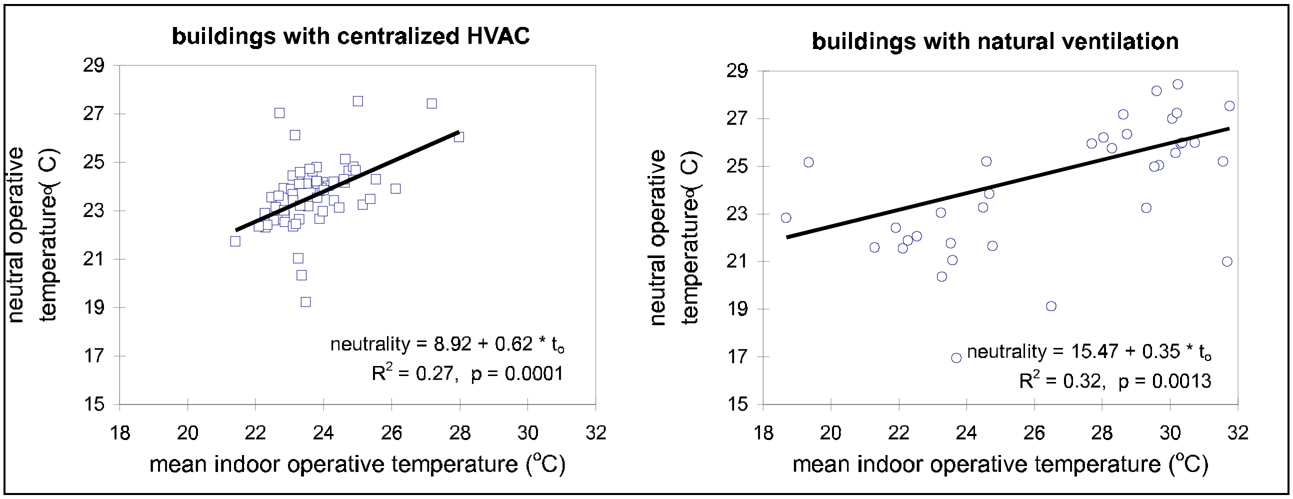

Figure 3 *Neutrality and indoor temperature. Dependence of indoor neutral temperatures on the mean operative temperature prevailing inside the building at the time of survey.*

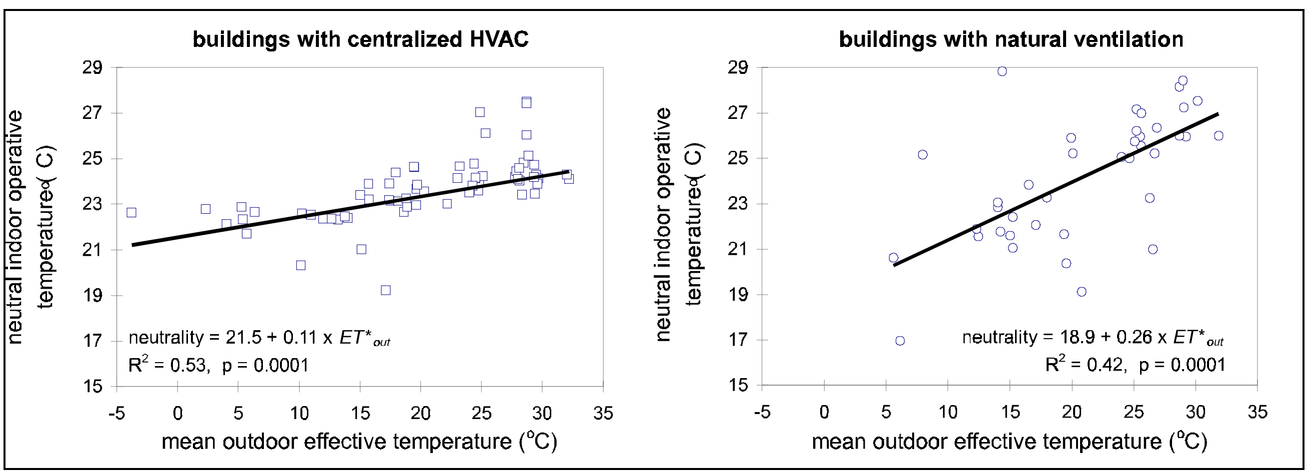

Figure 4 *Neutrality and outdoor temperature. Dependence of indoor neutrality on mean temperature recorded outdoors during each building survey.*

the indoor. If valid, this hypothesis can explain the tendency for indoor neutrality to increase as outdoor climate becomes warmer, and would predict this relationship to be stronger in buildings where people are more connected to the natural swings of the outdoor climate (i.e., naturally ventilated buildings). Figure 4 statistically tests this hypothesis using mean outdoor daily effective temperature (*ET**) as the index of outdoor climate. The range of average neutralities in the HVAC building sub-sample was generally confined to between 21°C and 25°C, compared to 20°C~27°C in the naturally ventilated buildings. Both sub-samples' regression models achieved statistical significance, but the gradient of the naturally ventilated buildings was more than twice that found in the centralized HVAC buildings. Using the method for comparing gradients of two straight regression models based on separate regression fits, as described by Kleinbaum et al. (1988), we found the difference in slopes between HVAC and NV sub-samples in Figure 4 was statistically significant ($T = 3.25$, $df = 101$, $p<0.01$).

Preferred temperatures were extracted from those buildings in the database in which the questionnaire included the appropriate item. In such cases, it was possible to examine the difference between building occupants' neutrality and their preferred operative temperatures. This enabled closer examination of the semantic artefact hypothesis that predicts that people prefer warmer-than-neutral temperatures in cold climates, and cooler-than-neutral temperatures in warmer climates. Regression models were fitted separately to the signed semantic discrepancy for centralized HVAC and naturally ventilated buildings, but only the former achieved statistical significance ($r = +0.62$, $p = 0.0001$):

$$\text{semantic discrepancy in HVAC buildings} = -0.95 + 0.07 \times (\text{outdoor } ET^*) \quad (1)$$

According to this model, occupants of a centrally-controlled HVAC building in a climate zone with a mean outdoor effective temperature of 0°C registered a temperature preference that was about one degree warmer than their thermal neutrality. At the other extreme, occupants of a centrally-controlled HVAC building in a climate zone with a mean outdoor *ET** of 28°C expressed a preference for indoor temperatures one degree cooler than neutrality. This seemingly theoretical question of semantics has a bearing on the practical outcomes of RP-884 in that we view preference as being a more appropriate indicator of one's optimum thermal condition than the customary assumption of neutral thermal sensation. We can now statistically account for preference by defining optimum temperatures in terms of neutrality, plus the correction for the semantic artefact. Figure 5 indicates that correcting HVAC buildings' optimum temperatures has the effect of decreasing their sensitivity to outdoor temperature.

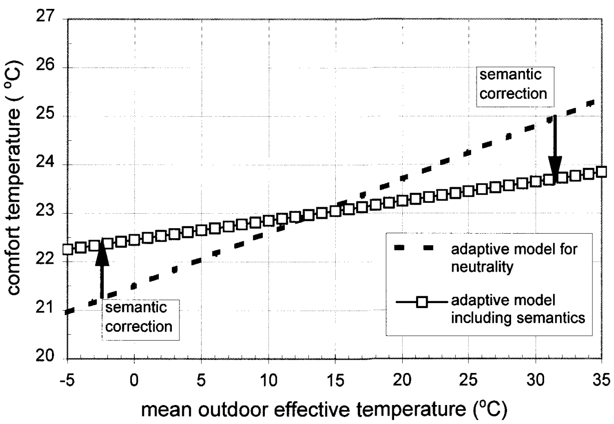

Figure 5 *Thermal sensation vs. preference. The effect of the semantic artefact on comfort temperatures inside buildings with centralized HVAC systems is to decrease their sensitivity to outdoor temperature. The adaptive neutrality model came from Figure 4 and the semantic correction factor between neutrality and preference came from Equation 1.*

Current thermal standards are presented in terms of acceptability. As noted in the Methods section, some buildings in the RP-884 database had questionnaires in which thermal acceptability was rated directly, and the overall observed thermal acceptability of such buildings can be quantified simply as the percentage of the sample of occupants who answered acceptable. Additionally, we were able to give buildings a predicted acceptability rating on the basis of the percentage of indoor climate observations falling within the relevant summer or winter comfort zones of the Standard 55. The latter were defined as the slanting *ET** limits of 20°C to 23.5°C in winter, and 23°C to 26°C in summer on Standard 55-92's psychrometric chart.

A comparison between buildings' observed thermal acceptability ratings and those predicted on the basis of their compliance with Standard 55-92's comfort zones is presented

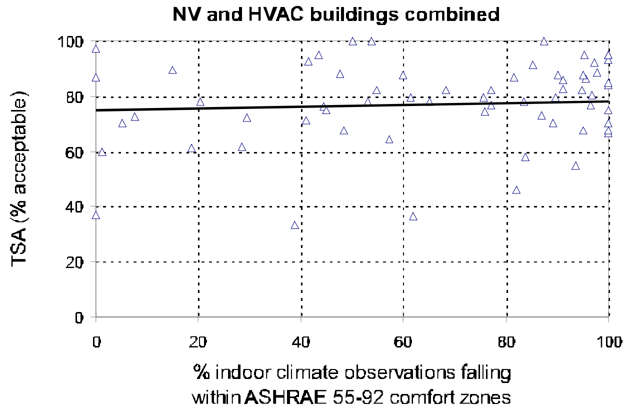

Figure 6 *Thermal acceptability. Thermal acceptability ratings of buildings show no relationship to the compliance of their indoor climates with the Standard 55 comfort zone prescriptions.*

in Figure 6. Admittedly, the total number of buildings in which this comparison could be performed was relatively small. Nevertheless, the insignificant line-of-best-fit (at about 80% acceptability in Figure 6) suggests that compliance with the Standard's *ET** prescriptions had little bearing on how buildings were rated by their occupants.

The limited availability of the direct thermal acceptability questionnaire item across the RP-884 database, combined with insignificant relationship between ratings and objective indoor climatic observations (Figure 6) led us to develop an alternative quantification of building thermal acceptability. In particular, we needed some empirical basis for defining the range of acceptable temperatures within buildings. Our approach was to accept one of the underlying assumptions of Fanger's PMV/PPD indices, namely that a group mean thermal sensation between the limits of $-0.85<\text{PMV}<+0.85$ corresponds with a predicted percentage dissatisfied (*PPD*) of 20%. A more stringent level of acceptability, *PPD*<10%, is assumed in Fanger's method to correspond with a group mean thermal sensation between the limits of $-0.5<\text{PMV}<+0.5$.

These assumptions were applied to our need for acceptable temperature ranges by simply substituting our buildings' observed thermal sensation regressions in place of the PMV index (i.e., acceptability obtained from our observed rather than predicted mean thermal sensation votes). Table 2 contains a statistical summary of acceptable temperature ranges inside our HVAC and NV sample buildings for the 80% and 90% acceptability criteria. The table indicates that both the 80% and 90% acceptable temperature ranges in naturally ventilated buildings were about 70% wider than those calculated for centrally controlled HVAC buildings, lending support to the adaptive hypothesis that occupants with higher levels of personal control will be more tolerant of wider temperature swings.

The end-use of the acceptable temperature ranges listed in Table 2 is their application around the optimum temperature, which was defined earlier as thermal neutrality after correc-

TABLE 2
Range of Acceptable Operative Temperatures

	Centrally Heated/ Air-Conditioned Buildings	Naturally Ventilated Buildings
Number of Buildings	108 (3 missing values)	41 (4 missing values)
Number of Buildings with Regression Models Achieving 95% Significance[1]	62 (57% of total)	33 (75% of total)
80% Acceptability Criterion, Mean (±stdev)	4.1 K (±1.91)	6.9 K (±2.79)
90% Acceptability Criterion, Mean (±stdev)	2.4 K (±1.12)	4.9 K (±3.27)

1. Based on those thermal sensation models ($y = a + b * t_o$) achieving 95% statistical significance or better.

tion for semantic effects (where applicable). Before making this step, we checked for the possibility that these acceptable ranges were statistically related to outdoor climate. Given that the scope for clothing adjustments probably has a bearing on acceptable temperature ranges, and the scope for such adjustments probably diminishes as mean thermal insulation levels approach socially or culturally defined minima, the range of acceptable temperatures also might be expected to diminish in warmer climate zones. Regression analyses indicated this not to be the case, leading us to regard the mean acceptable temperature ranges in Table 2 as constants suitable for application in comfort standards to be proposed later in this paper.

Comparison of Static Model (PMV) With Our Adaptive Models

One of the aims of this research was to compare the performance of the so-called static model with observations of temperature optima in the RP-884 database. Mean thermal insulation worn by building occupants and mean indoor air speeds (both of which are included as inputs to the PMV model) were shown earlier to have a statistical dependence on mean temperatures prevailing within buildings (Figures 1 and 2). Since both of these behavioral adaptations probably are related to outdoor climate, as well as indoor, the neutralities predicted by Fanger's PMV model for a given building and its occupants also can be expected to show some dependence on outdoor climate.

Obviously, the adaptive opportunity for manipulating these parameters is context specific, so comparisons between the PMV predictions and the optimum temperatures observed in our RP-884 database need to be conducted separately in both the centralized HVAC and NV building sub-samples. The static vs. adaptive comparison for RP-884's centralized HVAC buildings in Figure 7 shows that observed comfort temperatures, after correction for semantic effects, have only a moderate variation (less than 2 K) across a wide range of outdoor climates (spanning about 40 K). An interpretation of this finding could be that occupants of such buildings have

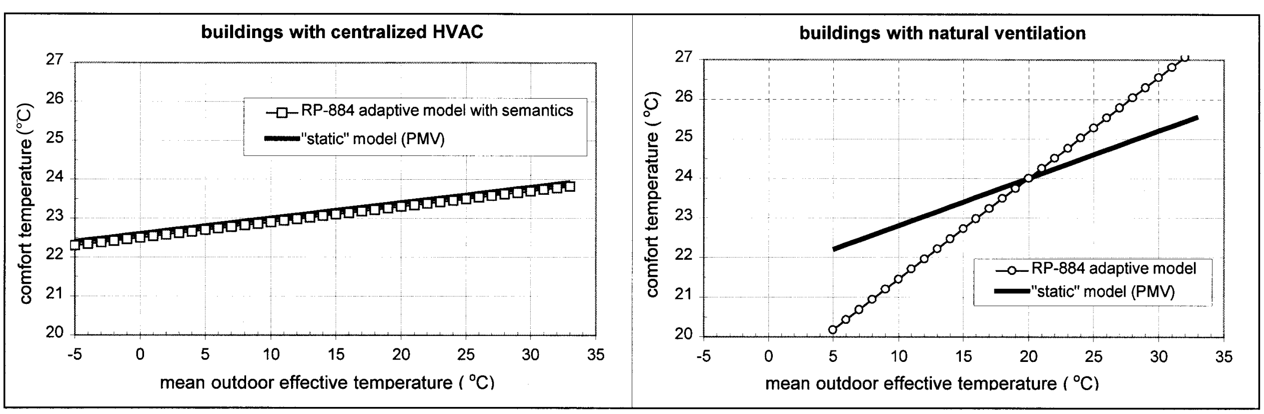

Figure 7 *Adaptive vs. static comfort model predictions. Comparison of the RP-884 adaptive models' predicted indoor comfort temperatures with those predicted by the static PMV model. The static model's comfort temperature for each building was derived by inputting the building's mean v, rh, clo, met into the PMV model and then iterating for different t_o until PMV = 0. The left-hand panel shows results from buildings with centrally controlled HVAC systems. The right-hand panel shows results from naturally ventilated buildings.*

become finely adapted to the mechanically conditioned and static indoor climates being provided by centralized HVAC services. The question of what type of adaptation this might be can be answered by the comparison with comfort temperatures predicted by the so-called static model (PMV). The observed (adaptive) and predicted (PMV) models appear close together in the left panel of Figure 7, with the discrepancy being a trivial 0.1 K offset in their Y-intercepts. PMV, therefore, appears to have been remarkably successful at predicting comfort temperatures in the HVAC buildings of RP-884's database. A corollary of this finding is that the behavioral adjustments to clothing and room air speeds observed for the occupants of HVAC buildings fully explain the systematic response in comfort temperature to outdoor climatic variation, and that these adaptive behaviors are, in fact, adequately accounted for by the PMV model.

It is interesting to note that this graph so closely matches predictions of PMV with observations in real buildings with centralized HVAC, whereas many of the earlier thermal comfort field research papers discussed in this paper's literature review indicated quite the opposite. Indeed, some of those anomalous papers were from authors who contributed their raw data to this project's database. Our success at bringing PMV predictions into line with optimum temperature observations in HVAC buildings most probably can be attributed to the quality controls and precautions we took when assembling the RP-884 database, which transformed, to some extent, the raw data used in the contributors' original analyses. Among the more important of these controls were:

1. setting minimum standards on instrumentation and protocols for data going into the RP-884 database,
2. conversion of all clo estimates throughout the entire database to a single standard (ASHRAE 55-92),
3. inclusion of the thermal insulation effects of the chairs used by subjects (McCullough and Olesen 1994),
4. recalculation of thermal indices from raw data throughout the entire database with a consistent software tool (Fountain and Huizenga 1996),
5. application of a consistent set of statistical techniques to all raw data instead of relying on different author's approaches to thermal neutrality, preference and other statistically derived parameters,
6. conducting the meta-analysis at the appropriate scale of statistical aggregation, namely the individual building.

The right-hand panel of Figure 7 repeats the adaptive vs. static comparisons for the naturally ventilated buildings within the RP-884 database. One important departure from the method just described for HVAC buildings, however, is the omission of the semantic effect. This was because we were unable to discern any systematic relationship between the preferred and neutral temperatures in our sample of naturally ventilated buildings. The close agreement found between PMV and adaptive models in the centralized HVAC building sample clearly breaks down in the context of naturally ventilated buildings where the regression line fitted to observation shows a gradient almost twice as steep as the heat-balance PMV regression's. This divergence tested positive using the Kleinbaum et al. technique (1988) ($T = 2.43$, $df = 80$, $p<0.05$). It therefore appears as if behavioral adjustments to body heat balance (clo and air speed adjustments) account for only about half of the climatic dependence of comfort temperatures within naturally ventilated buildings. In effect, the PMV model has been demonstrated to function as a partially adaptive model of thermal comfort in naturally ventilated buildings.

However, there still remains the other half of the adaptive effect to be explained. Having taken account of the effects of behavioral adaptations, what is left is the physiological (acclimatization) and psychological (habituation) hypotheses discussed in the Introduction to this paper. There it is noted that effects of acclimatization were not in evidence during climate chamber experiments on moderate heat/cold stress exposures, so it is not surprising that they failed to appear in the field setting of the RP-884 database. Therefore, by a process of elimination, we are left with psychological adaptation (i.e., expectation and habituation) as the most likely explanation for the divergence between field observations and heat-balance (PMV) predictions in naturally ventilated buildings. Apparently, the physics governing body heat balance are inadequate to explain the relationship between comfort in naturally ventilated buildings and their external climatic context. But these findings do support the adaptive hypothesis that thermal comfort is achieved by correctly matching indoor thermal conditions and expectations, based on past experiences and architectural norms.

PROPOSAL FOR AN ADAPTIVE COMFORT STANDARD

This section takes the RP-884 adaptive models forward into a proposal for a variable temperature thermal comfort standard. Analyses in the preceding section were conducted separately for buildings with and without centrally controlled HVAC systems, and yielded quite different results. It seems logical, therefore, to partition the variable temperature standards along these same lines. This distinction between buildings in which individual occupants have little or no control over their immediate thermal environment, and those in which occupants at least have control over windows is a unique feature of the ASHRAE RP-884 project. All thermal comfort standards to date, both extant and proposed, regardless of their static or adaptive bases, have been promulgated as universally applicable across all types of buildings. Earlier comfort standards, in effect, attempt to extrapolate from relationships established in centrally controlled HVAC settings to naturally ventilated contexts, or vice versa. In contrast, a fundamental tenet of RP-884 has been that the indoor climates found in centrally-controlled HVAC and naturally ventilated buildings are not only quantitatively different, but also qualitatively distinct, and as such, require separate comfort standards.

Standard for Buildings with Centrally Controlled HVAC

- ***Purpose:*** To specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within centrally heated and air-conditioned spaces.
- ***Scope:*** This standard applies to general thermal comfort conditions and excludes local discomforts such as draft, vertical thermal stratification, and radiant asymmetry. This standard is intended for use in the design of HVAC-systems, design of buildings, evaluation of existing thermal environments, prediction of the acceptability of expected thermal environments, building ratings or labeling, and testing of HVAC system performance. The standard applies exclusively to indoor environments with HVAC systems over which the occupants have no control. The occupants of such buildings are presumed to have no option to open/close windows.

Definitions

—**adaptive model:** A linear regression model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. Note that the range of applicable outdoor climates should be restricted to that appearing on the X-axis of the adaptive model's graph (i.e., they should not be extrapolated beyond the range of the regression model's X-variable).

—**insulation, thermal:** The resistance to sensible heat transfer provided by a clothing ensemble (i.e., more than one garment) and the chair upon which they are seated. It is described as the intrinsic insulation from the skin to the clothing surface, not including the resistance provided by the air layer around the clothed body; it usually is expressed in clo units. The (I_{cl}) provided by clothing ensembles can be estimated by summing the garment I_{clu} values as described in Standard 55 (1992). The incremental thermal insulation of chairs used by building occupants needs to be added to I_{cl}. The typical office chair's clo value is ~0.15 clo units.

—**mean monthly (or daily) outdoor effective temperature:** Arithmetic average of 6 am outdoor *ET** (assumed minimum), and 3 pm outdoor *ET** (assumed maximum) for a calendar month or particular day. Calculations are performed on air and humidity measurements taken in accordance with standard methods of meteorological measurement.

—**neutrality, thermal:** the indoor thermal index value (usually operative temperature) corresponding with a mean vote of neutral on the thermal sensation scale by a sample of building occupants. Note that this cannot be assumed to coincide with preferred temperature in centrally-controlled HVAC buildings (see Figure 5).

—**PMV, analytic:** Predicted Mean Vote index calculated analytically from mean measurements or estimates of the six primary comfort parameters: mean air and radiant temperatures, mean air speed, humidity, clothing (plus chair) thermal insulation, and metabolic rate.

—**PMV, adaptive:** the RP-884 adaptive regression model that predicts optimum thermal comfort temperature (thermal neutrality corrected for semantics—see Figure 5), as a function of outdoor climate. The name adaptive PMV is used for the model because it predicts essentially the same optimum operative temperature as the analytic PMV approach (assuming $t_a = t_r$), but uses mean outdoor effective temperature as the only input instead of the usual four inputs (*clo*, *met*, *rh* and *v*) required by the analytic PMV method to predict optimum operative temperatures (see left panel of Figure 7).

—**sensation, thermal:** a conscious feeling commonly graded into the categories, −3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, and +3 hot; it requires subjective evaluation. An individual's ideal thermal comfort does not necessarily correspond with a thermal sensation vote of neutral (zero).

—**summer:** operationally defined as the cooling season; climatologically defined for the purposes of this standard as having a mean daily outdoor effective temperature of 25^{o}C.

—**temperature, optimum operative:** the operative temperature that satisfies the greatest possible number of people at a given clothing and activity level. Due to the semantic offset between preferred and neutral temperatures, optimum operative temperature in centrally controlled HVAC buildings does not necessarily correspond exactly with thermal neutrality (i.e., optimum temperature is neutrality after correction for semantic offset—see Figure 5).

—**winter:** operationally defined as the heating season; climatologically, for the purposes of this standard, a typical winter condition is assumed to have a mean daily outdoor effective temperature of 0^{o}C.

Conditions for an Acceptable HVAC Thermal Environment. The conditions for an acceptable thermal environment shall be based on one of the following three techniques, listed in order of preference:

- the analytic PMV method, as described in ISO 7730 (1994), if mean clothing and metabolic rates are known in advance, or
- the adaptive PMV method in which indoor optimum operative temperature is predicted from a knowledge of outdoor effective temperature using RP-884 regression models, or
- the prescriptive method in which summer and/or winter comfort zones for either 90% or 80% thermal acceptability levels are selected from the RP-884 psychrometric charts.

Analytic PMV Method for HVAC Buildings. See the detailed procedures for estimation of the optimum operative temperature for a group of building occupants described in ISO 7730 (1994). Note that the optimum temperature predicted by setting PMV = 0 (neutral) will coincide with the temperature the majority of occupants actually prefer (a group mean preference for no change). But at that same predicted optimum, the actual mean sensation vote (as opposed to predicted mean vote) expressed by the group of building occupants may differ from neutral. This is due to the semantic offset between observed group thermal neutrality and preference, where people might actually prefer to feel a sensation other than neutral when they are at optimum conditions (Figure 5).

Adaptive PMV Method for HVAC Buildings. In centrally controlled HVAC buildings where the mean thermal insulation (clothing and chairs) and mean air speed cannot be observed or accurately anticipated, the adaptive PMV method may be applied. Weather data in the form of mean outdoor effective temperature for the relevant time of year are required. In the absence of current meteorological observation, published mean climatological data for the relevant month from the nearest weather station may suffice.

Prescriptive Method for HVAC Buildings. Where outdoor meteorological or climatological data are unavailable, the RP-884 prescriptive method may be used to define acceptable ranges of temperatures. The prescriptions are designed to provide environments in which minimum levels of thermal acceptability (based on general thermal comfort) can be selected as either 90% or 80%.

The comfort zones' slanting side boundaries in Figure 9 are defined in terms of effective temperature (*ET**) lines and are loci of constant thermal sensations. They were derived from the analyses in Table 2. The upper wet-bulb temperature limits were taken from the Addendum to Standard 55 but adjusted to restrict relative humidity in the summer season below 85% .

Standard for Naturally Ventilated Buildings

Purpose: To specify the thermal environmental conditions that will be acceptable to a majority of the occupants of naturally ventilated spaces.

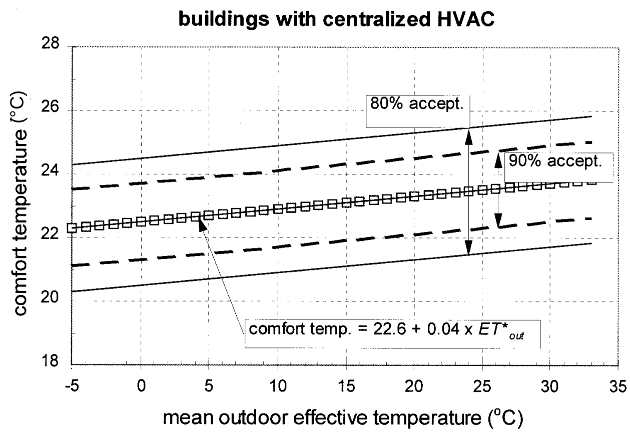

***Figure** 8 Variable temperature standard, adaptive method—Centralized HVAC. Adaptive PMV method for predicting optimum comfort temperature and acceptable temperature ranges (80% and 90% general comfort criteria) in centrally controlled HVAC buildings. The optimum comfort temperature model came from Figure 5 (including the semantic correction factor) and the 80% and 90% acceptable ranges came from Table 2.*

Scope: The scope of this standard is essentially the same as that for the preceding (HVAC) standard, except that this standard is intended for use in the design of naturally ventilated buildings and evaluation of existing or expected thermal environments within such buildings. The standard applies exclusively to indoor environments without centralized HVAC systems. Such buildings are presumed to have operable windows that the occupants have some degree of control over. They may have some form of heating installed, but it would be controlled by the building occupants, either individually or in small groups.

The standard cannot be used to decide when and where to install centralized air conditioning. While it may provide useful information in relation to such decisions, the standard cannot be regarded as the sole criterion. For example, the adaptive opportunity afforded the occupants of naturally ventilated buildings also should be borne in mind.

Definitions. The definitions presented in the preceding section apply to this standard as well, except in the case of the following terms.

—**naturally ventilated:** Those premises in which centralized heating, ventilation, and air-conditioning systems are absent and windows are operable. Some form of heating may be present, but it would normally be under the control of building occupants.

—**temperature, optimum operative:** the operative temperature that satisfies the greatest possible number of people at a given clothing and activity level. Optimum operative temperature in this standard corresponds reasonably well with both thermal neutrality and preferred temperature.

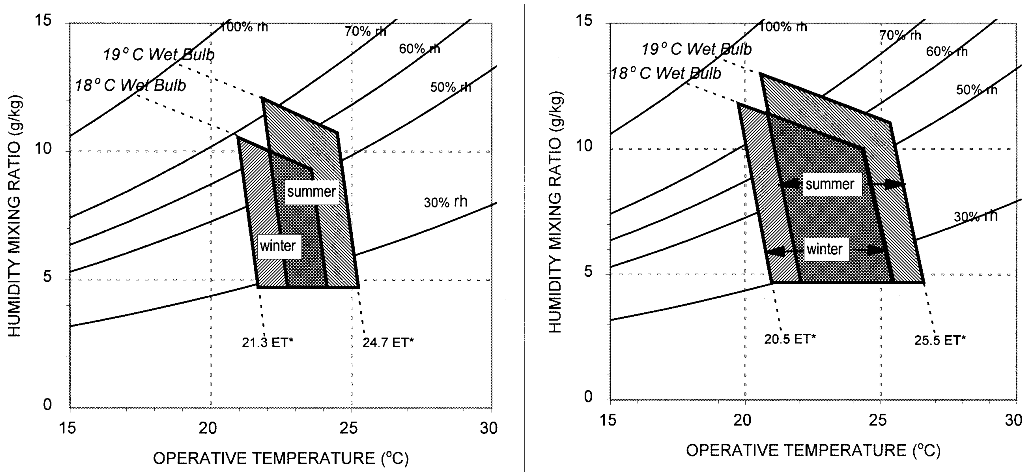

Figure 9 *Variable temperature standard, prescriptive method —Centralized HVAC. The prescriptive method for predicting acceptable temperature ranges in centrally controlled HVAC buildings. The left-hand chart shows summer and winter prescriptions for the 90% general acceptability criterion and the right-hand chart refers to the 80% general acceptability criterion. Selection of summer or winter comfort zone should be based on mean insulation levels seasonally described in Table 3.*

TABLE 3

Variable Temperature Standard, Prescriptive Method—Centralized HVAC[1]

Season	Description of I_{cl} Typical Thermal Insulation	clo	Optimum Temperature	Operative Temperature Range (90% accept.)	Range (80% accept.)
Winter	heavy slacks, long sleeve shirt, sweater and office chair	1.05	22.5°C	21.3°C to 23.7°C	20.5°C to 24.5°C
Summer	light slacks, short sleeve shirt and office chair	0.65	23.5°C	22.3°C to 24.7°C	21.5°C to 25.5°C

Note: Optimum and acceptable ranges of operative temperature for persons engaged in light, primarily sedentary activity ($\leq$ 1.2 mets) at 50% relative humidity and mean air speed $\leq$0.15 m s^{-1}. For use in buildings with centralized HVAC systems.

[1] For infants, certain elderly persons, and individuals who are physically disabled, the lower limits of Table 3 should be avoided.
Clo values in the table were derived from seasonal analyses of the HVAC buildings within the RP-884 database (de Dear, Brager and Cooper 1997). They include 0.15 clo for chair effects. The temperature ranges came from Table 2.

Conditions for an Acceptable Naturally Ventilated Thermal Environment. The conditions for an acceptable thermal environment shall be based exclusively on the adaptive model (linear regression) approach. The PMV/PPD model is inapplicable to naturally ventilated premises because it only partially accounts for processes of thermal adaptation to indoor climate. The model was developed in tightly controlled laboratory conditions where people had no control over their environment (a context quite similar to buildings with centralized HVAC systems, but much less relevant to naturally ventilated buildings). The prescription of summer and winter comfort zones is inappropriate for this standard because the steep gradient on the naturally ventilated adaptive model would render climatological definitions of universal summer and winter conditions misleading.

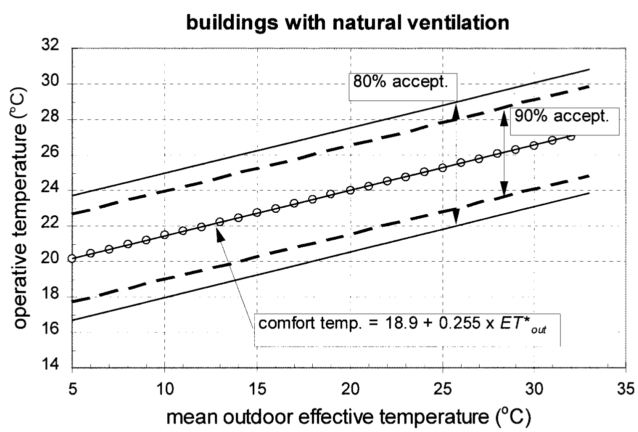

Figure 10 *Variable temperature standard, adaptive method—Natural ventilation. Adaptive model for predicting optimum comfort temperature and acceptable temperature ranges (80% and 90% general comfort criteria) in naturally ventilated buildings. The optimum comfort temperature line came from Figure 4 and the acceptable temperature ranges came from the deltas in Table 2.*

CONCLUSIONS

This work was premised on a conceptual framework combining features of both the static and adaptive theories of thermal comfort. The static heat balance model can be viewed as a *partially* adaptive model, accounting for the effects of behavioral adjustments that directly affect inputs such as clothing or air velocity. An adaptive model of comfort complements this conventional approach by accounting for additional contextual factors and thermal experiences that modify building occupants' expectations and thermal preferences. The RP-884 approach began by assembling a quality-controlled, thermal comfort database containing nearly 21,000 sets of raw field data compiled from previous thermal comfort field experiments conducted on four continents and across a broad spectrum of climatic zones. Data analysis was done separately for buildings with centrally-controlled HVAC systems, and for buildings that were naturally ventilated (i.e., had operable windows). The analysis examined the semantics of thermal comfort response in terms of thermal sensation, acceptability, and preference, all as a function of both indoor and outdoor temperatures. Observed responses also were compared to predicted thermal sensation using the PMV model.

By successfully accounting for behavioral adjustments, the so-called static model of comfort (represented in this paper by Fanger's PMV model) was demonstrated to be a partially adaptive model, and appears suitable for application as it was *initially* proposed back in 1970 by Fanger himself—as an engineering guide in centrally controlled HVAC buildings where occupants have little or no control over their immediate thermal environment. In the introductory chapter to *Thermal Comfort—Analysis and Applications in Environmental Engineering*, Fanger was quite clear that his book, and by implication, the PMV model at its core, were intended for application by the HVAC industry in the creation of artificial climates in controlled spaces (Fanger 1970). The extrapolation of the model's scope to all spaces intended for human occupancy, including those with natural ventilation, was a much later development that the results in this paper fail to justify.

Although there have been numerous publications from field studies showing differences between PMV-predictions and observed mean thermal sensations, the RP-884 analysis offers some insights into why these discrepancies might have occurred. One explanation is the diversity of methods used to estimate clo values. The present analysis demonstrated that clo estimates need to be standardized and the method described in *ANSI/ASHRAE 55-92* appears to be a logical choice. Clo estimates also need to include the incremental contribution of chair insulation. Another source of error in field research appears to be the assumption that neutral always coincides with ideal (preferred). This was shown not to be the case for people in buildings with centralized HVAC systems. Occupants were found to prefer a sensation slightly cooler than neutral in summer and slightly warmer than neutral in winter. So, if one accepts that preference is a more appropriate indicator of optimum than neutral, then the PMV model appears to accurately predict thermal optima in buildings where occupants have no control over their environment.

The relationship between optimum temperatures and prevailing indoor/outdoor temperatures presented in this paper demonstrates that adaptation is at work in buildings with centralized HVAC, but only at the biophysical (behavioral) level of clothing and air speed adjustments. HVAC building occupants appear to be adapted quite well to the conditions they are being given (22°C~24°C), but are intolerant of temperatures that fail to match these expectations.

The patterns of thermal responses in naturally ventilated buildings were significantly different. First, occupants appear tolerant of a much wider range of temperatures than in the centralized HVAC buildings, and find conditions well outside the comfort zones published in Standard 55-92 (ASHRAE 1992) to be acceptable. Physical explanations for the correlation between indoor comfort temperatures and outdoor climate, such as clothing insulation or indoor air speeds, accounted for only half the observed variance. By a process of elimination, we conclude that psychological adaptation in the form of shifting expectations—the subjective comfort set-points—account for the residual variation observed in the comfort temperatures of our database. Current standards such as *ANSI/ASHRAE 55-1992* and the PMV model prescribe a much too narrow range of conditions in such buildings, are inappropriate for predicting acceptability, and are unsuitable guides for deciding when and where HVAC systems are required.

The results of the RP-884 analysis enabled us to propose a variable temperature thermal comfort standard to supplement Standard 55 (1992). The proposed standard was presented in two separate sections—one for buildings with centrally controlled HVAC systems and the other for naturally ventilated premises. Both of the proposed standard's sections include 80% and 90% acceptability zones.

At least two suggestions for further research emerge from this project. The first involves a closer examination of the semantic artefact issue and its context specificity. We found a clear climatic relationship between the sensation-preference semantic offset and outdoor climatic context for occupants of buildings with centralized HVAC buildings, but not so in naturally ventilated buildings. This requires an explanation which, at this time, we are unable to offer. The second area for further research is an intervention field experiment in which buildings with centralized HVAC systems have their set points manipulated outside the 22~24 envelope by an adaptive algorithm more closely resembling the naturally ventilated model (see Figure 10), rather than the HVAC adaptive model (see Figure 8). Our results were interpreted to indicate that occupants of HVAC buildings had become finely tuned to the very narrow range of indoor temperatures being presented by current HVAC practice. But there is potentially a very high energy cost to maintaining those narrowly defined comfortable thermal conditions. In contrast, occupants of naturally ventilated buildings had a greater scope of adaptive opportunity, and were thus comfortable across a wider band of temperatures that more closely reflected the patterns of outdoor climate change. This suggests an opportunity to optimize both energy use and thermal comfort if we can take these broader adaptive mechanisms into account when designing and operating buildings. To this end, the challenge still remains to determine how far that adaptation can be pushed in the context of a building in which occupants have little or no individual thermal control.

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REFERENCES

ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Auliciems, A. 1981. Towards a psychophysiological model of thermal perception. *Int. J. Biometeor* 25: 109-122.

Auliciems, A. 1989. Thermal Comfort. In *Building design and human performance,* pp.71-88. Ed.: Ruck, N. New York: Van Nostrand.

Baker, N.V. 1993. Thermal comfort evaluation for passive cooling —A PASCOOL task. In *Proceedings of Conference on Solar Energy in Architecture and Planning.* Florence: HS Stephens and Associates.

Baker, N., and M. Standeven. 1994. Comfort criteria for passively cooled buildings—A PASCOOL task. *Renewable Energy* 5(5-8) (Aug.): 977-984.

Ballantyne, E.R., R.K. Hill, and J.W. Spencer. 1977. Probit analysis of thermal sensation assessments. *Int. J. Biometeor* 21(1): 29-43.

Berglund, L., and P.E. McNall, Jr. 1973. Human sweat film area and composition during prolonged sweating. *Journal of Applied Physiology* 35(5): 714-718.

Benton, C.C., and G.S. Brager. 1994. *Sunset Building: A study of occupant thermal comfort in support of PG&E's advanced customer technology test (ACT2) for Maximum Energy Efficiency,* Final Report, CEDR-06-94, Center for Environmental Design Research, University of California, Berkeley.

Black, F.A., and E.A. Milroy. 1966. Experience of air conditioning in offices. *J. Inst. Heat. Vent. Engrs.* 34: 188-196.

Brager, G.S., and R.J. de Dear. 1998. Thermal adaption in the built environment: A literature review. *Energy and Buildings* (in press).

Bruce, W. 1960. *Man and his thermal environment: Physiological adjustments to conditions and assessment of comfort in buildings. Technical Paper, No. 84: Division of Building Research*. Ottawa: National Research Council.

Busch, J.F. 1990. Thermal responses to the Thai office environment. *ASHRAE Transactions* 96(1): 859-872.

Clark, R.P., and O.G. Edholm. 1985. *Man and his thermal environment.* Edward Arnold.

de Dear, R.J. 1998. A global database of thermal comfort field experiments. *ASHRAE Transactions* 104(1).

de Dear, R.J. 1994a. Outdoor climatic influences on indoor thermal comfort requirements. In *Thermal comfort: past present and future.* Eds.: Oseland, N.A., and Humphreys, M.A. United Kingdom: BRE.

de Dear, R.J., and A. Auliciems. 1985. Validation of the Predicted Mean Vote model of thermal comfort in six Australian field studies. *ASHRAE Transactions* 91(2): 452-468.

de Dear, R. J., G.S. Brager, and D.J. Cooper. 1997. *Developing an adaptive model of thermal comfort and preference - Final Report on ASHRAE RP-884.* Sydney: MRL.

de Dear, R.J., and M.E. Fountain. 1994b. Field experiments on occupant comfort and office thermal environments in a hot-humid climate. *ASHRAE Transactions* 100(2): 457-475.

de Dear, R.J., and M.E. Fountain. 1994c. Thermal comfort in air-conditioned office buildings in the tropics. *Journal of the Australian Institute of Refrigerating, Air-Conditioning and Heating* 48(9): 14-30.

de Dear, R.J., M.E. Fountain, S. Popovic, S. Watkins, G. Brager, E. Arens, and C. Benton. 1993. *A field study of occupant comfort and office thermal environments in a hot-humid climate: Final report on ASHRAE RP-702.* Sydney: MPRL.

de Dear, R.J., K.G. Leow, and A. Ameen. 1991a. Thermal comfort in the humid tropics—Part I: Climate chamber experiments on temperature preferences in Singapore. *ASHRAE Transactions* 97(1): 874-879.

de Dear, R.J., K.G. Leow, and A. Ameen. 1991b. Thermal comfort in the equatorial climatic zone—Part II: Climate chamber experiments on thermal acceptability in Singapore. *ASHRAE Transactions* 97(1): 880-886.

de Dear, R.J., K.G. Leow, and S.C. Foo. 1991c. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology* 34: 259-265.

Donnini, G., J. Molina, C. Martello, D.H.C. Lai, L.H. Kit, C.Y. Chang, M. Laflamme, V.H. Nguyen, and F. Haghighat. 1996. *Field study of occupant comfort and office thermal environments in a cold climate: Final report on ASHRAE RP-821*. Montreal, Quebec, Canada: AND Inc.

Fanger, P.O. 1970. *Thermal Comfort—Analysis and Applications in Environmental Engineering*. Copenhagen: Danish Technical Press.

Fanger, P.O. 1972. Improvement of human comfort and resulting effects on working capacity. *Biometeorology* (II): 31-41.

Fanger, P.O., J.H. Hobjerre, and J.O.B. Thomsen. 1977. Can winter swimming cause people to prefer lower room temperatures? *International Journal of Biometeorology* 21(1): 44-50.

Finney, D.J. 1971. *Probit analysis*, 3d ed. United Kingdom, Cambridge: Cambridge Univ. Press.

Fishman, D.S., and S.L. Pimbert. 1982. The thermal environment in offices. *Energy and Buildings* 5(2): 109-116.

Folk, G.E. 1974. Adaptation and heat loss: The past thirty years. Heat loss from animals and man: Assessment and control. In *Proceedings of the 20th Easter School in Agricultural Science, Univ. of Nottingham*. J.L. Monteith, and L.E. Mount, eds. London: Butterworths.

Folk, G.E. 1981. Climatic change and acclimatization. From *Bioengineering, Thermal physiology and comfort*, Cena, K., and J.A. Clark, eds., pp. 157-168. Amsterdam: Elsevier.

Fountain, M.E., and C. Huizenga. 1996. *WinComf©: A Windows 3.1 thermal sensation model—User's manual*. Berkeley, Calif.: Environmental Analytics.

Fox, R.H. 1974. Heat acclimatization and the sweating response. Heat loss from animals and man: assessment and control. In *Proceedings of the 20th Easter School in Agricultural Science, Univ. of Nottingham*. J.L. Monteith, and L.E. Mount, eds. London: Butterworths.

Frisancho, A.R. 1981. *Human Adaptation*. Ann Arbor: U. of Mich. Press.

Givoni, B., and R.F. Goldman. 1973. Predicting effects of heat acclimatization on heart rate and rectal temperature. *Journal of Applied Physiology* 35(6): 875-879, Dec.

Glaser, E. 1966. *The physiological basis of habituation*. London: O.U.P.

Goldsmith, R. 1974. Acclimatization to cold in man—Fact or fiction? Heat loss from animals and man: assessment and control. In *Proceedings of the 20th Easter School in Agricultural Science, Univ. of Nottingham*. J.L. Monteith, and L.E. Mount, eds. London: Butterworths.

Gonzalez, R.R. 1979. Role of natural acclimatization (cold and heat) and temperature: Effect on health and acceptability in the built environment. *Indoor Climate*. P.O. Fanger, and O. Valbørn, eds., pp. 737-751. Copenhagen: Danish Building Research Institute.

Heijs, W., and P. Stringer. 1988. Research on residential thermal comfort: some contributions from environmental psychology. *J. Environ. Psychol*. 8: 235-247.

Humphreys, M.A. 1975. Field studies of thermal comfort compared and applied. *U.K. Department of Environmental Building Research Establishment Current Paper. (76/75)*.

Humphreys, M.A. 1978. Outdoor temperatures and comfort indoors. *Building Research and Practice* 6(2): 92-105.

Humphreys, M.A. 1994a. Field studies and climate chamber experiments in thermal comfort research. In *Thermal comfort: Past present and future*. N.A. Oseland, and M.A. Humphreys, eds. United Kingdom: BRE.

Humphreys, M.A. 1994b. An adaptive approach to the thermal comfort of office workers in North West Pakistan. *Renewable Energy* 5(ii): 985-992.

ISO. 1984. *International Standard 7730, Moderate Thermal Environments—Determination of the PMV and PPD indices and specification of the conditions of thermal comfort*, 1st ed. Geneva: International Standards Organization.

ISO. 1994. *International Standard 7730, Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions of Thermal Comfort*, 2nd ed. Geneva: International Standards Organization.

Kempton, W., and L. Lutzenhiser, eds. 1992. *Energy and buildings*, vol. 18.

Kleinbaum, D.G., L.L. Kupper, and K.E. Muller. 1988. *Applied regression analysis and other multivariable methods*, 2d ed. California: Duxbury Press.

McCullough, E., and B.W. Olesen. 1994. Thermal insulation of chairs, *ASHRAE Transactions* 100(1): 795-802.

McIntyre, D.A. 1980. Design requirements for a comfortable environment. *Bioengineering: Thermal Physiology and Comfort*. K. Cena, and J.A. Clark, eds., pp.157-168. Amsterdam: Elsevier.

Nicol, J.F., and M.A. Humphreys. 1972. *Thermal comfort as part of a self regulating system. Proceedings of CIB Commission W45 Symposium—Thermal comfort and moderate heat stress*. Langdon, M.A. Humphreys, and J.F. Nicol, eds., pp. 263-274. Building Research Establishment Report. London: Her Majesty's Stationery Office (HMSO).

Nicol, F. 1993. *Thermal Comfort—A handbook for field studies toward an adaptive model*. United Kingdom: University of East London.

Nicol, J.F., G.N. Jamy, O. Sykes, M.A. Humphreys, S. Roaf, and M. Hancock. 1994. *A survey of comfort tempera-*

tures in Pakistan: Towards new indoor temperature standards. Oxford: Oxford Brookes Univ. (Report).

Nicol, J.F., and I.A. Raja. 1996. *Thermal comfort, time and posture: Exploratory studies in the nature of adaptive thermal comfort.* School of Architecture, England: Oxford Brookes University.

Oseland, N.A. 1995. Predicted and reported thermal sensation in climate chambers, offices and homes. *Energy and Buildings* 22: (in press).

Paciuk, M. 1990. The role of personal control of the environment in thermal comfort and satisfaction at the workplace. *Coming of age.* EDRA 21/1990. R.I. Selby, K.H. Anthony, J. Choi, and B. Orland, eds., pp. 303-312. Oklahoma City, Okla. U.S.: Environmental Design Research Association, xviii, 372 pp.

Parsons, K. 1994. Thermal comfort standards: Past, present and future, and open discussion that follows. In *Thermal Comfort: Past, present and future.* N.A. Oseland, and M.A. Humphreys, eds., pp.184-197. Garston, United Kingdom: BRE.

Prosser, C.L., ed. 1958. *Physiological adaptation.* Washington, D.C.: Am. Physiol. Soc.

Rohles, F.H., R.B. Hayter, and L.G. Berglund. 1977. Comfort and cold and warm discomfort during summer and winter in northern and southern United States. *ASHRAE Transactions* 83(1): 78-87.

Rowe, D., S.G. Lambert, and S.E. Wilke. 1995. Pale green, simple and user friendly: Occupant perceptions of thermal comfort in office buildings. In *Standards for thermal comfort.* J.F. Nicol, M.A. Humphreys, O. Sykes, and S. Roaf, eds., pp. 59-69. London: E and FN Spon.

Schiller, G., E. Arens, F. Bauman, C. Benton, M. Fountain, T. Doherty. 1988. A Field study of thermal environments and comfort in office buildings. *ASHRAE Transactions* 94(2): 280-308.

Sprague, C.H., and D.M. Munson. 1974. A composite ensemble method for estimating thermal insulating values of clothing. *ASHRAE Transactions* 80(1): 120-129.

Williams, R.N. 1995. Field investigation of thermal comfort, environmental satisfaction and perceived control levels in UK office buildings. *Healthy Buildings.*